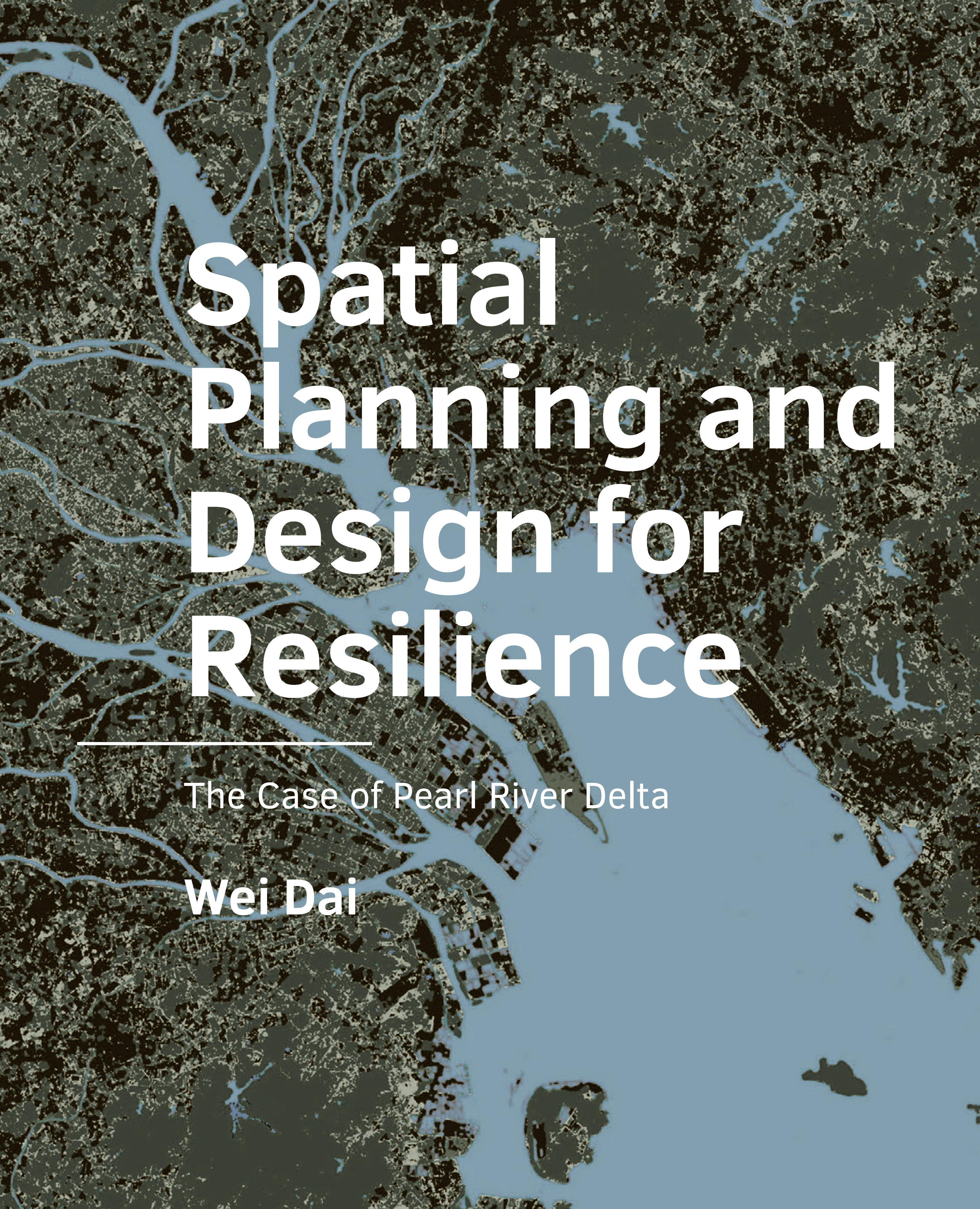

Spatial Planning and Design for Resilience

The Case of Pearl River Delta

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TOC

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Spatial Planning and Design for Resilience

The Case of Pearl River Delta

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Monday, 15 March 2021, at 10:00 o’clock

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To my dear family
To my dear friends

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TOC

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TOC

Contents

List of Tables

List of Figures

Summary

Pearl River Delta (abbreviated as the PRD) has become a pioneer region in China since the Reform and Open-door policy in 1978. After more than 40 years of rapid urbanization, the PRD has made remarkable improvements in its economic development. The PRD is one of three urban agglomerations, and it has the characteristics of the largest population concentration, the strongest innovation and the strongest comprehensive strength in China. At the same time, we should also be aware that the rapid economic development makes the land resources in the PRD scarce, and the role of the natural base layer has been ignored during the process of urbanization. Issues such as the extensive use of land resources, the fragmentation of the blue-green networks, the disorderly reclamation of sea areas, and the shrinkage of tidal flats alongside estuaries, etc. make the natural base layer of the PRD vulnerable. In recent decades, natural disasters, such as flooding, land subsidence, typhoon, and storm surges which occurred in the PRD have become more varied, frequent and destructive than those in other regions.

The future spatial development of the PRD is highly uncertain. Faced with the highly overlapping factors of the external disturbances -- natural disasters caused by extreme climate change, and internal interactions -- the contradiction between natural conditions and rapid urbanization, traditional spatial planning and design used to pursue economic development could not be flexible enough to respond to the dynamic and uncertain future of the PRD. In the future, spatial planning and design should pay great attention to the fragile natural base layer and unexpected external disturbances that will negatively impact the PRD caused by natural disasters, such as flooding and land subsidence situation. Therefore, it is of great theoretical and practical significance to research for a possible alternative approach to maintain the health of the natural base layer and to better adapt to the condition of climate change through spatial planning and design for resilience.

On the basis of an extensive study of current literatures, this doctoral dissertation deeply analyzes the current spatial system, previous planning and design practices of the PRD, as well as the case studies of the relevant spatial planning and design practices in other deltas in America and the Netherlands. Based on the idea of spatial resilience, the combination of ‘theoretical research and empirical validation’ is applied as the streamline of this research. The main theoretical attributes are researched, including the core capacities pursued by spatial planning and design for

resilience, the fundamental thinking characteristics of spatial planning and design for resilience, and the main spatial characteristics of resilience presented by planning and design. The knowledge obtained from the theory and the method is applied to the further empirical research of spatial planning and design for a resilient PRD.

The research question of this doctoral dissertation is '**What are the theories and methods of spatial planning and design for resilience? How is it possible to apply the theory and method of spatial planning and design for resilience to the PRD?**'. Based on that, this doctoral dissertation carries out a systematic research from four parts: theory, method, application and conclusion. The main research contents of this doctoral dissertation are as followings.

1 In order to understand the background of the PRD, literatures on exploring the physical context, the crucial stages of spatial transformation, as well as spatial planning and design practices of the PRD are reviewed. Spatial planning and design of typical deltas in America and the Netherlands are also studied from the perspective of both theory and practices, which can be applied as case reference.

2 The theory of spatial planning and design for resilience is systematically researched. Based on the analysis of the development of the concept of resilience, the meaning of resilience in this doctoral dissertation is explained. The core capacities pursued by spatial planning and design for resilience, the fundamental thinking characteristics of spatial planning and design for resilience, the main spatial characteristics of resilience presented by planning and design, and the internal thinking logic of the approach of spatial planning and design for resilience are systematically researched. The reasons why these characteristics can help to improve the capacity of resilience of a spatial system is explained in details. This doctoral dissertation systematically puts forward that the 'robustness and adaptability' are two core capacities pursued by spatial planning and design for resilience, the 'systematic, collaborative, bottom-line and foresight thinking' are four fundamental thinking characteristics of spatial planning and design for resilience, the 'regionality, connectivity, diversity, multifunctionality, redundancy and modularization' are six spatial characteristics of resilience presented by planning and design. It points out that the approach of spatial planning and design for resilience need to pay more attention to expound the understanding of driving forces such as nature, ecology, society and economy, and to emphasize that spatial development of the PRD must be built on basis that enough land carrying capacity can be provided and harmonious human-nature relationships can be established, based on a comprehensive grasp of the natural base layer and socio-economic development trends.

3 Implementation method for spatial planning and design for resilience is provided. Guided by the theory of spatial planning and design for resilience, this doctoral dissertation focuses on the way to transform the theoretical knowledge into the implementation method that can be conducted by spatial planning and design. The dissertation proposes a guiding ideology of spatial planning and design (process based) for resilience and explains its implementation principle, organization, and technical route. The key phases such as target determination, system interpretation, system projection, planning and design for resilience, evaluation and feedback are established. The operational guidelines of spatial planning and design for resilience are put forward.

4 The empirical research of the theory and method of spatial planning and design for resilient PRD is conducted and possible new schemes are produced. This doctoral dissertation takes the situation of huge precipitation and sea level rise caused by extreme climate change as external disturbances, and systematically analyses spatial status, spatial evolution and existing main problems in the PRD. Based on the projection of the future scenario under the condition of extreme climate change, the corresponding principles and strategies of spatial planning and design for the resilient PRD are researched in terms of land use, blue-green networks and coastline. From the perspective of land use, it proposes that future resilient land-uses distribution needs to combine the results of land-use suitability assessment. The possible new scheme of land use that consists of the spatial characteristics of 'three-circle coordinated space, four categories of land use' is put forward. From the perspective of blue-green networks, the possible new scheme is suggested by integrating regional natural environmental resources and creating cross-regional hydrological-ecological corridors, based on the technical assistance of minimum cumulative resistance (MCR) model. From the perspective of the coastline, the possible new scheme of coastline is provided with the contents of arranging the coastline function and creating coastline buffering belt, based on the technical assistance of coastline development suitability assessment.

5 The corresponding principles and strategies of resilient flood control and drainage on Hengli Island are proposed. Hengli Island is the most important core area of the Pearl Bay in the PRD. With the continuous urbanization on the island, the coordination between urbanization and water environment is very prominent. According to the theory and method of spatial planning and design for resilience, a new approach that can better lead the site to adapt to future climate change condition is proposed by widely applying the spatial characteristics of resilience that can be presented by planning and design, such as regionality, connectivity, diversity, multifunctionality, redundancy and modularization. Principles and strategies with modularized water collective units, improved water networks, classified inner-river

functions, diversified and multifunctional water storage spots, appropriate dykes' height, appropriate distance between dyke and shoreline, and multifunctional shorelines, etc. are proposed. Water level management measurements in different scenarios including regulation, self-drainage and artificial-extraction with the combination of nature-based work and civil engineering are proposed. The new scheme of resilient flood control and drainage can integrate the function of both flood control and drainage and landscape-viewing together.

Key words: Resilience; Spatial planning and design; Principle and Strategy; Climate change; Pearl River Delta;

Samenvatting

De Parelrivierdelta (afgekort tot PRD) is sinds de hervorming en het 'Open Deur'-beleid van 1978 in China een pioniersgebied geworden. Na meer dan veertig jaar van snelle verstedelijking is de economische ontwikkeling van de PRD opmerkelijk verbeterd. De PRD is een van drie stedelijke agglomeraties en wordt gekenmerkt door de hoogste bevolkingsconcentratie, de sterkste innovatie en de grootste algehele sterkte van China. Tegelijkertijd mag niet uit het oog worden verloren dat de snelle economische ontwikkeling ertoe heeft geleid dat de bodemschatten in de PRD schaars zijn geworden, en dat de rol van de natuurlijke onderlaag tijdens het verstedelijkingsproces is genegeerd. Het intensieve gebruik van bodemschatten, de fragmentering van blauw-groene netwerken, de onordelijke drooglegging van zeegebieden en de afname van droogvallende platen langs estuaria en dergelijke hebben de natuurlijke onderlaag van de PRD kwetsbaar gemaakt. De afgelopen decennia zijn natuurrampen zoals overstromingen, bodemdaling, tyfoons en stormvloeden die zich voordoen in de PRD gevarieerder, frequenter en destructiever geworden dan in andere regio's.

De toekomst van de ruimtelijke ontwikkeling van de PRD is zeer onzeker. Gezien de zeer grote overlap tussen externe verstorende factoren – natuurrampen veroorzaakt door extreme klimaatverandering en interne interacties – en de tegenstelling tussen de natuurlijke omstandigheden en snelle verstedelijking, zijn traditionele ruimtelijke planning en ontwerp gericht op economische ontwikkeling mogelijk niet flexibel genoeg om in te spelen op de dynamische en onzekere toekomst van de PRD. In de toekomst zal bij ruimtelijke planning en ontwerp bijzondere aandacht moeten worden besteed aan de fragiele natuurlijke onderlaag en onverwachte externe omstandigheden die als gevolg van natuurrampen zoals overstromingen en bodemdaling negatieve gevolgen zullen hebben voor de PRD. Daarom is het van groot theoretisch en praktisch belang om onderzoek te doen naar een mogelijke alternatieve benadering van het in een goede staat houden van de natuurlijke onderlaag en de klimaatverandering beter op te vangen door ruimtelijke planning en ontwerp te richten op veerkracht.

In deze dissertatie wordt op basis van een uitgebreide studie van de actuele literatuur een diepgravende analyse gepresenteerd van het huidige ruimtelijke systeem, eerdere plannings- en ontwerppraktijken in de PRD én de casestudy's van de relevante ruimtelijke plannings- en ontwerppraktijken in andere delta's in

Amerika en Nederland. Uitgaand van het concept ‘ruimtelijke veerkracht’ wordt in dit onderzoek een combinatie van theoretisch onderzoek en empirische validatie toegepast. De voornaamste theoretische kenmerken worden onderzocht, inclusief de kerncapaciteiten die bij ruimtelijke planning en ontwerp gericht op veerkracht worden nagestreefd, de fundamentele gedachtegang achter ruimtelijke planning en ontwerp gericht op veerkracht en de voornaamste kenmerken van veerkracht die in planning en ontwerp tot uiting komen. De kennis die vanuit de theorie en de methode is opgedaan wordt toegepast bij verder empirisch onderzoek naar ruimtelijke planning en ontwerp gericht op een veerkrachtige PRD.

De onderzoeksvraag van dit proefschrift is ‘**Wat zijn de theorieën en methoden van ruimtelijke planning en ontwerp voor veerkracht? Hoe is het mogelijk om de theorie en methode van ruimtelijke ordening en ontwerp voor veerkracht toe te passen op de PRD?** ’ Gebaseerd op dat, in deze dissertatie wordt systematisch onderzoek uitgevoerd in vier delen: theorie, methode, toepassing en conclusie. De voornaamste onderzoeksinhoud van deze dissertatie is als volgt.

1 Om inzicht te krijgen in de achtergrond van de PRD wordt literatuur beoordeeld over de fysieke context, de cruciale fases van ruimtelijke transformatie en ruimtelijke plannings- en ontwerppraktijken in de PRD. Daarnaast worden vanuit het perspectief van zowel theorie als praktijk de ruimtelijke planning en ontwerp in karakteristieke delta’s in Amerika en Nederland bestudeerd, die als referentiecasus kunnen worden gebruikt.

2 De theorie van ruimtelijke planning en ontwerp gericht op veerkracht wordt systematisch onderzocht. Op basis van de analyse van de ontwikkeling van het concept veerkracht wordt de betekenis van ‘veerkracht’ in deze dissertatie uitgelegd. De kerncapaciteiten die bij ruimtelijke planning en ontwerp gericht op veerkracht worden nagestreefd, de fundamentele gedachtegang achter ruimtelijke planning en ontwerp gericht op veerkracht en de voornaamste ruimtelijke kenmerken van veerkracht die in planning en ontwerp tot uiting komen worden systematisch onderzocht, evenals de interne mentale logica van de benadering van ruimtelijke planning en ontwerp gericht op veerkracht. Er wordt in detail ingegaan op de redenen waarom deze kenmerken de capaciteit voor veerkracht van een ruimtelijk systeem kunnen helpen verbeteren. In deze dissertatie wordt systematisch betoogd dat ‘robuustheid en aanpassingsvermogen’ twee kerncapaciteiten zijn die worden beoogd door ruimtelijke planning en ontwerp gericht op veerkracht, dat ‘systematisch, samenwerkingsgericht, bottom-line en vooruitziend denken’ vier fundamentele kenmerken zijn van de gedachtegang achter ruimtelijke planning en ontwerp gericht op veerkracht en dat ‘regionaliteit, connectiviteit, diversiteit, multifunctionaliteit, redundantie en modularisering’ zes ruimtelijke aspecten van

veerkracht zijn die tot uiting komen in planning en ontwerp. Er wordt op gewezen dat bij de benadering van ruimtelijke planning en ontwerp gericht op veerkracht meer aandacht moet worden besteed aan het uitdiepen van inzicht in drijvende krachten zoals de natuur, ecologie, de maatschappij en de economie, en er wordt benadrukt dat de basis voor de ruimtelijke ontwikkeling van de PRD wordt gevormd door het realiseren van voldoende draagkracht van het land en het bewerkstelligen van harmonieuze relaties op basis van volledig inzicht in de natuurlijke onderlaag en trends in de sociaaleconomische ontwikkeling.

3 Er wordt een methode geboden voor de uitvoer van ruimtelijke planning en ontwerp gericht op veerkracht. Deze dissertatie focust zich, geleid door de theorie van ruimtelijke planning en ontwerp gericht op veerkracht, op de wijze waarop theoretische kennis kan worden omgezet in een methode voor de uitvoer van ruimtelijke planning en ontwerp gericht op veerkracht. In deze dissertatie wordt een leidende ideologie voor ruimtelijke planning en ontwerp gericht op veerkracht voorgesteld en worden het principe, de organisatie, het technische traject en het proces voor de uitvoering van ruimtelijke planning en ontwerp gericht op veerkracht uiteengezet. De belangrijkste fases, zoals het vaststellen van targets, systeeminterpretatie, systeemprojectie, planning en ontwerp gericht op veerkracht, evaluatie en feedback, worden vastgesteld. De operationele richtlijnen voor ruimtelijke planning en ontwerp gericht op veerkracht worden gepresenteerd.

4 Er wordt empirisch onderzoek gedaan naar de theorie en methode van ruimtelijke planning en ontwerp gericht op een veerkrachtige PRD en er worden potentiële nieuwe schema's geproduceerd. In deze dissertatie worden de enorme neerslag en zeespiegelstijging die het gevolg zijn van extreme klimaatverandering als externe verstoringen beschouwd en wordt een systematische analyse uitgevoerd van de ruimtelijke status, ruimtelijke evolutie en voornaamste bestaande problemen in de PRD. Op basis van de projectie van het toekomstscenario bij extreme klimaatverandering worden de daarbij behorende uitgangspunten en strategieën van ruimtelijke planning en ontwerp gericht op een veerkrachtige PRD onderzocht in termen van landgebruik, blauw-groene netwerken en de kustlijn. Vanuit het perspectief van landgebruik wordt voorgesteld dat bij een toekomstige veerkrachtige verdeling van het landgebruik de resultaten van een beoordeling van de geschiktheid van landgebruik moeten worden meegenomen. Er wordt een potentieel nieuw schema voor landgebruik gepresenteerd dat als ruimtelijke kenmerken 'in drie cirkels gecoördineerde ruimte en vier categorieën van landgebruik' heeft. Vanuit het perspectief van blauw-groene netwerken wordt een mogelijk nieuw schema gesuggereerd door de integratie van regionale natuurlijke rijkdommen uit de omgeving en het creëren van transregionale hydrologisch-ecologische corridors, gebaseerd op technische ondersteuning aan de hand van een 'minimum cumulative

resistance’-model (MCR). Vanuit het perspectief van de kustlijn krijgt het mogelijke nieuwe schema voor de kustlijn een ordening van de kustlijnfunctie en de creatie van een bufferzone voor de kustlijn, gebaseerd op technische ondersteuning in de vorm van een beoordeling van de geschiktheid van kustlijnontwikkeling.

5 Er worden corresponderende uitgangspunten en strategieën voor veerkrachtige bestrijding van overstromingen en afwatering op het eiland Hengli voorgesteld. Het eiland Hengli is het belangrijkste kerngebied van de Parelbaai in de PRD. Door de aanhoudende verstedelijking van het eiland is de afstemming tussen de verstedelijking en de wateromgeving van groot belang. Aan de hand van de theorie en methode voor ruimtelijke planning en ontwerp gericht op veerkracht wordt een nieuwe methode voorgesteld waarmee de locatie zich beter kan aanpassen aan toekomstige klimaatverandering door een brede toepassing van de ruimtelijke kenmerken van veerkracht die tot uiting kunnen komen in planning en ontwerp, zoals regionaliteit, connectiviteit, diversiteit, multifunctionaliteit, redundantie en modularisering. Er worden uitgangspunten en strategieën voorgesteld met gemodulariseerde collectieve watereenheden, verbeterde waternetwerken, geclassificeerde functies voor de binnenrivier, gediversifieerde en multifunctionele wateropslaglocaties, passende dijkhoogtes, passende afstanden tussen dijk en kustlijn, multifunctionele kustlijnen et cetera. Er worden maatregelen voor waterbeheer voor verschillende scenario’s voorgesteld, waaronder regulering, eigen afwatering en kunstmatige extractie met een combinatie van op de natuur gebaseerde werken en civiele techniek. Het nieuwe schema voor veerkrachtige overstromingsbestrijding en afwatering kan de functies van overstromingsbestrijding en afwatering combineren met die van landschapsbezichtiging.

Trefwoorden: Veerkracht; Ruimtelijke planning en ontwerp; Uitgangspunten en strategie; Klimaatverandering; Parelrivierdelta;

TOC

1 Introduction

1.1 Problem statement and the significance of research

1.1.1 Problem statement

The Pearl River Delta (abbreviated as PRD) is located in the South-Central Guangdong province, P.R.China (Figure 1.1). It is formed by alluvial flowing water and sand from the West, North, East, and Pearl Rivers. It covers an area of 11,281 square kilometers and has a permanent resident population of 66 million, including 9 cities of Guangzhou city, Shenzhen city, Foshan city, Dongguan city, Zhongshan city, Zhuhai city, Jiangmen city, Zhaoqing city, and Huizhou city.

The PRD is surrounded by mountains and hills in the east, west, and north side. Its south side reaches the South China Sea (Figure 1.2). The Great PRD (GPRD), also known as Chinese south gate, comprises 12 cities which include Hong Kong Special Administrative Region, and the Macao Special Administrative Region.

The PRD has a subtropical climate with an average annual temperature of 23-26°C (China Climate Net, 2019). Strong typhoons and concentrated rainfall often occur from June to October every year. The average annual rainfall is over 1500 mm. Average annual evaporation is 900-1600 mm (Global Water Partnership, 2016). The rainfall in the wet season accounts for more than 80% of the annual rainfall. The PRD is also subsiding at an average rate of about 1.5-2.0 mm/year (Guangzhou Water Bureau, 2014). In the PRD, geomorphological types are diverse. Soft soils are widely distributed. The size of plains accounts for 49.2% of the total areas (Dong et al., 2012).

FIG. 1.1 Location of PRD in China

The PRD is a pioneer region under the policy of ‘Reform and Open-door’ in China. Thanks to these policies, the PRD has improved its innovation capacity and has experienced the most comprehensive socio-economic development in China. According to the 2015 World Bank report, the PRD has overtaken Tokyo by becoming the world’s largest cluster of cities, in terms of both population and the size of areas (World Bank, 2015). Recently, the PRD has partnered with Hong Kong and Macao to create the Guangdong-Hong Kong-Macao Greater Bay Area, which together creates one of the four major bay areas in the world (World Bank, 2015).

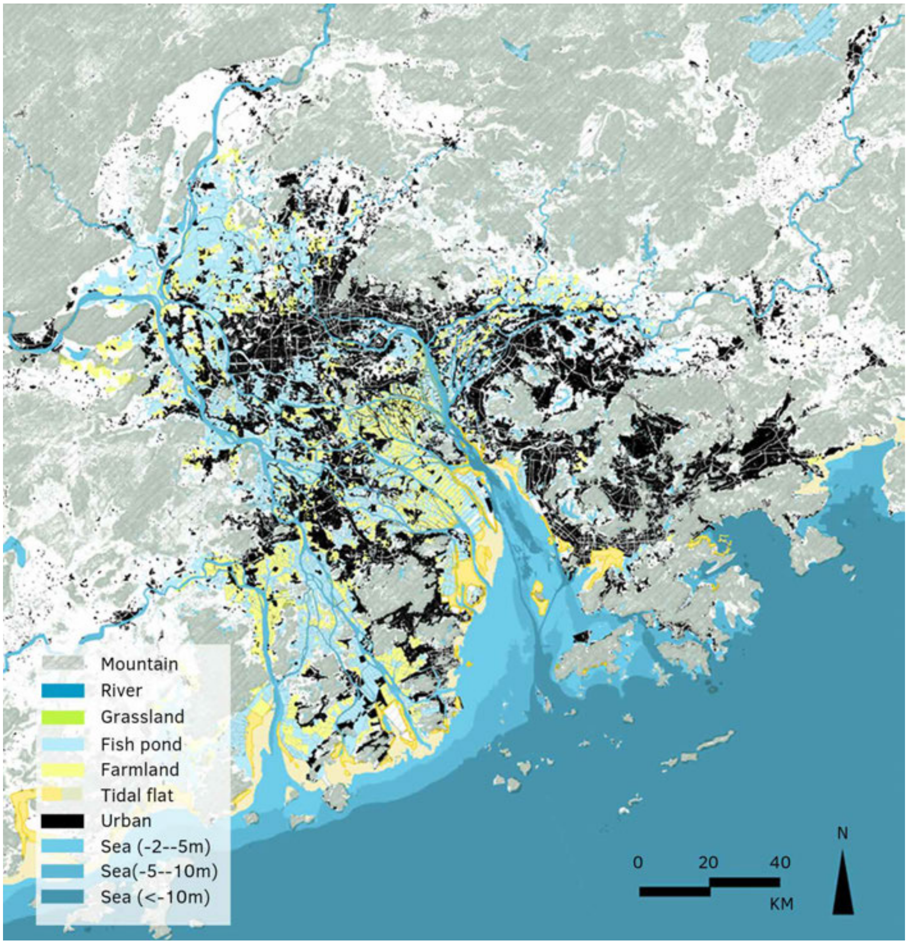


FIG. 1.2 Current spatial layout with multi-layer structure in the PRD

According to the evolution rate, most of the delta can be divided into a multi-layer structure based on the flow of spatial elements (Meyer et al., 2015). The first layer is the natural base layer, which is composed of soil, water, and ecologically significant green space. Although this layer has the slowest evolution rate, it has obvious effects on the development of other layers. The second layer is the infrastructure network layer, consisting of water conservancy, the municipal and transportation network, where development is restricted by the natural base layer. The third layer is the urban occupation layer, which is composed of land-use, shipping ports, industry, agriculture, fishing, and animal husbandry, etc., with the fastest evolution rate and the most human influences. The spatial elements of each layer have fluidity and are closely related with each other.

The evolution of the natural base layer is deeply influenced by natural forces. The flow of natural elements greatly affects the layout of space. Topography, landform, geological structure, climate, and hydrology all are natural factors in the delta, which has specific natural attributes. The natural base layer is the material carrier for the formation and growth of various spatial elements in the delta, and it is the support and foundation for shaping the infrastructure network and urban occupation layer. Rivers, lakes, and mountains are important features and guide the direction, function, and spatial layout of urban spatial development.

The landscape pattern in the PRD is the result of the long-term interaction between nature, society, economy, culture, and other elements. Its spatial structure dynamically changed in time and layered in elements.

A detailed historical background of the PRD can be seen in Appendix A. Conclusively, after 40 years' rapid development, the following main problems exist in the current spatial system of the PRD.

1 **The fundamental role of the natural base layer is neglected**

Compared with the layers of infrastructure network and urban occupancy, the role of the nature base layer has been neglected during the rapid urbanization of the PRD. The interdependence among the nature base layer, infrastructure network and urban occupation layer is disrupted, which leads to the PRD being increasingly exposed to the shortcomings of the spatial characteristics of low-lying areas. Urban space presents the phenomenon of unsustainable occupation that is not coherent with land carrying capacity, which causes water and ecosystems to become increasingly fragile. Some key blue-green spaces have been eroded by rapid urban development. The natural order of rivers is gradually broken down in the process of urbanization. Some key hydro-ecological transition zones and blue-green corridors lack protection. The coastline has been reclaimed considerably.

1 Blue-green space are fragmented inside urban areas

2 High-valued mountain areas are gradually reclaimed

3 Dyke occupies valuable waterfront

4 Roads are built on the waterways that impair the ecosystem service

FIG. 1.3 Real photos that shows the natural base layer is neglected

2 **The water environment has been changed and tidal flats have been reduced**

Fluvial and pluvial flooding and seawater intrusion are the biggest climate disturbance to the PRD. Large-scale land reclamation activities have led to the continuous decrease of natural shorelines, which increases the siltation of surrounding river channels and estuaries, raises water levels under extreme climate condition, destroys the balance of runoff dynamics, directly weakens the tidal energy of estuaries and upstream river networks, and increases the frequency of tidal occurrence. Due to a large number of construction requirements, the riverbed form has been changed greatly, which aggravates the pressure on flood controls in surrounding cities. Some buildings constructed on water surfaces have reduced the capacity of rivers to transfer or store excess water, which causes congestion at river crossings, leads to accumulated floodwaters, and affects the safety of flooding channels in upstream and midstream areas.

1 Inner-rivers are narrowed by concrete dykes

2 Urban space are fragmented by dykes

3 Coastline is polluted

4 Tidal flats are broken

FIG. 1.4 Real photos that shows the water environment is changed and tidal flats are reduced

3 The pattern of extensive land-use is unsustainable

The natural base layer is the cornerstone of the spatial structure in the PRD and the framework for urban development. Presently, the contradiction is prominent between the increasing construction demand and the intensive model of land-use. Unsustainable land-use leads to squeezed hydro-ecological space, which intensifies the contradiction between humans and nature. The constructible land resources in the PRD are approaching exhaustion.

1 Natural space is distructed for real estate

2 Disconnected ditches are polluted by surrounding urban space

3 Factory with high pollution is constructed alongside waterfront

4 Urban areas gradually occupies valuable agricultural lands

FIG. 1.5 Real photos that shows the unsustainable extensive land use situation

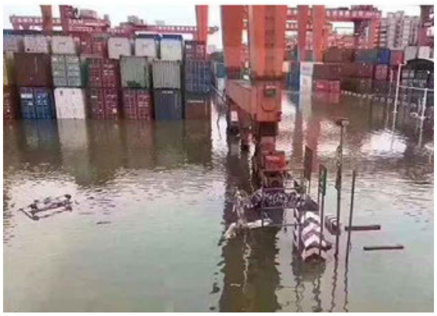
TOC

4 **The problem of flood control and drainage under extreme climate change is challengeable**

Climate change has become the most uncertain factor affecting the future development of the PRD. The impact of extreme climate condition on the PRD has intensified in the past two decades. Due to the low-lying terrain of the region, the elevation differences across the basin are obvious. Many important large rivers in the PRD are under great flood pressure, which causes the phenomenon of accumulated floodwaters. Since 2006, there have been more than 10 severe storms that caused flooding in major rivers (Peng et al., 2019). The problem of flood control and drainage under extreme climate condition is prominent.

1 Extreme precipitation causes serious waterlogging

2 Fluvial flooding submerge surrounding residential areas alongside rivers



3 Tidal flooding causes malfunction of international port

4 Storm surge distories high-valued natural areas

FIG. 1.6 Real photos that shows the challengeable flooding events caused by extreme climate change

1.1.2 Literature review and research gaps

After understanding the problems in the PRD, a literature review on the theory and practice of spatial planning and design in the delta, which can be seen in Appendix B is conducted. There are still two major research gaps that deserve to be paid enough attention.

A Research gaps in the theory and method on spatial planning and design for the delta

The adaptability of the delta to flooding is the key to improve the spatial resilience of the delta in the future

One of the biggest uncertainties facing the development of the delta in the future is sea level rise and extreme precipitation caused by climate change. Some scholars have established the framework of environmental assessment from the aspects of spatial form and elements. For example, Costanza et al. (1997), Millennium Ecosystem Assessment (2005) established an ecosystem service evaluation model which provides a basis for evaluating spatial elements from the aspect of ecosystem functions. Alberti (2008) used the environmental assessment model to study a variety of spatial forms of the Puget Delta in American, and determined the threshold of the corresponding indicators. Lijdsman (2019) discussed the relationship between the distribution of spatial elements and the effects of flood control and drainage in Rotterdam under multiple scenarios. Tai (2018) expounded the mechanism of urban water system in response to climate change from the perspective of water system value.

Some scholars studied the spatial vulnerability assessment model by combining methods such as historical disaster data statistics, comprehensive index method, functional model method, ArcGIS spatial overlay analysis, questionnaire, expert guidance, and analytic hierarchy process (Meerow et al., 2016; Michael & Jule, 2007; Cariloet et al., 2019). IPCC (2014) established an evaluation system based on exposure, sensitivity and adaptive ability to evaluate flood control capacity. Adnan et al. (2020) drew a map of rainstorm flood vulnerability assessment in New York based on various future land use development scenarios. Adnan et al. (2020) drew a map of flood vulnerability in New York based on various future land use development scenarios.

TOC

Some researchers studied strategies from the perspective of natural-based solution. Bacchin (2015) proposed the idea of regulating multi-scale blue-green network to deal with rainwater flooding. The 'Big U' project in New York prevented the waterfront from rainstorms and sea level rise by constructing a multifunctional sea wall (New York Government, 2014). Staten Island adopted ecological dykes to prevent storm surge disasters and purify rainwater (New York Government, 2014). The project of Dutch 'the Hague Zandmotor' advocated natural-based strategies to resist the process of continuous coastline erosion (Slobbe et al., 2013).

Some researchers studied strategies from the perspective of mitigation in order to reduce the frequency of natural disasters. Zeeliner (2016) analyzed the flood mitigation effect of green infrastructure in delta cities. 0 'Malley (2014) used the ENVI-MET model to study the impact of building forms on the mitigation of urban heat island effect and storm flood risk.

At present, in response to the flooding issues caused by climate change in the delta, there is still an absence of a methodology of spatial planning and design, which includes spatial evolution, vulnerability assessment, future scenario projection, planning and design, evaluation. The key of delta spatial planning and design in the future is to improve the ability of delta spatial system to respond to climate change.

Planning and design based on deterministic environment and single scale cannot well cope with future disturbances

The delta is essentially a complex system with multiple temporal and spatial attributes. The analysis of delta spatial system from the perspective of multiple spatial and temporal scales and multiple elements is the foundation of delta spatial planning and design (Batty, 2003; Portugali et al., 2012; Meyer et al., 2015) . Meyer (2010, 2012, 2015) proposed a 'Layer-model' which decompose the delta space into the natural base layer, the infrastructural layer, and the occupancy layer. Xiong (2020) proposed a planning and design mapping method based on multi-scale and multi-disciplinary interaction. Cai (2018) proposed a research method of spatial evolution from three spatial scales and four elements. Kim et al. (2016) and Lin et al. (2020) combined the Landscape Dynamic Succession Analysis Model (SD) with the Cellular Automata (CA) to simulate the evolution characteristics of the delta urban system. Alexander (2016) and Shaw (2007) illustrated the relationship between diversity and post-disaster economic losses at a micro scale. The Dutch 'Room for Rivers' project proposed a corresponding planning and design scheme based on the short-term water level rise data of the Waal River (Ruimtevoorderivier, 2014).

The Great New Orleans Water Plan put forward suggestions on the improvements of blue-green networks from the meso scale (Great New Orleans Water Plan, 2012).

There is still a lack of understanding of the particularity of the natural base layer of the delta. It is necessary to study the spatial coupling mechanism, the layout of blue-green network, the systematises and coordination of different spatial scales' planning and design and multiple elements in order to improve the resilience of the delta to environmental change.

Lack of research on spatial planning and design for resilience

The PRD is a complex social-ecological system. The contradiction between special geographical conditions and rapid urbanization is the internal cause of the vulnerability of the spatial system in the PRD, while the uncertainty of climate change is an external factor that exacerbates the vulnerability of the spatial system in the PRD. Facing the challenge of future development in the PRD, future spatial planning and design should start from the overall situation, and properly handle the dialectical relationship among land carrying capacity, natural base layer protection and urban development. The idea of resilience offers a possible spatial planning and design approach to achieving this goal.

Achieving the goal of resilience requires the collaborative effects among planners and designers, social economists, ecologists, and political scientists. Existing literatures that studied on resilience are very diverse. Most of them focus on the aspects of the interpretations of resilience and the assessment of the vulnerability. For instance, the research of resilience in the field of ecology focuses more on a system's ability to withstand disturbances and its recovery time. The research on resilience in the field of social economics focuses more on the self-organization, learning and adaptability of a system. The results of studies provided by different disciplines come to very broad. For example, Foster (2014) believed that resilient cities are independent, diverse, and renewable. Wildavsky (1988) believed that a resilient city should have six characteristics such as dynamic balance, multi-compatibility, efficient flow, flat feature buffering and moderate redundancy. Allan & Bryant (2011) believed that resilient cities should be of variability, adaptability to change, modularity, innovation, rapid response, saving ability of social capital, and ecosystem services. Forgaci (2018) proposed 35 indexs of resilient cities Colding (2007) believed that spatial form, land use and urban sprawl efficiency are main evaluation indexes of resilient cities. Newman et al. (2009) stated that resilient cities are of redundancy, modularity, flatness, intelligence, feedback, cooperation and mobility.

In existing literatures, specific studies on the theory and implementation method of spatial planning and design for resilience are still absence. It is necessary to focus on the spatial elements and systematically study on the theory of spatial planning and design for resilience including several aspects such as core capacities pursued by spatial planning and design for resilience, fundamental thinking characteristics of spatial planning and design for resilience, main spatial characteristics of resilience presented by planning and design, and internal thinking logic of the approach of spatial planning and design. Only when the features and spatial characteristics are theoretically understood can the concept of resilience be transformed into implementation method and organization guidelines, which lays a theoretical foundation for the application of spatial planning and design for resilience in the delta.

B Research gaps in the previous spatial planning and design practice of the PRD

In the past 40 years, there have been some problems in the PRD, such as the neglect of the basic role of the natural base layer, the deterioration of the water environment and the shrinking of the tidal flats, unsustainable land-use pattern, and challengeable flood control and drainage system, which are mainly reflected in the following three aspects in the previous spatial planning and design practice of the PRD.

Overemphasis on the economic benefits of land use

In the past 40 years, the PRD has achieved a rapid increase in population and urbanization. In order to meet this achievement, the previous spatial planning and design practice of the PRD excessively pursued the economic benefits of land use. The constrain of delta natural base layer on spatial development has not been paid enough attention. Most of the land use patterns in the planning and design documents of the PRD were simply based on the data of population, economy and land development costs. For instance, whole land-use scheme in the PRD was formed based on directly use the land-use pattern of each city in *1994-2020 Scheme of economic metropolitan area in the PRD (Guangdong institute of urban and rural planning, 1994)*. The land-use method in *2004-2020 scheme for coordinated development of metropolitan areas in the PRD (Guangdong institute of urban and rural planning, 2008)* promoted the development of urbanization, but had insufficient analysis of the hydro-ecological environment factors. Therefore, the results of assessment of land-use suitability are not solid and the projections of multiple scenarios for the future development are not scientific.

Overemphasis on engineering-based flood control and drainage methods

The flood control and drainage system in the PRD has experienced the process of traditional flood control and drainage and engineering-based flood control and drainage. The engineering-based flood control and drainage system is mainly used to prevent flooding in the PRD at present. Although the constructions of dykes and dams in upstream can prevent excessive water and generate electricity, these dykes and dams actually separate the internal and external original water systems and block water circulation, which have a significant negative impact on the flexible swing of the rivers and the erosion and sedimentation phenomenon of coastline. Large-scale reservoirs have weakened the network connectivity of regional water corridors, which lead to an increasing amount of peak discharge in upstream and the imbalance of the diversion proportion of the peak discharge in downstream. This kind of engineering-based flood control and drainage method was reflected in the flood control and drainage planning and design documents of *Planning for Flood Control and Drainage of the PRD (2010)* and *The Planning and Design of Flood and Tide Surfaces of the Lower West and North Rivers in PRD (2012)*. The flooding issues caused by climate change fail to be well dealt with by raising the height of dykes and intensify the drainage pipe network.

Security risks along the coastline

Coastline is an important spatial element to ensure the security of the PRD and first spatial barrier to improve the hydrological and ecological environment, which has the regional characteristics of the boundary between land and water. The key of the spatial planning and design of the PRD is to ensure the smooth flow of the main estuaries, and to construct the system of dynamic ecological flood control and drainage which have the functions of seepage, stagnation, storage, utilization, purification and drainage. The previous planning and design schemes of the PRD fail to make good use of the characteristics of the coastline of the PRD, which result in the unreasonable functional division of the coastline area and the insufficient distance of coastal buffer belts. *In 2004-2020 Scheme for Coordinated Development of Metropolitan Areas in the PRD (Guangdong institute of urban and rural planning, 2004)*, *2015-2020 Spatial Planning and Design of the PRD (Guangdong institute of urban and rural planning, 2015)*, the improvement of coastline and regional blue-green network was only proposed at the conceptual level, which lacked an in-depth study on how to improve the security level of the coastline from the aspects of the re-arrangement of coastline’s function and creation of coastal buffering belt.

In summary, the cognition of the above two aspects is an important basis for the formulation of the research objectives, research contents and research routes of this doctoral dissertation.

1.1.3 Research questions

Faced with the challenges of future development in the PRD, the traditional method of planning and design that used to pursue economic development as the main objective is no longer sustainable, when considering fragile natural base layer and unexpected impacts posed by the changing climate (IPCC, 2014). In the future, spatial planning and design of the PRD should face the inevitability of extreme climate disturbances in the delta, properly consider the dialectical relationship between urbanization and natural protection, and make spatial resilience as a primary goal for planning and design.

Since the concept of resilience was put forward, research on the topic of resilience has been deepened. Based on existing literature, research on resilience has been conducted from various perspectives, most of which are from the fields of sociology, economy, ecology, disaster prevention, etc., and the research conclusions are very broad. It has not been found that the theory of spatial planning and design for resilience are systematically studied from the field of planning and design.

Based on above understanding, this doctoral dissertation aims to provide answers to the following research questions.

Overall Research Question:

What are the theories and methods of spatial planning and design for resilience? How is it possible to apply the theory and method of spatial planning and design for resilience to the PRD?

This overall question consists of five research questions. Each research question (Q) consists of several sub questions (SQ). All these sub questions will be explicitly reflected in the final conclusion and discussion chapter, which will be gradually developed in this doctoral dissertation.

Q1: What is the scientific basis for transforming traditional planning and design into a new method of spatial planning and design for resilience in the PRD?

- **SQ1-1:** What are the main existing problems in the PRD?
- **SQ1-2:** What role can spatial planning and design for resilience play in addressing the above problems in the PRD?

Q2: How is it possible to improve the resilience of a spatial system?

- **SQ2-1:** What does the resilience mean in this doctoral dissertation? What are the core capabilities under the theory of spatial planning and design for resilience?
- **SQ2-2:** How is it possible to improve the core capabilities of robustness and adaptability in spatial planning and design?
- **SQ2-3:** What are the fundamental thinking characteristics of spatial planning and design for resilience?
- **SQ2-4:** What are the main spatial characteristics that can be presented by spatial planning and design for resilience?
- **SQ2-5:** What is the internal thinking logic of spatial planning and design for resilience?
- **SQ2-6:** What are the innovations of the approach of spatial planning and design for resilience?

Q3: How is it possible to implement the theory of spatial planning and design for resilience in to practice?

- **SQ3-1:** How can we organize the work of spatial planning and design for resilience?
- **SQ3-2:** What is the process of spatial planning and design for resilience?
- **SQ3-3:** What can be the key points of spatial planning and design for resilience at different scale?

Q4: How is it possible to apply the theory of spatial planning and design for resilience to the PRD?

- **SQ4-1:** What could be the general spatial planning and design framework of spatial planning and design for resilient PRD?
- **SQ4-2:** What are the characteristics of current spatial status in the PRD?
- **SQ4-3:** What could be principles for improving land-use distribution in resilient PRD?
- **SQ4-4:** How can we improve land-use distribution based on land-use suitability assessment in resilient PRD?
- **SQ4-5:** What could be principles for improving blue-green network in resilient PRD?

- **SQ4-6:** How can we improve the blue-green networks based on minimum cumulative resistance (MCR) model in resilient PRD?
- **SQ4-7:** What could be principles for improving coastline quality in the PRD?
- **SQ4-8:** How can we arrange the coastline function and create buffering belt based on coastline development suitability assessment in resilient PRD?

Q5: How is it possible to apply the theory of spatial planning and design for resilience to address the flood control and drainage problem on Hengli Island?

- **SQ5-1:** What can be the general framework of spatial planning and design for resilient flood control and drainage on Hengli Island?
- **SQ5-2:** What spatial planning and design strategies and measures for resilience can be taken in resilient flood drainage on Hengli Island?
- **SQ5-3:** What spatial planning and design strategies and measures can be taken in resilient flood prevention on Hengli Island?
- **SQ5-4:** How can the new scheme adapt to more severe extreme climate?
- **SQ5-5:** How can one evaluate the scheme's effectiveness for resilient flood control and drainage?

1.1.4 Research significance

To prepare for future challenges, this doctoral dissertation considers that the traditional spatial planning and design of the PRD should be transformed into an alternative, resilient approach. Planning and design should consider the overall situation of a spatial system and correctly consider the dialectical relationship between natural carrying capacity and urban development. It should set up the bottom-line thinking, face the unavoidable disturbances caused by extreme climate change in the delta, and take the initiative to address external disturbances caused by climate change based on foresight thinking. Spatial planning and design for resilience should attach great importance to the full cognition of the evolution, flow process and surface/subsurface structure of various elements in the PRD's spatial system and strengthen the research and effective prevention of possible scenarios in the future. Planning and design should start from systematic thinking and look for multi-factor and multi-scale collaboration. The focus should be on improving the robustness of the natural base layer, the connectivity of the blue-green network, and ensuring spatial safety, so as to guide the way for spatial development based on the concept of resilience. Through the foresight and guidance of spatial planning and context sensitive design measures, the spatial system can largely reduce the impact caused by external disturbances and maintain its core function and structure.

1.2 Research contents and objectives

This doctoral dissertation systematically studies the theory of spatial planning and design for resilience, and applies the theoretical research results to the PRD. Research contents and objectives are organized based on above research questions and sub-questions.

Research content 1: Research on the theory of spatial planning and design for resilience

On the basis of an extensive literature review, this doctoral dissertation systematically studies the theory of spatial planning and design for resilience from a system point of view. The main research contents include: (1) What are the core capabilities pursued by spatial planning and design for resilience? (2) What are the fundamental thinking characteristics of spatial planning and design for resilience? (3) What are the spatial characteristics of a resilient space? (4) What is the internal relationship between the above spatial characteristics? (5) What are the special characteristics of the method of spatial planning and design for resilience?

Corresponding research objective 1: The theoretical basis of spatial planning and design for resilience with core capabilities, thinking characteristics and spatial characteristics is researched. The reasons why these core capabilities, thinking characteristics, and spatial characteristics pursued by spatial planning and design can improve the level of resilience of a system are researched. The theoretical knowledge lays the foundation for further research on the method of spatial planning and design for resilience and the empirical research in the PRD.

Research content 2: Theoretical research for the implementation method of spatial planning and design for resilience

The implementation method of the theory of spatial planning and design for resilience is studied. The main research contents include: target determination, system interpretation, system projection, spatial planning and design for resilience, and evaluation and feedback.

Corresponding research objective 2: The key points of macro-, meso-, and micro-scale spatial planning and design for resilience are clarified and the implementation method of spatial planning and design for resilience is put forward from the perspective of principles, organizational work, technical route, and management of the planning and design process.

Research content 3: Empirical research on spatial planning and design for resilient PRD.

Under the guidance of theory and implementation methods for spatial planning and design for resilience, empirical research on spatial planning and design for resilient PRD is systematically conducted on the basis of an in-depth study on the spatial evolution and climate scenario projections of the PRD.

Corresponding research objective 3: Under the context of huge precipitation, sea level rise and extreme land subsidence, the main spatial problems and future risks of the PRD are systematically analysed and the strategies of spatial resilience planning and design for the PRD are proposed from the aspects of land-use, blue-green networks, and coastline.

Research content 4: Empirical research on spatial planning and design for resilient flood control and drainage on Hengli Island under extreme climate change condition

Guided by the theory and method of spatial planning and design for resilience, a special study on resilient flood control and drainage on Hengli Island is conducted. On the basis of understanding flood control and drainage, a way in which to widely apply the theory of spatial planning and design for resilience in order to propose principles and strategies for resilient flood control and drainage on Hengli Island is explained.

Corresponding research objective 4: Multiple resilient spatial characteristics are applied, such as regionality, connectivity, diversity, multifunctionality, redundancy and modularization. After understanding the research case and project the negative impacts from future climate change, principles and strategies for improving the resilient flood control and drainage are proposed. From aspects of modularized water collection units, improved water networks, the classification of function of inner-rivers, diverse and multifunctional water retention, a diversity of water level regulation, multifunctional buffering zones, etc., new possible scheme for resilient flood control and drainage on Hengli Island are proposed.

TOC

1.3 Research method

The research methodology mainly applies the combination of literature review and field investigation, theoretical analysis and computer simulation, classified and multi-scale planning and design.

1.3.1 Combination of literature review and field investigation

The information, data about theory and cases are collected by using internetwork retrieval tools.

Several planning and design projects are investigated in the Dutch Delta area, focusing on the Nijmegen Section, the Noordward section of the project of 'Room for Rivers', the 'Hague Zandmotor' project, the Rotterdam Water Square, the Amsterdam Ring Canal, and examples from Guangzhou city, Shenzhen city, and Nansha in the PRD.

1.3.2 Combination of theoretical analysis and computer simulation

This doctoral dissertation applies the method of combining theoretical analysis and computer simulation. The main open data sources include the Landsat remote sensing database with a raster rate of 30m, SRTM elevation with a raster rate of 30m, Navionics Chart View ocean isobath map, Openstreet map, Google maps, Baidu maps, etc. The technical support for evaluation and simulation mainly included ArcGIS, Envi, GeosOS, FLUS model, Depthmap, and Fragstat, etc.

1.3.3 Classified and multi-scale planning and design

Research by planning and design is an effective way to test all the principles, strategies and measurements that are learned from theoretical study in empirical research. The PRD is a complex social-ecological system with both spatial heterogeneity and diversity. Multi-scale planning and design can be applied for research. Due to the different tasks and emphases on planning and design, corresponding to different types of space, the method of classified and hierarchical planning and design can be adopted for different types of spatial characteristics.

1.4 Research route

The research route of this doctoral dissertation is shown in figure 1.7.

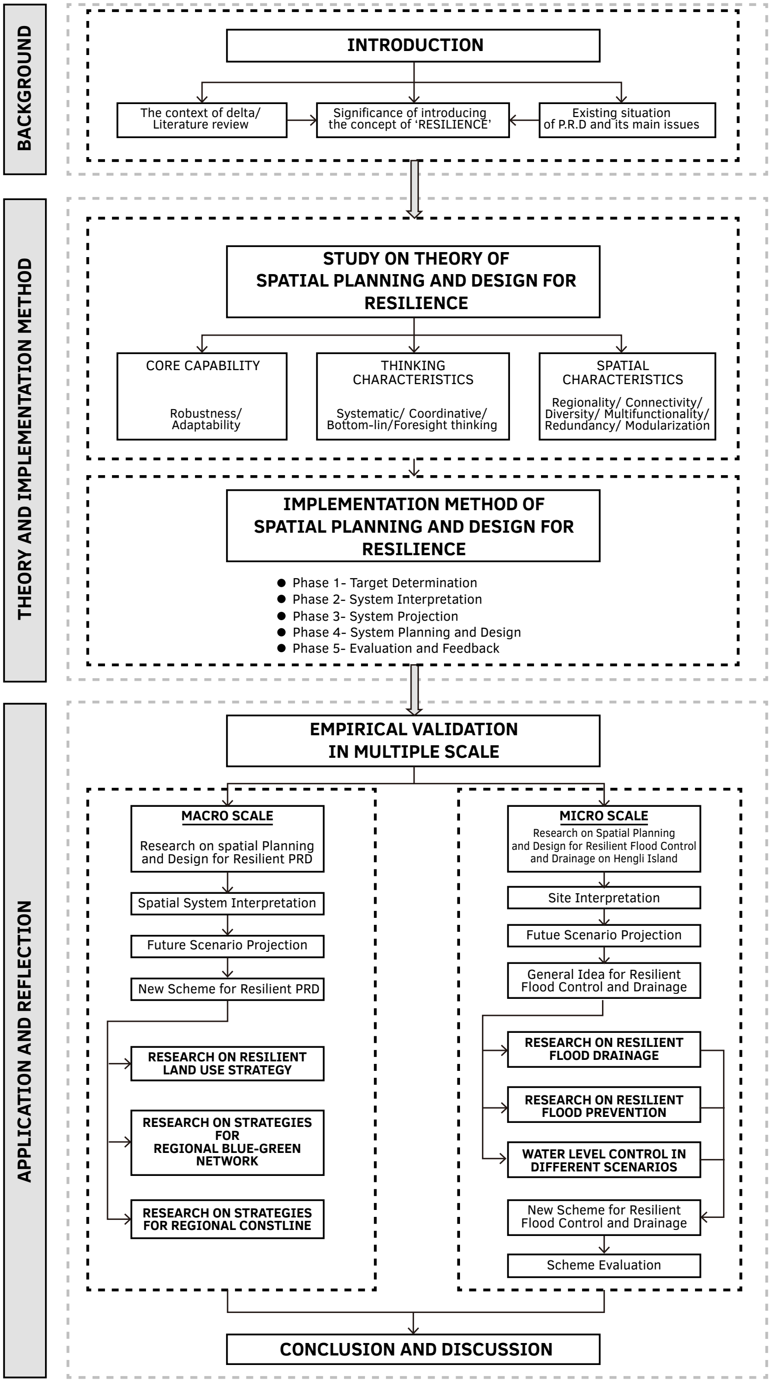


FIG. 1.7 Research technic route of the whole doctoral dissertation

1.5 Structure of the doctoral dissertation

This doctoral dissertation consists of six chapters.

Chapter One: Introduction

Chapter 1 describes the problem statement, research gaps and the significance of research topic. The necessity for the transformation from a traditional planning and design method to spatial planning and design for resilience in the PRD is demonstrated from the perspective of the superposition of three factors which are: a fragile natural base layer, land-use situation and extreme climate change condition in time and space. The research contents, objectives, methods, technical route, and the dissertation's structure are mainly expounded.

Chapter Two: Research on the theory of spatial resilience planning and design

Chapter 2 systematically studies the theory of spatial planning and design for resilience. Based on a literature review of the topic of resilience, the framework consists mainly of the core capabilities pursued by spatial planning and design for resilience, fundamental thinking characteristics of spatial planning and design for resilience, and spatial characteristics that can be presented by planning and design for resilience are systematically studied. The reasons why these properties and characteristics can be beneficial to improve the resilience of a spatial system are demonstrated. This chapter also highlights the internal logic and the unique characteristics of spatial planning and design for resilience.

Chapter Three: Implementation methods of spatial planning and design for resilience

In this chapter, the spatial planning and design principles, organization, technical route, and the process of spatial resilience are described in details. The process and key points of improving spatial resilience by planning and design are described from the aspects of target determination, system interpretation, system projection, system planning and design, evaluation and feedback. Chapter 3 aims to build an implemental bridge between the theory of spatial planning and design for resilience and its application.

Chapter Four: Research on empirical study of spatial planning and design for resilient PRD

Guided by the theory and method of spatial planning and design for resilience proposed in the previous two chapters, chapter 4 conducts an empirical study of spatial planning and design for resilient PRD. Based on the systematic analysis of spatial characteristics, the spatial evolution and climate scenario projections of the PRD, the principles and strategies of spatial planning and design for resilient PRD and Nansha District (in the central of PRD) are put forward from the perspective of land-use, blue-green networks, and coastline.

Chapter Five: Research on empirical study of spatial planning and design for resilient flood control and drainage on Hengli Island

In chapter 5, the application of the theory and implementation method of spatial planning and design for resilience is emphatically applied in resilient flood control and drainage on Hengli Island. Hengli Island is a vulnerable island in Nansha, which is selected as a case for further empirical study. Focusing on the main problems of flood control and drainage on the low-lying island of Hengli under extreme climate change conditions, chapter 5 systematically puts forward spatial planning and design principles and strategies for resilient flood control and drainage on Hengli Island from decentralized and modular water collective units, improved water networks, multifunctional and buffering dyke system. Afterwards, possible water level management for multiple scenarios under the concept of the combination of natural work and engineering are proposed.

Chapter Six: Conclusion and discussion

Chapter 6 summarizes the main research outcomes, reflects on research questions, points out the originality of this doctoral dissertation, as well as deficiencies and some expected works for future study.

2 Study on the Theory of Spatial Planning and Design for Resilience

2.1 Introduction

This chapter systematically researches on the theory of spatial planning and design for resilience and lays theoretical foundation for the empirical research of the PRD.

This chapter consists of 10 sections. Section 2.2 introduces the formation and the development of the concept of resilience. Section 2.3 proposes a research framework of the theory of spatial planning and design for resilience. Section 2.4 studies the core capabilities of resilience pursued by spatial planning and design. It is proposed that robustness and adaptability are two core capacities for resilience from the perspective of spatial planning and design. Section 2.5 studies the internal thinking logic of spatial planning and design for resilience. It is proposed that the essential thinking characteristics of spatial planning and design for resilience are systematic, coordinative, bottom-line and foresight thinking. Section 2.6 studies the spatial characteristics for resilience that can be presented by spatial planning and design. It is proposed that the characteristics of spatial resilience mainly include regionality, connectivity, diversity, multifunctionality, modularization and redundancy. The reasons why these characteristics can help to improve the capacity of spatial resilience are explained. Section 2.7 studies the relationship between characteristics of spatial resilience. Section 2.8 studies the main characteristics of spatial planning and design for resilience. Section 2.9 lists key points of spatial planning and design for resilience. Section 2.10 provides the conclusions.

2.2 Formation of the concept of resilience and the current status of research

2.2.1 Formation and development of the concept of resilience

The word 'resilience' comes from Latin language, which means the recovery process of a damaged system to its original state. Since Holling (1973) put forward this concept in the field of ecology in the 1970s, the concept of resilience has been widely applied. Many famous international research institutions developed the meaning of resilience. For example, according to the IPCC (2007), resilience described the ability to absorb disturbances and to maintain the basic structure and functions, which is the ability of self-organization and adapting to pressures and changes. The United Nations international program for disaster reduction (UNISDR, 2007) defined the word resilience as systems have ability to resist, absorb, adapt and recover from the negative influence in a timely and effective manner when being exposed to disturbances. By summarizing the existing literatures, it can be seen that the understanding of resilience gradually deepens.

The first research phase is based on the understanding of engineering resilience. During the 1980s and 1990s, engineering resilience was the mainstream of the research in the field of resilience. Engineering resilience highlights the ability of a system to restore to its original condition. The emphasis on 'the ability of a system to return to an equilibrium or stable state after being disturbed' is closer to the concept of engineering resilience. External disturbances can be natural disasters such as floods or earthquakes, or social problems. According to Folke et al. (2002), a resilient system can be restored to its pre-disturbance equilibrium state by its ability to resist, reduce and absorb disturbances.

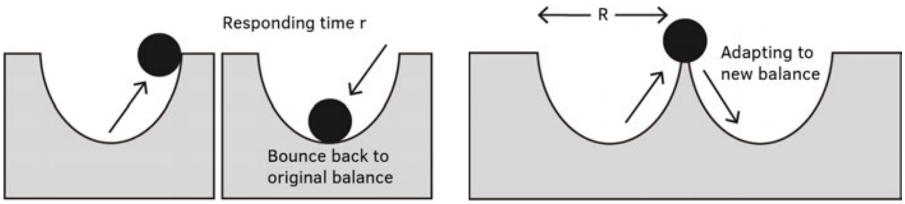
In the 1980s and 1990s, engineering resilience was the mainstream view. In engineering field, resilience means reliability and rapid recovery (Wang & Blackmore, 2009). The faster a system's functions are recovered, the more resilient the system is (Adger et al., 2005; Folke et al., 2004). Thus, resilience can be measured by the speed at which the system returns to a stable state. The faster the recovery speed is, the more resilient the system is (Holling, 1996). The core of engineering resilience is that the system has only one equilibrium state.

With more research involved, some deficiencies of engineering resilience have been found. The biggest deficiency of engineering resilience is that it states that a system has only one stable state or equilibrium. After being exposed by unexpected disturbances, a system will either lose balance or return to the original state and the performance of the system cannot be improved. Holling (1996) revised his previous concept of resilience and defined ecological resilience as 'the number of disturbances that a system can withstand before changing its main structure and functions'.

The measurement of resilience includes not only the recovery time after being impacted, but also the number of disturbances a system can withstand and the threshold to maintain stability. Ecological resilience focuses on the capacity of persistence and adaptability of a system (Alberti, 2000; Adger et al., 2005). It is believed that the concept of resilience not only means the speed of a system to return to its original state, but also the number of disturbances that the system can absorb (Carpenter et al., 2009; Ahern, 2011). The main difference between engineering resilience and ecological resilience is that ecological resilience acknowledges multiple equilibrium states and the possibilities of a system to change from one equilibrium state to another equilibrium state (Ahern, 2013).

Adger (2006) believed that the steady-state of a system can be changed with time, and the capacity of the system's resilience after disturbance depends on its self-organizing ability. Berkes & Folke (1998) believed that there might be multiple equilibrium states in a system, and the system could be transformed from the original equilibrium to a new equilibrium after being disturbed. Ecological resilience emphasizes the possibilities of a system to survive and states the potential transition from one equilibrium state to another equilibrium state. This is a great breakthrough compared with the original concept of engineering resilience.

Gunderson (2003) used the cup-ball model (Figure 2.1) to explain the difference between engineering resilience and ecological resilience. According to engineering resilience, a system is disturbed out of its original equilibrium, but due to its own mechanism, after time r, the system overcomes the influence of the disturbance and returns to the original equilibrium. The smaller the value r is, the greater the capacity of engineering resilience is. According to the concept of ecological resilience, a system will not return to the original equilibrium state before the disturbance, but enter into a new equilibrium state if the disturbance is greater than the threshold R. Therefore, R can be the value of the maximum threshold of external disturbances that can be accepted by a resilient system.



1 Enginnering resilience

2 Ecological resilience

FIG. 2.1 Different between engineering resilience and ecological resilience
(Source: Gunderson, 2003)

On the basis of ecological resilience, many scholars put forward the concept of evolutionary resilience. Davoudi et al. (2012), Desouza et al. (2013) believed that a system can change with time regardless of whether external disturbances exist or not. Walker & Salt (2006) proposed that resilience was the capacity of socio-ecosystems to change, adapt and transform in response to external disturbances. Godschalk & Xu (2015), Deal et al. (2017) believed that evolutionary resilience was mainly reflected in continuity, adaptability and transformation. Evolutionary resilience considers complex, nonlinear and uncertain systems. In an uncertain environment, a system is impacted and may become a new state. The reasons for the transformation of a system are not mainly external disturbances, but also mismatches between the functions of micro scale and the macro scale.

Based on the reality that nonlinear systems have multiple equilibrium states, Gunderson & Hollin (2002) proposed the model of adaptive cycle. The adaptive cycle model is constructed (figure 2.2), which reveals four phases of life cycle-development, preservation, release, and reorganization. In the development phase, due to the diversity and relative flexibility of the organization of elements, the connectivity of a system increases and the capacity of resilience of the system also increases. Development phase is of low systematic vulnerability and high systematic resilience. In the conservative phase, the organization of a system is gradually fixed and the vitality of the system gradually decreases. Conservative phase is of high systematic vulnerability and high systematic resilience. In the release phase,

TOC

the capacity of resilience of a system is lower, which is the phase of high systematic vulnerability and low systematic resilience. In the reorganizing phase, a system either restructures itself by innovation or eventually declines.

The above model is extended and applied to the coupling study of multi-scale systems. Each phase of adaptive cycle model is neither continuous nor fixed. Systems are interacted with each other at different speeds at different scales and over different time periods, and the trajectory of their evolution depends on bottom-up or top-down interactions.

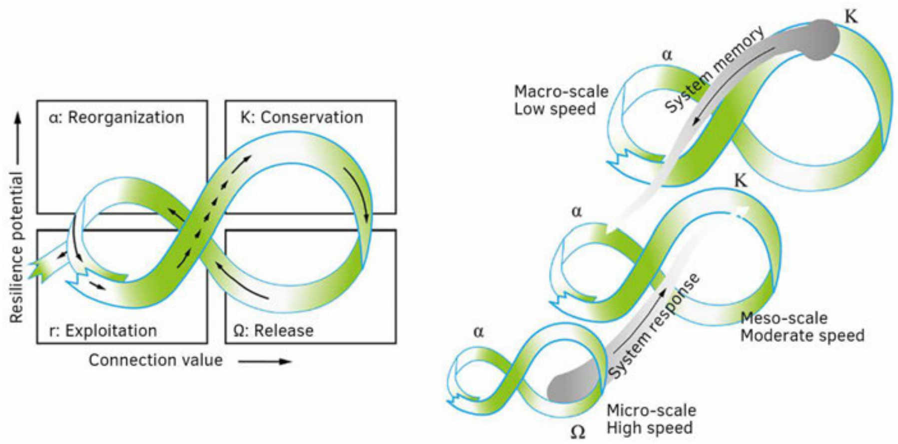


FIG. 2.2 Adaptive cycle model (Panarchy).
(Source: Gunderson & Holling, 2002).

In conclusion, resilience is an important attribute of a system that respects to its evolutionary mechanism and in response to external disturbances. Research on resilience has evolved from the initial pursuit of single equilibrium state to the emphasis on multiple equilibrium states, from recovery to adaptation. The research cases also expanded from linear to non-linear and uncertain systems. Table 2.1 summarizes the concept of resilience in different development phases.

TABLE 2.1 Three development phases of resilience

Item	Engineering resilience	Ecological resilience	Evolutionary resilience
Research objective	Bounce back to original equilibrium	Preparing for potential external disturbance	Continuously changing to adapt to new environment
Research case	Simple system	Nonlinear complex system	Nonlinear complex system
Hypothesis	System has single equilibrium	System has multiple equilibrium	System has spatial-temporal interactions and cycling
Measurement indicator	Recovery speed after external disturbances	Absorbing capacity for preparing external disturbances	Changing, adapting, transforming and cycling ability under external disturbances

2.2.2 Research status of resilience

Since the early 1970s, some scholars have discussed resilience from a multidisciplinary perspective. The research field has been expanded from ecosystem, social system to social ecosystem. Holland (1992) proposed the characteristics of complex adaptive system, which have relationships with a resilient system. Many scholars have made in-depth discussions on spatial resilience from the perspective of the complexity and vulnerability of a system, and study how the capacity of resilience can respond to structural changes and reconstruction. Allan & Bryant (2011) believed that variability, adaptability to change, modularization, innovation, rapid response, saving capacity of social capital and ecosystem service are 7 characteristic indicators to measure spatial resilience. Newman et al. (2009) explained the key indicators of a resilient system, such as redundancy, modularization, flattening, intelligence, feedback, cooperation and mobility. Forster et al. (2012) believed that a resilient system is independent, diversified, renewable and functionally redundant. Pickett et al. (2004) discussed the role of resilient spatial systems in the integration of ecological, socio-economic and planning design fields. Alberti (2005) believed that the focus of planning and design is to consider the correlation between different planning and design forms and environmental performance. Colding (2007) considered that the main aspects of describing spatial resilience in planning and design field can be constructed by spatial form, land use, urban sprawl and expansion efficiency. Meyer et al. (2015) believes that the coordination among natural system dynamics, blue-green network, port development, agriculture and urban system is the beginning of a new paradigm of planning and design for improving spatial resilience.

TOC

Chinese scholars' studies on the field of resilience focus on the translations of foreign literatures, the introduction of the concept of resilience or the application of the theory of spatial resilience to planning and design field. Dai et al. (2017) introduced the concept of resilient thinking by preparing to unstable environment. Peng et al. (2015) elaborated the evaluation system for measuring spatial resilience and created improvement strategies based on the evaluation results. He et al. (2012) researched on the paradigm of urban planning responding to uncertainty. Ni & Li (2019) discussed about three types of resilient city evaluation systems and their new development. Li et al. (2014) proposed a research framework for resilience. Yu (2015) made a review of urban water resilience and proposed that the resilience of urban water system needs to take both pluvial and fluvial impacts into consideration. Lin (2015) proposed the theory of resilience and flood carrying by applying the function of natural flood plain. Xu & Shao (2015) put forward the evaluation criteria for flood resilience. Jing & Huang (2016) put forward the evaluation purpose, attention content and indictors composition of systems in different spatial scales. Liao (2015, 2016) introduced flood resilience to China by providing 'floodable index'.

Some doctoral dissertations also have relationships with the topic of resilience. Looman (2017) explored the principles of the way that buildings can possibly adapt to the climate, by building planning and design guidelines from terrain, wind, water, heat and energy. Wohl (2018) proposed the idea of planning and design improvement from form to process from the perspective of complex adaptive system. Forgaci (2018) constructed 35 indicators including connectivity, absorptive capacity, cross-scale and synergy for measuring a resilient system by using urban river corridor as case study. Veelen (2016) constructed adaptive planning and design pathways based on the full life cycle of the project. Gersonius (2016) proposed a four-dimensional model and illustrated it from the perspectives of policy, adaptive threshold, and regretless strategy. Flora (2017) explored the adaptability of embankments, buildings and foundations. Feng (2015) studied on storm surge adaptive landscape infrastructure from the perspective of resilient cities. Cao (2016) studied on the theory and method of regional adaptability of mountain urban design. Yuan (2015) studied on the ecological adaptability model of complex systems in mountain cities, and providing relevant planning and design strategies for creating adaptive mountain cities from green-blue and cultural perspectives.

2.3 The research framework of spatial planning and design for resilience in this doctoral dissertation

Since the concept of resilience was put forward, the research on the topic of resilience in the world has been deepened constantly. The research perspectives are very diverse, including sociology, economy, management, ecology, spatial planning and design and many other fields. Different disciplines have different emphases on the concept of resilience, most of which focus on the interpretations of resilience, the assessment of the vulnerability degree of the current complex system. For example, the research of resilience in the field of ecology focuses more on a system's ability to withstand disturbances and its recovery time. The research on resilience in the field of social economics focuses more on systematic self-organization, learning and adaptability. Studies of resilience in different disciplines have drawn very broad conclusions.

Resilience refers to space that has characteristics such as self-recovery, self-organization and innovation under external disturbances. Resilient space mainly includes spatial components and organizational management that are compatible with surrounding environment. The core for improving spatial resilience is to anticipate external disturbances and take measures in advance to mitigate possible losses. The realizations of spatial resilience require not only from planning and design in terms of material aspects, but also from social organization and management, actions in non-material aspects.

Therefore, spatial planning and design is one of the important and creative actions to realize spatial resilience, by arranging, controlling and distributing interdependent elements (such as land use, blue-green networks, strategic points, etc) in appropriate locations. It focuses on applying both creative drawing and technical assistance for the realization of spatial resilience from the perspective of interrelated space and time. Spatial planning and design for resilience studied in this doctoral dissertation attempts to provide a possible planning and design method, as well as related outcomes guided by the concept of resilience. It studies the planning and design thinking, principles and strategies, technical assistances, implementation processes of planning and design for improving spatial resilience, which can possibly address the problems existing in the PRD.

In addition, spatial planning and design for resilience is a kind of technic-based method aimed at improving the level of resilience of spaces at different scales. It is embodied in thinking characteristics, strategies, technologies, steps, measures and other aspects of spatial planning and design under the guidance of resilience. Because the research cases of spatial planning and design are always complex and different, there is no unified research framework of spatial planning and design for resilience. Existing literatures show that spatial planning and design for resilience mainly focuses on clarifying one of four important aspects, including **resilience of what, resilience to what, resilient stage and resilient characteristics.** Existing literatures also show that spatial planning and design for resilience mainly focuses on the phase of improving resilience, including preparation phase, absorption phase, recovery phase and adaptation phase.

For studying the theory of spatial planning and design for resilience, one should clarify what are the characteristics of spatial planning and design for resilience? And what are the spatial characteristics that can be presented by planning and design for realizing spatial resilience? These two questions are the focus of the theoretical study.

For the above two questions, existing literatures lack direct indications. However, a large number of literatures have studied what characteristics a resilient city (both in material and non-material aspects) should have, and the conclusions obtained can be used as references. For example, Wildavsky (1988) believes that an excellent resilient city should have six characteristics: dynamic balance, multiple compatibility, efficient flow, flat characteristics, buffering and moderate redundancy. Allan & Bryant (2011) believe that variability, adaptability to change, modularity, innovation, rapid response, saving capacity of social capital and ecosystem services are seven characteristic indicators to express a resilient city. Newman et al. (2009) elaborates seven key indicators of resilient environment, namely redundancy, modularity, flatness, intelligence, feedback, cooperation and mobility. Liu (2018) believes that a resilient city is independent, diverse, renewable and functionally redundant, and could improve capacity reserve through replication, interchangeability and interconnectivity. Meanwhile, research institutions in America, Japan and China other countries have given evaluation framework for describing a resilient city, which can also be used as references. The evaluation framework and main indicators are shown in Table 2.2.

This doctoral dissertation tries to systematically study the theory of spatial planning and design for resilience, based on existing literatures and the author's own thinking. Core capabilities, thinking characteristics, the internal thinking logic, and the characteristics of resilient space from planning and design perspective are researched from a system point of view. This doctoral dissertation aims to build a theoretical framework of spatial planning and design for resilience and apply the theoretical study outcomes to the empirical research in the PRD.

In this doctoral dissertation, spatial planning and design for resilience focuses on improving resilience from a spatial (material) perspective. It makes a spatial system more resilient when facing future uncertain disturbances, and maintains the core structures and functions of the system. The research framework of spatial planning and design for resilience is proposed in figure 2.3.

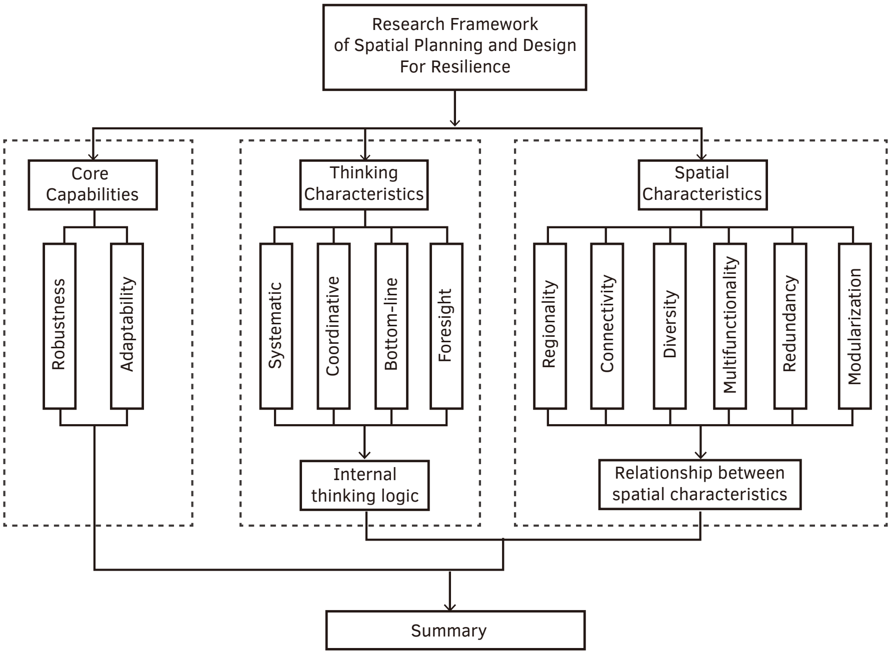


FIG. 2.3 The research framework of spatial planning and design for resilience in this doctoral dissertation

TABLE 2.2 The evaluation framework and main indicators for describing a resilient city

Perspective	Institution name	Indicators
Region, rural or urban system	Rockefeller Foundation, US	Life, health and welfare; Economic and society, Leadership and strategy, Urban management and services
	HOSEI University, Japan	Urban indicators, administrative indicators, citizen indicators
	Kitakyushu City Center, Japan	Urban planning system; Spatial facility infrastructure; Urban institutional configuration
	Agency for International Development, US	Governance; socio-economic; coastal resource management; land use and structural planning and design; knowledge of education; blast and evacuation; emergency response; disaster recovery
	Berkeley Metropolitan Area	Economic dimension; social dimension; demographic dimension
	Chinese resilient assessment institute	Economy; population; social foundation; policy management
Disaster prevention and climate change	Nagoya University, Japan	Prevention; adaptation; conversion
	Osaka University, Japan	Reserve materials; risk scenarios; flow and stock
	RATA, Australia	System description; material management; adaptive governance and management

(Source: Prabhakar et al., 2009; Cai et al, 2012; Rockefeller Foundation, 2014; Kenshi et al., 2014; Li et al., 2015)

2.4 Core capabilities pursued by spatial planning and design for resilience

The concept of resilience not only emphasizes on the recovery ability of a system, but also stresses on the adaptive ability of the system. Adaptive ability is reflected in the foresight thinking in the process of spatial planning and design, and is embedded in the spatial characteristics of multifunctionality and redundancy in a spatial system. The objective of improving the level of resilience is to make a spatial system have the ability to address external disturbances and adapt to the changing environment, because the future is always uncertain and hard to be predicted.

Figure 2.4 is the schematic diagram of each stage during the resilient process of a system. In this figure, T_1 is the moment when the system is disturbed, T is the responsive time of the system for recovering or entering to a new stable state, T_2 is the moment when the system enters to a new stable state, P is the core capability that the system must maintain, and D is the maximum capability losses caused by the disturbance. R represents the difference of performance between the value after system enters into a new stable state and that of the original stable state. Obviously, for the responsive process of a particular disturbance, the smaller the values of T, R and D are, the higher the capacity of resilience of the system is. Only by absorbing the experience and lessons of a system in response to the external disturbances in time, and transforming the disturbances into the improvement and perfection of the system, can the value R be changed from negative to positive and make the new system have higher performance. The level of robustness and adaptability all reflect the resilient level of a system.

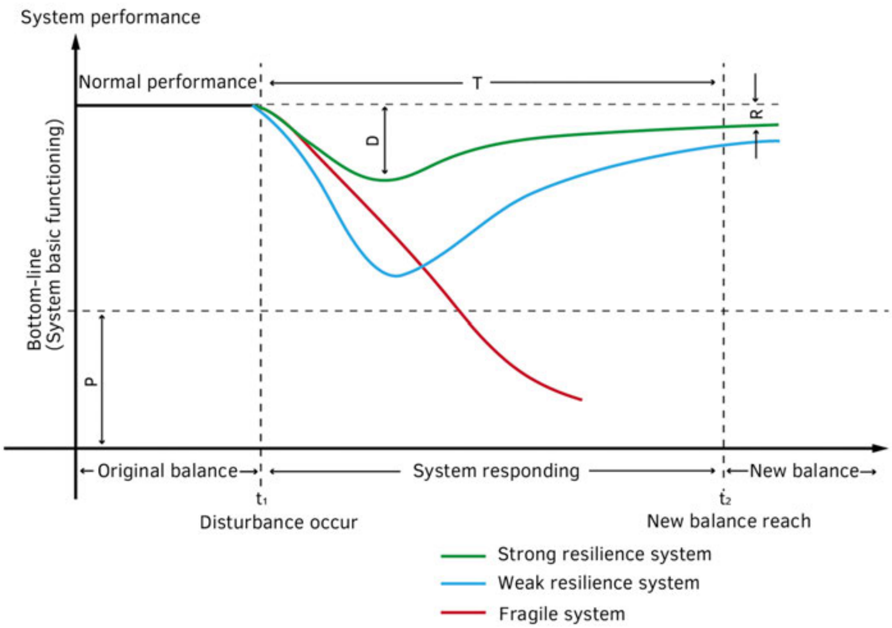


FIG. 2.4 The schematic diagram of resilient process

2.4.1 Robustness

Robustness describes the stability of a system. It refers to the extent to which a complex system is capable of resisting sudden, unexpected extreme conditions so that such conditions do not lead to a breakdown of the entire system. Robustness is a term originally used in control science to describe the insensitivity of a system to environmental changes and disturbances. Strong robustness indicates that a system has strong resistance and ability to address external shocks. Once the system is disturbed, it still has the ability to maintain core functions and can quickly enter to a stable state. Robustness is the ability that a system can still have its core structures and functions after experiencing external disturbances, disaster impacts or partial function losses.

A A spatial system that has a fragile natural base layer requires robustness

A spatial system that has a fragile natural base layer requires robustness. For instance, the delta, the mountainous areas are all included in this kind of spatial systems. In the PRD, due to the topographical characteristics of low altitude and the vulnerability of natural base layer, the need for maintaining the robustness of natural base layer is necessary for supporting future urbanization. Low land carrying capacity and high degree of habitat fragmentation increase the need for enhancing the capacity of robustness for improving resilience of a spatial system. Spatial planning and design should take the enhancement of robustness as the most important orientation.

B Improving the level of robustness is an inevitable choice when facing inevitable climate change

Climate change becomes the most uncertain factor affecting the future urbanization process of a spatial system such as the delta. At present, the disturbance of extreme climate is getting more and more intense. Under the pressure of extreme climate change, spatial planning and design for resilience can only adopt corresponding resilient technologies to improve the robustness level of a system based on prevention and aimed at the future possible disturbances.

C Robustness is the primary requirement for improving resilience

Enhancing robustness is a key for the healthy operation of a spatial system in order to reduce the damage caused by external disturbances. A resilient spatial system should not only have a certain tolerance to the changes of spatial structure within a certain range, but also have a certain resistance to external disturbances and even disruptions. A system with particularly strong robustness should also be fault-tolerant to overcome the impact of external environmental changes and internal structural changes. Only by taking strong robustness as an important goal of spatial planning and design can the spatial system absorb the influence of external disturbances, maintain core functions and quickly enter to a new stable state. Robustness is a required quality for spatial systems to maintain the most important functions. As mentioned in above sections, the range of value R in Figure 2.4 reflects the robustness of a spatial system. The smaller the value R is, the stronger the capacity of robustness of the system is.

D Identification of future major disturbances is an important basis for improving the level of robustness

Identify the most likely occurring disturbances is an important basis for improving the level of robustness of a spatial system. Spatial planning and design is future-oriented, the effectiveness of resilience can only be determined after experiencing disturbances. One of the most difficult points of spatial planning and design for resilience is to project uncertain future disturbances. Sometimes these uncertain disturbances contradict each other. Therefore, spatial planning and design for resilience should be good at identifying the main disturbance from the numerous complex disturbances. It is necessary to analyse the mechanism of natural base layer and project the negative influence of climate change, slow variables and thresholds based on the protection of natural base layer and urbanization trends.

2.4.2 Adaptability

Adaptability refers to the ability of a system to adjust adequately to changing conditions that were difficult to foresee or prepare for or extremely uncertain, such as surrounding environment and future climate change. A spatial system should adapt to the changing trend of climate conditions, society, economy, culture and ecology for providing conditions of the all-round development of human beings. The core to improve the capacity of adaptability is to make the spatial system advanced, modular and extensible in its networks and strategic points.

A Initiative adapt to regional conditions and natural laws

The way of spatial development is restricted by natural base layer, historical evolution and external disturbances. The negative influence from extreme climate has intensified in the past decades in the PRD. Under such natural conditions, the way that spaces can possibly be developed harmoniously with the natural environment is an issue that spatial planning and design for resilience needs to consider.
New schemes should actively adapt to the future climate change based on the improvement of robustness and take appropriate adaptive measures to ensure that the spatial system can be operated healthily in the face of external disturbances.

B The key to enhance the level of adaptability is to make networks multifunctional and extensible

Before the occurrence of future disturbances, effective measures for establishing networks should be taken in advance. At the same time, the networked spatial system should be flexible and extensible to create conditions for adapting to new changes in the future or provide preparation for flexible changes. When new changes appear in the environment, the original multifunctional, extensible networked space only needs to adjust the structure or function properly to provide a kind of spatial function transformation possibility and adapt to the new changes with the least cost and sacrifice. Adaptability requires that the layout of some key networks should be redundant to provide conditions for addressing future changes.

C Realize bidirectional adaptability of subject and object

Spatial planning and design for resilience should also realize bidirectional adaptability of both subject and object of a research case. Planning and design method is the subject while the spatial system that needs to be improved is the object. Spatial systems can possibly adapt to regional environment, climate change and future uncertain urbanization through appropriate planning and design methods. It is necessary to comprehensively consider the scale, structure and layout of a space and its surrounding environmental development. According to the differences between the subject and the objective conditions, various corresponding measurements should be adopted for harmonious relationship between subject and object. Only when the subject and object are compatible and harmonious can they co-exist and develop together.

D Realize adaptation among multiple spatial attributes

Spatial planning and design for resilience should use systematic and foresight thinking, and actively pursue the mutual adaptation of spatial elements and regional conditions, in order to improve mutual adaptation among spatial elements. Through reasonable spatial organization and the configuration of spatial elements, the attributes of land use type, functional layout, spatial form, and cultural inheritance of a spatial system can be adapted together to the future condition. Realizing adaptation among multiple spatial attributes also means that the service function of a spatial system can possibly be improved together in terms of cultural, ecological, hydrological and socio-economic attributes.

2.5 Fundamental thinking characteristics of spatial planning and design for resilience

After the analyses of the core capabilities of spatial planning and design for resilience, how is it possible to realize these core capabilities? Facing a complex context with multiple objectives, multiple factors, and multiple scales in any spatial system, what is the internal thinking logic of the approach of spatial planning and design for resilience? Therefore, this section researches on the internal thinking logic of the approach of spatial planning and design for resilience, and proposes that systematic thinking, coordinative thinking, bottom-line thinking and foresight thinking are four thinking characteristics of planning and design necessary for improving spatial resilience.

2.5.1 The internal thinking logic of the approach of spatial planning and design for resilience

The objective of spatial planning and design for resilience is to improve the ability of spatial system when facing uncertain future disturbances. Through the coordination of physical, social and information dimensions and the extensive use of resilient technologies, a spatial system can effectively address disturbances, overcome disturbances or reduce the loss caused by external disturbances to the space and quickly enter to a new stable state.

The disturbance has the characteristics of high uncertainty and strong randomness. The type of disturbance includes not only natural disasters but also other socio-economic disturbances. In literatures, resilience can be divided into four aspects: economic resilience, social resilience, institutional resilience and spatial resilience. The first three types of resilience belong to the management field which mainly emphasizes the adaptive ability, self-learning ability and self-organization ability of resilience. For example, economic resilience focuses on the economic perspective by emphasizing the development goal of diversified economic structures and the ability to address external economic turbulence. Social resilience is studied from the perspective of management by focusing on the ability to cope with social changes. It emphasizes the systematic construction process combining social governance and public participation with the social level, so as to enhance the ability of social organization and the resilience of self-renewal. Law resilience focuses on the legal perspective to improve the legal resilience through institutional mechanism reform, establishment and improvement of various rules and regulations, decision-making procedures, and legal supervision.

In this doctoral dissertation, the concept of resilience focuses on spatial resilience. Through spatial planning and design, the spatial layout and valuable resources should be rationally allocated and the spatial structure can be improved to address external disturbances caused by climate change.

The theory of spatial planning and design for resilience emphasizes more on the comprehensive grasp of the combination of natural base layer and future urbanization, so that the method of future urbanization is based on the healthy natural base layer and sufficient land carrying capacity. The theory of spatial planning and design for resilience emphasizes on thinking characteristics such as systematic thinking, coordinative thinking, bottom-line thinking and foresight thinking. It extensively applies some spatial characteristics such as regionality, diversity, redundancy, connectivity, modularization and multifunctionality for improving the core capabilities of robustness and adaptability. The key points of spatial planning and design for resilience are as follows:

- Identification of spatial evolutions and projection of external disturbances. Spatial evolution among different layers needs to be explored. By applying modern technology and integrating land carrying capacity, current vulnerability, etc., the most likely occurring disturbances in the future will be projected and selected from the uncertain multiple future risks, and the main disturbance will be taken as the scenario for spatial planning and design for resilience.

- The strategies are formulated to address external disturbances. Improving robustness and adaptability is the essential requirement of spatial resilience. This could be achieved by learning from local, national and international best practices when addressing external disturbances, and take them as an important source of wisdom so as to improve planning and design capacity. In order to improve the robustness and adaptability of a spatial system, some resilient spatial characteristics are context sensitive, others can be widely used.

- Spatial planning and design for resilience is carried out for addressing major disturbances and development scenarios. For a specific scheme, the resilient ability of space to cope with disturbance can be determined as soon as the new scheme is made. Since it is not 100% certain to accurately predict major disturbances and development scenarios, it is necessary to adopt various measures conducive to improving system robustness in formulation, such as the diversity, multifunctionality, redundancy, connectivity, medialization and regionality, which will be discussed in detail later.

— Due to the limitations of objective conditions and cognitive levels during planning and design, there needs to be testing and evaluation of whether the results of spatial planning and design can improve the predetermined resilient purpose, after actually experiencing external disturbances. Therefore, planning and design must timely summarize experience and lessons from disturbance experience, learn from disasters, and absorb the results of learning and reflection into the improvement of planning and design.

To sum up, the internal thinking logic of the approach of spatial planning and design for resilience proposed in this doctoral dissertation is shown in figure 2.5.

The following further explains the systematic thinking, cooperative thinking, bottom line thinking and foresight thinking that should be applied in spatial planning and design for resilience.

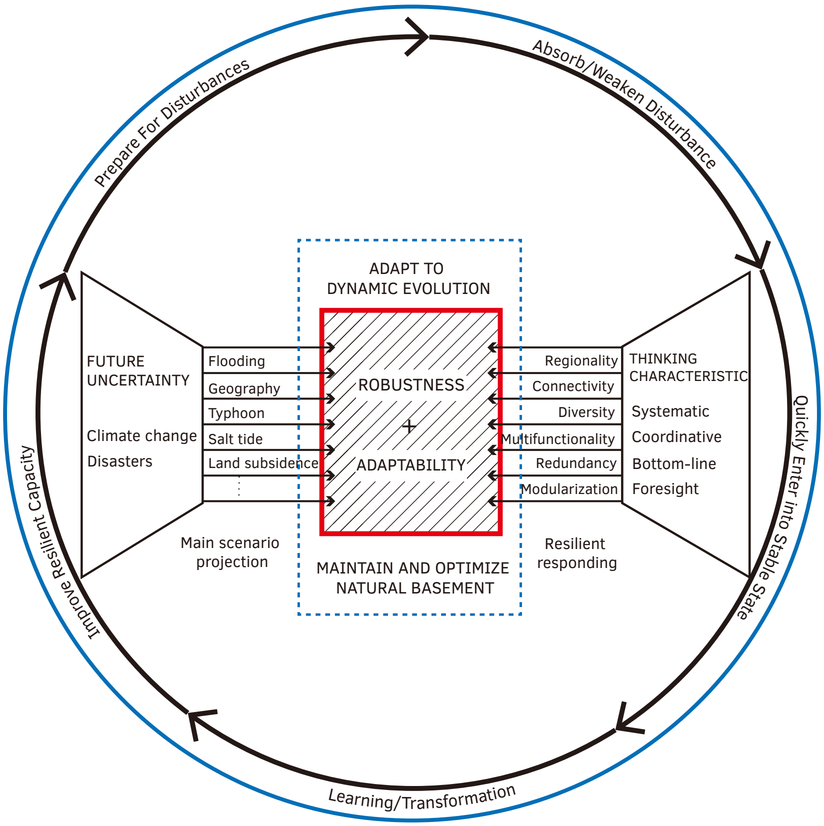


FIG. 2.5 Internal thinking logic of the approach of spatial planning and design for resilience

2.5.2 Systematic thinking

A Emphasizes the wholeness of a system

Systematic thinking is the fundamental attribute of spatial planning and design for resilience. Spatial planning and design for resilience needs to study the interactions and constraints among system, subsystems and elements, as well as between systems, subsystems and environment. Any individual element can be regarded as one part to the whole system. Therefore, spatial planning and design for resilience should understand the characteristics of a spatial system from an overall perspective and coordinate all elements of the spatial system.

B Emphasizes on high relationship between elements

Each element in the system has a specific location and function. An element does not exist in isolation. Different levels of the spatial system play different roles, which reflects the various status and roles of the whole system. This qualitative difference determines the multilevel nature of the system. Each layer is affected and interacted by other layers. The purpose of understanding the relationship between elements is to find out the main factors that affect the overall function from such complex and associative coupling factors. The overall function is realized by hierarchical and ordered structure. The function, form and location distribution of all spatial elements are products of a spatial system under the influence of its evolutionary order.

C Focus on multi-scale relationships

Spatial planning and design for resilience has multi-scale properties. A resilient system has interconnected feedback loops in the structure. Once the system is disturbed, these loops support each other in a variety of ways that enable the system to maintain its core functions. At present, various chronic pressures and acute shocks become normal, and the failure of one subsystem may cause a wider range of spatial problems. Facing these problems, spatial planning and design for resilience needs to focus on cross-scale relationships, which requires overall thinking and carrying out multi-scale coordination.

D Identify openness of the system to address external disturbance

It is the attribute of a spatial system to keep close contact with the external environment and continuously exchange material, energy and information with the environment. Interactions take place through flows of elements, people, goods and information between a system and its environment. The openness attribute of spatial system determines that spatial planning and design for resilience needs systematic thinking. Spatial planning and design for resilience should take the initiative to address external disturbances instead of avoiding them. Therefore, administrative boundaries need to be broken during the process of planning and design.

2.5.3 Coordinative thinking

A Coordinative thinking is both the means and goal of spatial planning and design for resilience

A spatial system is a multi-level and complex nonlinear open system. System elements overlap with each other, and the interests of different groups are different. The stages, conditions and goals of development are diverse with obvious regional differences. Coordination is an important attribute of spatial planning and design for resilience. By collaborative thinking, the spatial system can generate new functions in an ordered structure.

B Multi-level and cross-scale coordination is required

Spatial planning and design for resilience requires a coordinated layout of production, life and environment. It is necessary to strengthen the understanding of multi-level and cross-scale coordination. The construction should be arranged in a scientific, reasonable and orderly way so as to improve overall regional coordination, heterogeneous landscape and complementary functions as much as possible. It needs to coordinate the process of urbanization and natural protection to improve common protection and governance of the environment, connectivity of facilities, joint construction and sharing of municipal infrastructure, and common cultural integration.

C The relationship between elements should be taken into account

Elements make up the system. There are interactions among elements of the system, subsystems and systems at different levels, as well as correlations between the system and the environment. Spatial planning and design for resilience should raise the individual and unit component characteristics to the overall relation of the system. While considering the function of elements, spatial planning and design should pay special attention to the grasp of the whole function. As a part of the whole system, the spatial element must play its own part under the context of the whole system. The overall function of the system is not the simple mechanical superposition of the functions of each part, but to integrate the system as a whole through including properties within the overall function that emphasize that each element does not exist in isolation.

D Coordination between the structure and elements of the system are required

Whether the system has coordinative effects or not is determined by the interaction of various elements within the system. If the elements, structure, parameters, order and organization approach in the planning and design system are properly matched, the coordination effect will be experienced in a positive direction, which can lead to the mutual enhancement of attributes among things, and the overall function of the system can greatly exceed the sum of their original functions. On the contrary, if the elements, structure, parameters, order and organization approach of the system are not properly matched, the coordinative effect will not function well and the internal consumption of a system will increase, and the system will fall into a disorderly state.

E The leading role of key elements should be played

When there are contradictions among elements, the key factors should be clarified through comparative analysis and the collaborative elements should be actively sought. It is necessary to study the correlation mechanism of elements and make them complement and interact with each other through scientific matching of elements and reasonable spatial organization, so as to promote mutual support between subject and object, elements and system.

F Discipline collaboration should be emphasized

Multidisciplinary collaboration should be emphasized. The planning and design team need to be composed of experts from different disciplines with expertise in fields such as infrastructure engineering, landscape planning and design, spatial planning and design, architecture construction. The planning and design team includes not only relevant professional scientists, but also government administrators, landowners and other stakeholders.

2.5.4 Bottom-line thinking

A Resilient thinking is essentially bottom-line thinking

The bottom line is the critical line where the performance, functionality and/or structure of a system are disrupted. Spatial planning and design for resilience prepares for future disturbances. The purpose is that the system has the ability to resist disturbance, and reduce the influence of disturbance. Spatial planning and design for resilience should be based on precaution. The bottom line of spatial planning and design for resilience is the threshold to be maintained for the core functions of a spatial system.

B Bottom line thinking is problem-oriented

It is necessary to establish a strong sense of problem and insist on the process of problem orientation. The types, probabilities and possible losses of various risks are fully analysed in multiple directions and dimensions. Spatial planning and design for resilience is problem-oriented which focuses on the analysis of problems, finding out the source of problems, taking effective preventive measures and reducing losses caused by risks. The more thoroughly the problem is studied, the more specific the resilience needs to be.

C Bottom line thinking is risk-prevention thinking

Spatial planning and design for resilience focuses on the prevention of the bottom line. On the basis of making clear the existing land use status and natural base layer, it is necessary to pay special attention to the influence of the vulnerable areas to prepare for external disturbances.

The bottom line needs to be respected. Not only does one need to understand the consequences of breaching the bottom line, but one also needs to understand the planning and design measures to prevent bottom lines, and propose corresponding countermeasures from the worst possible scenarios. For outstanding issues concerning the bottom line, spatial planning and design for resilience will vigorously raise standards for capital grey and green infrastructures. It is needed to turn external disturbances into opportunities to enhance the capacity of resilience and seek long-term development.

D Bottom line thinking is of ‘rigid constraint’

For spatial planning and design for resilience, the delineation of some rigid protected areas should be based on the overall spatial pattern. It is needed to prohibit the constructions of low-valued buildings in important natural protection area, such as important water reserves, forest parks and wetland parks. The key areas which are planned and designed for natural protection should be strictly controlled. Disordered constructions should be restricted according to the respect to water and ecological environment. The red lines for natural protection, permanent basic farmland and the urban growth line should be strictly observed. It is necessary to establish rigid and elastic interface, formulate typed- land category control, and strengthen the utilization and control approach of land resources.

E Land-use suitability evaluation is the basis of bottom-line prevention

Land-use suitability assessment should be based on the comprehensive understanding of hydrological, geological, socio-economic situation and natural disasters. It is necessary to strengthen the constructions of infrastructure and improve comprehensive land carrying capacity with reasonable land use distribution. Land use arranged for the protection of blue-green bodies such as rivers, lakes, reservoirs, canals and wetlands cannot be used for development purposes.

F Combination of rigid and flexible control

For the elements that can be composed for bottom line, rigid control must be implemented by reasonable management. For other elements, the flexible control methods and control indicators can be formulated. It is needed to focus on the combination of short - term, medium - term and long-term scheme. The effects of long-term planning and design scheme can be used as a test for the short-term planning and design which allows for appropriate modification based on future climate conditions and natural variability.

2.5.5 Foresight thinking

A Aim at future main scenario

Future-oriented is an important characteristic of spatial planning and design for resilience. There are always uncertain external disturbances in the future. Whether the current tolerable state can maintain the core function of a spatial system when facing future uncertain disturbances depends on whether the spatial system has enough spatial resilience. Therefore, spatial planning and design must have a sense of crisis that can occur in the future. Only by strengthening prevention and implementing preventive measures into specific practices can the system remain in good condition when disturbance happens.

B Foresight thinking highlights the evolutionary law of a spatial system

The progressive history of a spatial system carries its past and present information hidden in its spatial system. It reflects the context and characteristics of a spatial system that also contains a lot of information about the future tendency. It is needed to dig into the rule of spatial evolution, grasp the future tendency by historical research and explore the future development trend. It should be based on the current situation and find possibilities for various development models. Spatial planning and design for resilience should leave some redundant space for future uncertain events.

C Foresight thinking should be based on prevention

Spatial planning and design for resilience should give priority to improving the resilient level of infrastructure networks. At present, aging infrastructure, backward function, insufficient capacity and other problems have led to the increasingly prominent vulnerability of space. When improving the resilient level of infrastructure, spatial planning and design should stick to limited targets. The level of resilience should be enhanced through the improvement of construction standards. The combination of grey and blue-green infrastructure can be used to enhance the resilience of the spatial system.

2.6 Main spatial characteristics of resilience presented by planning and design

Spatial characteristics of resilience are outcome expressions improved by planning and design. After studying the core capabilities of robustness and adaptability to be pursued by spatial planning and design for resilience, and the thinking characteristics of systematic thinking, coordinative thinking, bottom-line thinking and foresight thinking of spatial planning and design for resilience, what kind of spatial characters should be realized to improve these core capabilities by related thinking characteristics? Therefore, this section studies the main spatial characteristics of resilience presented by planning and design.

This doctoral dissertation argues that the theory of spatial planning and design for resilience highlights the harmonious relationship among natural, network and urban structure. It emphasizes the systematic, coordinative, bottom–line and foresight thinking of spatial planning and design for resilience, and has its own spatial characteristics in addition to the application of traditional planning and design methods and technologies. Although different main spatial characteristics of resilience presented by planning and design represent different emphasis that need to be improved by planning and design in a space, there is an intrinsic relationship between these spatial characteristics. The spatial characteristic of resilience that can be adopted depends on the actual situation of the research case. The main spatial characteristics of resilience presented by planning and design mainly include regionality, connectivity, diversity, multifunctionality, redundancy and modularization.

2.6.1 Regionality

A Respect to regional characteristics

Spatial planning and design for resilience is always influenced and restricted by the geographical, climate, historical and cultural elements of the specific research case. Based on the comprehensive analysis of the local natural environment, historical changes, socio-economic development and cultural influence, a distinctive regional spatial structure that is suitable for the local condition can be created by considering the natural endowment and resources.

B Respect to the natural base layer

In order to set up the guiding ideology of harmony between human and nature, appropriate utilization of natural elements should be the first choice for spatial planning and design for resilience. The characteristics of landform and geology and the characteristics of hydro-ecological flow of the research case should be fully considered to avoid artificially blocking or inhibiting the natural process. New schemes should try to make the function layout, spatial form and network system coincide with the landform and natural base layer. Only by complying with and reasonably utilizing the natural conditions in accordance with the characteristics of the natural environment, artificial system and the natural system can harmouniously be opened to each other and improve the spatial adaptability of the spatial system.

C Make full use of regional spatial resources

The capacity of robustness and adaptability of spatial systems are the orientation of spatial planning and design for resilience. However, the realization of these orientations in different regions and stages should be combined with regional natural conditions and socio-economic reality. Local resources, socio-economic development conditions and infrastructure conditions vary greatly, which determine the different land-use protection and development direction, infrastructure construction and spatial form in future. On the basis of the comprehensive identification of natural resources, spatial planning and design for a resilient space with local characteristics can be put forward. Only in this way can the spatial layout of production and hydro-ecology be coordinated with natural resources, infrastructure, land structure, land type and environmental resources.

2.6.2 Connectivity

A Connectivity is an important support to maintain system functions

Connectivity is an important characteristic of spatial planning and design for resilience. In order to absorb external disturbances as much as possible, the system structure needs to be multi-point, connected and interactive. It should not only improve the close connection among strategic points, but also improve the connection of lines and planes. Multi-scale connectivity is very important in spatial planning and design for resilience. When the external disturbances occur, connectivity enables the system resources to be mobilized and replenished in time. The lack of connectivity will lead to the isolation between elements, which are often the root cause of failure of a spatial system.

Because of the lack of connectivity, it is difficult to form effective links between the elements in a spatial system. In this spatial system, the exchange of matter, information and energy cannot be smooth. Such a spatial system cannot effectively mobilize the resources of multiple strategic points that form a resultant force once it encounters the external disturbances, therefore it has no ability to resist the disturbances. On the contrary, if a space has multi-network connectivity, the structure can make the material, information and energy flow fully and the strategic points can complement each other. The network creates close connections between the components of the system and forms the characteristic of multiple feedbacks, which becomes an important measure for a resilient system to absorb disturbance, disperse risk and reduce risk.

B Connectivity has multi-dimensional and multi-scale properties

Networking is the structural requirement of the connection between elements in a system. Through physical, non-physical, tangible or intangible association, it will connect the system into a crisscrossing, mutual connection, mutual penetration of the tight association to improve the smooth exchange of matter, information and energy. Networking is the structural form of connectivity. Connectivity of a resilient system cannot be considered from a single spatial dimension, but should be coordinated from multiple dimensions. Connectivity enables the smooth communication between the internal elements of the system and the external environment so as to realize the common protection and management of the hydro-ecological environment, connectivity of facilities, joint construction and sharing of municipal infrastructure and common culture.

C Blue-green networks are important carriers for connectivity

Spatial planning and design for resilience has to network the blue- green infrastructures. Not only will the standards of individual facilities be raised, but multiple facilities will be networked. Based on the measurements of networking flood detention areas, green river channels, infiltration systems, runoff management and structural infrastructure, it is necessary to gradually improve the flood control and drainage capacity for preventing potential water-related issues and land subsidence risk. It is needed to build a blue-green network as key factors of connectivity based on hydro-ecological corridors to improve the standard of blue-green infrastructure and take the network of blue-green facilities as an important carrier of connectivity construction.

2.6.3 Diversity

A Diversity is the basis for improving multi-services of a spatial system

Diversity is the basis for realizing the multifunctional service of a spatial system. It is embodied in all aspects including social diversity, economic diversity, cultural diversity and ecological diversity. People's different needs and different lifestyles are the objective requirements of spatial diversity. The intersection of people's different needs in a specific space forms the diversity of the functions of a spatial system. Just as there is a positive correlation between the abundance of hydro-ecological functions and the abundance of organisms, there is also a positive correlation between the abundance of multiple functions and the richness of space. Diversity increases the efficiency of resource utilization and is the basis for the provision of multifunctional services for the spatial system.

B Creating diversity is necessary when facing external disturbance

Lacking diversity will lack the motive force to maintain stable development when facing external disturbances. On the contrary, when a space faces uncertain disturbances, diversity will increase the possibility of multiple element combinations of the spatial system. Diversity increases the probability of innovation and breeds new opportunities. Diversity leads to more ideas, information and opportunities to

TOC

solve problems. Multiple performances can address disturbances more effectively and enhance the adaptability of space. Therefore, diversity is conducive to the improvement of the spatial resilience. For example, if the public transport system can quickly adjust its service model from land-based to water-based transportation when floods occur, it will ensure more opportunities for a spatial system to be survived when facing external disturbances like flooding.

C The realization of diversity needs scientific structure arrangement

Diversity is an important feature in spatial planning and design for resilience. It is not simply a multiple superposition. Spatial diversity needs to be improved and implemented in land use, municipal facilities and public services according to the current situation of a spatial system. For example, without the surrounding commercial environment, it is impossible to meet the diverse needs of people and realize the rational use of public facilities by relying on a single transportation.

D Diversity of implementation methods

Spatial planning and design for resilience should be good at learning and absorbing the experiences and lessons of addressing disturbance in the past, and take them as the main source of wisdom for planning and design. Planning and design must be problem-oriented. According to the natural conditions and socio-economic status of the objects, implementation methods and technical measures are proposed based on regional conditions, natural base layer and technical routes. Because of the complexity of the object, the technical route, implementation methods and technical measures are generally diversified. Planning and design should be oriented to the realization of the target and put forward diversified schemes with comprehensive consideration of technological advancement and feasibility. Through comparative analysis, the most appropriate scheme can be selected.

TOC

2.6.4 Multifunctionality

A Multifunctionality is the main representation of the need for diversity on limited land

Reasonably matching land use type and intensity to appropriately increase the density of natural space has a positive regulation effect on climate change. On the contrary, unreasonable proportion of land use types and disconnected blue-green network are easy to cause runoffs, pollution, flood, heat island, soil erosion and other problems. The realization of each function in the spatial system requires a corresponding amount of land supply as the basis.

On the one hand, with the development of social economy, people's material and spiritual needs are increasingly diversified. The need for diversity is higher and more pressing than ever before both quantitatively and qualitatively. On the other hand, limited by natural resources, the available land resources become less. There is a growing tension between the demand for diverse land and the amount of land the spatial system can supply. In this context, the utilization of multifunctional land use has become an inevitable requirement of spatial planning and design. The multifunctional land use provides a possible way to provide more sustainable and diverse services in a limited space.

B Diversity of the utilization of land-use function

It is the regulating key factors such as land use type, model and intensity that increase multifunctional utilization of land organically. Multifunctionality changes the way of land use and stimulates the benign flow of matter, energy and information, and creates conditions for improving a spatial system's functional diversity and compatibility with the environment. In order to save land resources and enhance hydro-ecological stability, it is necessary to change the land use model from extensive to intensive, which forms three-dimensional functional composite modules. Spatial planning and design for resilience emphasizes the composite utilization of land to improve land use efficiency, making each piece of land serve a variety of functions. It requires compact, intensive and compound spatial layout, advocates mixed use space, and improves land use value.

C Multifunctionality should be based on local conditions

Spatial planning and design for resilience should find appropriate ways to realize multifunctional use of lands according to local conditions. There are various ways to realize the multifunctional utilization of lands. In addition to meeting the basic functional requirements, the infrastructure can be effectively integrated with the hydro-ecological environment to transform the hard infrastructure into a multifunctional landscape. In addition to realizing the function of preventing flooding, dykes can be used as blue-green traffic and tourism facilities at ordinary times. A public space can build a shallow drainage ditch along the drainage channel, and the grass planted on the surface can not only be used for viewing but also for the infiltration of rainwater runoff, which exceeds the infiltration capacity into the wetland. Through reasonable land conversion, forest, grassland, water area, swamp and farmland can not only play their functional role, but also play their hydro-ecological landscape aesthetic function, which integrates the functions of river corridors, ecological environment restoration and green open space.

D Spatial stacking and time shifting

The multifunctional use of space can be realized through the method of spatial stacking or time shifting, which is a way of the usage of space that the same space provides different requirements in different time periods. For example, rivers and green corridors are available for people's activities in daily life. It can act as a flood detention area when the site is hit by extreme precipitation. The buffering areas on both sides of the dykes are open to the public as landscape belts during normal times. During rainstorm, they serve as flood control and drainage detention areas. Spatial stacking and time shifting gives different functions of the same resource, makes the use objects more diversified in various ways to improve the efficiency of land use.

2.6.5 Redundancy

A Redundancy is not a waste but a necessity

Redundancy refers not only to nature space for some key elements, but also to the space or facilities provided in advance by spatial planning and design to cope with new changes that may occur in the future. Redundancy emphasizes the positive creation of conditions to address the possible changes of the spatial system in the future. Through the appropriate transformation or expansion of original spatial organization or functions, the space can adapt to the new changes. Redundancy is an important measure to improve system adaptability.

When the system is in a normal state, redundancy makes the system have a certain margin. Redundancy becomes a necessity when the system is subject to major disturbance which leads to the failure of functions or services. It is redundancy that maintains the core functions of the system. For serious natural disasters, the consequences of a disaster on the system can be severe if inadequate prevention is combined with inadequate resilience of the natural base layer. Redundancy is an important technic measure to realize the adaptability of a resilient system.

B The core facility needs to have moderate duplication and backup modules

Essential infrastructure must be replaceable and moderately redundant. When some facilities are damaged by the impacts, the functions assumed by them can be supplemented by redundant facilities or replaced by other facilities. The forms of redundancy need to be varied. Disaster management involves a diverse approach to disaster mitigation, preparedness, response and restructuring that reflects integrated redundancy capabilities across different levels.

C Redundant facilities should play a multifunctional role

There must be redundancy in very important facilities, not as a superfluity but as a necessity in the event of a disaster. For general facilities, however, unnecessary redundancy should be reduced to avoid waste. Even for the necessary redundant elements, it is necessary to plan and design these elements scientifically so that the redundant facilities can play a multifunctional role. For example, on the basis of the construction of blue-green sponges in the covered area, more green spaces and hydro-ecological wetlands are set to play the role in rainwater regulation and storage. At ordinary times, these blue-green spaces and hydro-ecological wetlands provide landscape. When facing flooding, these blue-green spaces, hydro-ecological wetlands, rivers and lakes play a role in preventing floods. In the main roads of riverside and coastal areas, enough blue-green open space should be left in the planning and design to serve as storm water buffer in disaster and main landscape belt during normal periods.

2.6.6 **Modularization**

A Modularization is an important organization method

To decompose the planning and design of a complex system into several relatively independent and interacting modules for better control, adjustment and management is an organizational method of spatial planning and design for resilience. Spatial planning and design should be divided into several modules from top to bottom under the guidance of integrity so that each module has certain independence, self-restraint and self-regulation to complete specific functions. Spatial planning and design for resilience realizes the whole function of the system by decompressing the complex system into several interrelated, interacting, complementing and cooperating modules.

B Distributed modular configuration is advocated

A centrally configured system is vulnerable to disruption. To prevent the whole system from collapsing, modules with the same or similar functions are needed to provide functional backups for spreading the potential risk across diverse modules. The distributed module should have the function of autonomy and stability and can realize the self-detection for the early fault. For important infrastructure, modularization and distributed arrangement are advocated to ensure that even if the failure of individual modules occurs, the replacement method for redundancy can prevent the further spread of the fault and prevent the complete failure of the system.

C The module should be flexible and easy to expand

A module is a subsystem of the previous system. The management of modules should be strengthened according to the systematic requirements, so that each module can have robustness, adaptability and self-organization ability. Extensibility requires flexible interface of each module to facilitate the extension, replacement and combination of modules. The necessity of land carrying capacity and actual needs should be considered comprehensively for module expansion. In order to maintain the healthy operation of the whole system, it is necessary to strengthen the coordination between modules and improve the self-organization ability of modules.

2.7 The relationship among main spatial characteristics

From the perspective of spatial resilience, the main spatial characteristics of resilience presented by planning and design have been proposed in the above sections such as regionality, diversity, redundancy, connectivity, modernization and multifunctionality. They constitute the basic expressions of the spatial results that can be realized by the method of spatial planning and design for resilience. Although they focus on different aspects, these spatial characteristics are intrinsically related.

2.7.1 Relationship between diversity and multifunctionality

Diversity and multifunctionality have internal connections. It is generally believed that the more functions that a spatial system have, the richer the diversity that the system has. For a spatial system, the demand for diversity requires more lands. The realization of each function of diversity requires a corresponding amount of land supply, as the foundation and corresponding spatial support. From this logic, the following statement can be generated: if a spatial system can provide more lands, the diversity will be more abundant, and more multifunctional services will be provided, and there will be more alternative solutions when facing external disturbance. As a result, the spatial system will be more resilient.

Diversity asks more requirements on land demand. Diversity increasingly requires intensive usage of lands. It is in this context that the concept of multifunctionality emerges. The concept of multifunctionality emphasizes more on the functions that can be provided by a spatial unit in the spatial system. For example, a public space can not only be served as a place for residents to relax, it can also be used as a place to collect excessive water. In this way, the same public space has multiple functions. Therefore, the spatial characteristics of multifunctionality focus more on the function that can be provided by a same spatial unit, while diversity focuses more on the different functions that can be obtained by the whole spatial system. Multifunctionality is closely related to intensive land use. Sometimes multifunctional land use is synonymous with intensive land use. With the intensive use of lands, the same spatial unit can play multiple functions and have more diversity to improve the efficiency of land use.

2.7.2 Relationship between redundancy, modularization and multifunctionality

Redundancy refers to the backups of the same functionality. To prevent accidents, redundant facilities are often used for particularly important facilities. When the same function is provided by several modules with the same function, it has a stronger resilience to disturbance so as to have a strong positive connection and interaction after an emergency occurs. For example, because the spatial system is equipped with multiple transmissions, when one of transmissions means fails, it will switch to the other means immediately so as to guarantee the healthy operation of the spatial system. The value of redundancy is truly realized in the event of a failure or disaster.

The core of redundancy is to enhance the reliability with backup space. But the redundancy must be moderate and select the accurate needed-redundancy facility. Spatial resilience requires the addition of spare modules for critical infrastructure. It is ensured that when a facility is damaged, its functions can be supplemented by backup facilities or replaced by another system.

Redundancy is not essentially a waste but a necessity. Considering that some facilities could be damaged when facing impacts, redundant facilities will play very important roles in reducing the heavy losses of the whole spatial system. Therefore, redundant facilities must be selected and the degree of redundancy can be moderate. On the other hand, for facilities that must be redundant, cost and investment must be paid. Adequate backup modules must be available for critical infrastructure and facilities.

Redundancy is a substitute for the original function. Therefore, the original facility and the standby facility are sometimes viewed as two separate units or modules. If major functions or services are provided only by a centralized entity or a single module, it is more likely to be impacted to failure. In order to reduce the 'waste' phenomenon of redundancy under normal conditions, it is necessary to use the redundant facilities as much as possible. So, redundant facilities could be arranged by multiple functions, and sometimes redundant spaces could be associated with multiple functions. For instance, there should be enough blue-green spaces in the layout of the main roads along the river, the riverside, the coastal areas and the new development area, as a backup to address the uncertain development.

Redundant facilities are usually distributed in a decentralized model. Stability margin is also a representation of redundancy. Sometimes the actual configuration of critical facilities is larger than the theoretical capacity to leave the necessary margin. Raising the standard of infrastructure construction can be regarded as a form of redundancy from a certain point of view.

2.7.3 Relationship between connectivity, network, module and diversity

The essence of network is connectivity. The core of network is the extensive interconnections. Through networking, the components of the system form strong connections and feedback can support each other when facing disasters.

Network and module are closely related. Network emphasizes on the wholeness of a spatial system and the integration of modules inside the system. Networks are also closely related to diversity, which is an organizational structure that can bring more diversity. The lack of network often leads to the separation and isolation of landscape elements, which results in the lack of diversity.

Complex system is a network of simple modules. The approach to complex systems is usually 'decompositions + syntheses'. That is, according to the principle of system theory, the complex network is first decomposed into simple modules. Then the research results of each module are synthesized according to their structural correlation.

Network is not only the connection of the physical form, but also the connection and association of the non-physical form. The essential meaning of network is mutual connectivity. Network aims to maintain smooth communication of materials, information and energy between the internal elements of the system and the external environment by the interconnections of important connective facilities, co-construction and sharing of municipal infrastructure.

2.8 Typical characteristics of the approach of spatial planning and design for resilience

There are many differences between spatial planning and design for resilience and traditional planning and design methods. The concept of resilience should shift from resisting the disturbance to allowing the disturbance, taking the uncertain disturbance as a normality to work with.

— Spatial planning and design for resilience emphasizes a spatial ability to address future disturbances. It is a new planning and design method for addressing the disturbance from uncertain future. It needs to comprehensively evaluate various impact factors of future uncertainties. When facing multiple disturbances, spatial planning and design for resilience should provide spatial support for improving the capacity of robustness and adaptability of the spatial system. The overall evaluation factors including the disaster frequency, defensiveness, affected regions, losses, the secondary disasters as well as the recovery time of the catastrophe needs to be combined with current states' layer, in order to make projections for challenging places in space by mapping technologies. Therefore, spatial planning and design for resilience emphasizes the sustainable development based on natural base layer and land carrying capability.

— The main scenario for an uncertain future should be identified. The main scenario should be generated from various possible scenarios. The generation of the main scenario should take into comprehensive consideration the natural base layer, socio-economic trend and potential risk influence.

— A series of related technologies of spatial planning and design for resilience should be adopted to improve the robustness and adaptability of the spatial system against the background of major scenarios and future major disturbances. Under the guidance of systematic, coordinative, bottom-line and foresight thinking, some spatial characteristics such as regionality, diversity, connectivity, redundancy, modernization, multifunctionality can be applied appropriately on the basis of traditional planning and design methods. The connectivity of blue-green network and infrastructure should be especially highlighted.

— Spatial planning and design for resilience is not totally contradictory to other planning and design methods. Resilience requires more comprehensive understanding of the multiple driving forces and potential disturbances of the research case such as natural conditions. It should be based on the comprehensive grasp of the natural base layer, major disturbances and urbanization trends. Spatial resilience emphasizes spatial protection and development on the basis of sufficient land carrying capacity.

2.9 Key points of spatial planning and design for resilience

Table 2.3 summarizes key points of spatial planning and design for resilience.

TABLE 2.3 key points of planning and design for resilience.

Characteristics	Effect	Key Points
Robustness	Capability	Robustness refers to the degree of tolerance to external disturbance. Robustness is derived from the fact that the spatial system is always disturbed. It is a prerequisite for the healthy operation and an important quality of spatial resilience. The pertinence and discrimination of future major disturbances are the foundation work of robustness.
Adaptability	Capability	Adaptability refers to the ability of a spatial system to actively adjust its structure and function to adapt to the environment and future climate change. Foresight thinking, extensibility and moderate redundancy in spatial planning and design are the key points to improve the level of adaptability of a spatial system.
Systematisms	Thinking characteristic	Systematic thinking emphasizes the integrity, hierarchy, relevance and openness of spatial system that can be improved by planning and design.
Coordination	Thinking characteristic	Coordination is not only the goal of spatial planning and design for resilience, but also the means to improve the goal. Spatial planning and design for resilience emphasizes the harmony between urbanization and the land carrying capacity of natural base layer, addresses the relationship between the whole system and elements, advocates multi-level and cross-scale regional cooperation and multi-disciplinary cooperation, and takes into account the needs of different subsystems.
Bottom-line	Thinking characteristic	Maintaining the core function of the system in all circumstances is the bottom line of spatial planning and design for resilience. Spatial planning and design for resilience should be problem-oriented. It highlights the ‘bottom line constraint’ and corresponding countermeasures from the worst possibility based on the prevention of major future disturbances. It is needed for adhering to the spatial development with natural priority.
Foresight	Thinking characteristic	Foresight thinking means that spatial planning and design for resilience should take targeted measures in advance based on the major future scenarios and the prevention of major disturbances.
Regionality	Spatial character	Regional feature means that the planning and design should be based on the site characteristics, fully respectful to the natural base layer and make use of regional resources to create the spatial structure and form with distinct regional characteristics.

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TABLE 2.3 key points of planning and design for resilience.

Characteristics	Effect	Key Points
Connectivity	Spatial character	Connectivity refers to the strong connection and feedback between the components of the system through the connection of elements such as points, lines and planes. Connectivity is an important support to maintain the function of the system and has multi-dimensional and multi-scale properties. Networking is an important organizational form to realize connectivity. Blue - green network is an important carrier to improve connectivity.
Diversity	Spatial character	Diversity not only refers to that of spatial multi-structure and multifunctionality, but also refers to a variety of ways to improve the orientation of spatial resilience. Diversity is the basic condition for a resilient spatial system when facing external disturbances. It needs scientific structure arrangement, which has special practical significance.
Multi-functionality	Spatial character	Multifunctionality refers to the utilization of multiple functions from the same space. Multiple functions are the need to realize diversity under the condition of limited land resources. The implementation of multifunctionality should be adapted to local conditions. Spatial planning and design for resilience should adhere to the combination of the function from both normal time and disaster period, and the integrations of natural function and the water, ecosystem service function in different periods
Redundancy	Spatial character	Redundancy refers not only to the replaceable feature of the core elements and functions, but also to the preparation provided in advance for future changes. The spatial characteristics of redundancy emphasizes the positive creation of conditions to cope with future changes of the system, and the ability to adapt to new changes through appropriate transformation or expansion of original spatial functions and organizations. The key points of redundancy are extensibility and flexibility. Redundancy provides a buffer and margin for contingencies. Redundancy is an important measure to improve system adaptability.
Modularization	Spatial character	Modularization divides the complex system into several controllable, reasonable modules under the guidance of integrity, and each module has certain robustness, adaptability and self-grouping diagnostic ability. Spatial planning and design for resilience advocates distributed and modular spatial organization.

2.10 Summary

This chapter systematically researched the theory of spatial planning and design for resilience from the aspects of the core capability pursued by planning and design, the thinking characteristics of spatial planning and design for resilience, and the main spatial characteristics of resilience presented by planning and design with a system point of view. The main contents of this chapter are as follows:

1 The formation and development of the concept of resilience are introduced. The characteristic, differences and the relationship between engineering resilience, ecological resilience and evolutionary resilience are introduced respectively. The orientation of resilience gradually changed from ‘pursuing a single stable state’ to ‘emphasizing continuous adaptability to multiple stable states’. The division of the three stages marks the deepening and improvement of people’s cognition of resilience.

2 Three core capabilities pursued by spatial planning and design for resilience are proposed, namely, robustness and adaptability. It is pointed out that the robustness is the key to the healthy operation of the system, the inner vulnerability of the spatial system and the external frequent disturbance urgently call for high level of robustness. Spatial planning and design for resilience should adapt to natural changes and urbanization trends, and has two-way interactive adaptability. Spatial planning and design for resilience should have the capacity for learning and transformation.

3 Four essential thinking characteristics of spatial planning and design for resilience are proposed, namely, systematics, coordinative, bottom- line and foresight thinking, and the four essential attributes of resilience planning and design are discussed in details. Due to the openness, hierarchy and high elements’ relevance of the research case, spatial planning and design for resilience is an integral action with comprehensiveness, multi-dimensional and multi-scale process. Coordination is not only the means but also the goal of spatial planning and design for resilience.

4 It systematically discusses that a resilient space has six characteristics, namely regionality, connectivity, diversity, multifunctionality, redundancy, and modularization. The fundamental reason why these factors can help improve the spatial resilience is expounded.

- Regionality is essential for improving spatial resilience. The method of land use is the most important factor to determine the spatial resilience. When reasonably distributing land use for the future, compliance with natural conditions is the source of regionality. Spatial planning and design for resilience presents different regional characteristics due to the differences of natural, historical and cultural conditions, which have distinct regionality. Spatial planning and design for resilience should respect the natural base layer and the stability of environment after construction activity occurs.

- It is demonstrated that connectivity is an important feature of spatial resilience. The purpose of connectivity is to make the exchange of material, information and energy smooth. Connectivity has multi-dimensional and multi-scale. Overall coordination is the foundation of realizing multi-point, interconnectedness, interactivity and multi-scale network. Connectivity is the key to networking. Lack of connectivity is often the root of the cause of structural failures or functional failures. Networking has powerful connections and feedback. The network of infrastructure and the network of grey, blue and green facilities are the basic requirements of the interconnection of spatial elements, structures and functions.

- Diversity originates from the different needs of spatial functions. Diversity is reflected in physical space through multiple functions. The essence of diversity is to provide different functions to maintain the core function and structure of a spatial system when facing future external disturbances. Diversity provides more ideas, information, and opportunities to solve problems, which can enhance adaptability, and provide multiple options.

- It is demonstrated that multifunctionality is another important feature of resilient space. The limitation of land supply determines the multifunctional use of lands. With the multifunctional use of land, it can provide as many service functions as possible on the limited land. The multifunctional use of land should be implemented in accordance with local conditions by mixed use of land, function combination, space stacking and time shifting.

- It is demonstrated that redundancy is another important feature of spatial resilience. Resilience requires the system to be redundant in its core structure and function. Redundancy of key parts is a pre-set backup and supplement to ensure the maintenance of core functions in the face of disasters. Redundancy is not a simple repetition. As long as the redundant elements can be set scientifically, it can help the spatial system to realize multifunctionality.

- It is demonstrated that modularization is another important feature of resilient space. It is a kind of organizational structure process to decompose complex spatial system into better control, easier adjustment and better management modules. Modules are decomposable, replaceable, extensible subsystems, and easy to be controlled and managed. Distributed modules can effectively reduce risk transmission in a spatial system. Spatial planning and design for resilience is usually organized and implemented in the form of modules.

5 The internal relations among main spatial characteristics of resilience presented by planning and design are explained. Different main spatial characteristics of resilience presented by planning and design have different emphases. Specific planning and design for resilience completely depends on the actual situation. The utilization of multiple main spatial characteristics of resilience presented by planning and design is encouraged.

6 The internal thinking logic and characteristics of spatial planning and design for resilience is put forward. Resilient planning and design has distinct characteristics. It is needed to comprehensively analyse historical data and extensively apply modern technology to identify and select major scenarios in the future. Spatial characteristics such as regionality, connectivity, diversity, multifunctionality, redundancy and modernization, can be applied to realize the spatial resilience of a certain spatial system.

3 Implementation Method of Spatial Planning and Design for Resilience

3.1 Introduction

In this chapter, the implementation method for the application of spatial planning and design for resilience is proposed. It can be applied as guidelines for further empirical research of the PRD.

This chapter consists of 6 sections. Section 3.2 studies implementation principles of spatial planning and design for resilience. Section 3.3 studies the organization of spatial planning and design for resilience. Section 3.4 studies technical route. Section 3.5 studies major works in each phase of spatial planning and design for resilience. Section 3.6 concludes the main research outcomes.

3.2 Implementation principles

The implementation principles of spatial planning and design for resilience are summed up as follows.

Spatial planning and design for resilience need to take ‘theoretical guidance, overall coordination, adaptation to local conditions and the environment, natural priority, moderate redundancy and gradual evolution’ as means (Dai et al., 2019). It needs to widely apply resilient spatial characteristics and ensures that the spatial system has robustness and adaptability. Resilience also enables to maintain the steady operation of a system under the pressure of future disturbances.

The specific content of the implementation principle is described as follows.

3.2.1 Guided by the theory of spatial planning and design for resilience

The future urbanization of a spatial system cannot be separated from the natural base layer. The principle of planning and design is to properly consider the relationship between natural protection and urban development. It is needed to fully realize that conservation and construction are fundamentally of equal importance. The view of vigorous development at the expense of the environment should be changed. The orientation of spatial planning and design for resilience is to create a good environment for supporting the socio-economic development of a spatial system. It focuses on improving the blue-green networks and enhances the capacity for resilience and extending the life cycle of the space.

The core of spatial planning and design for resilience is that the method of spatial development and protection should be based on the land carrying capacity, as well as natural protection area identification and land-use suitability assessments (Nijhuis et al., 2020). The spatial system is an integral of subsystems with specific functions, which is composed of subsystems with mutual influence and correlation according to certain relations. The overall function of the system is not a simple mechanical superposition of the functions of each subsystem. Spatial planning and design for resilience should comprehensively analyse the element, structure, function and coupling mechanism.

A Overall coordination and key node shaping

The development of the spatial system should not only be reflected in the wholeness of the target, but also in the coordination of multiple fields, links and stages. Spatial planning and design for resilience originates from the harmonious coexistence of human and nature. Under the guidance of the overall coordination, it is necessary to improve the overall resilience of the space by shaping important strategic points and multiple linkages.

B Adaptation to local conditions and the surrounding environment

The items such as geological features, hydro-ecologic characteristics, and socio-economic factors in different regions will profoundly influence the future transformation tendency of the spatial system. Therefore, spatial planning and design for resilience should adapt to local conditions and address specific problems. It is necessary to carry out a comprehensive pre-evaluation of the spatial environment, the characteristics of existing construction conditions, land use and infrastructure. Based on the results of pre-evaluation, the spatial development principles and strategies suitable for a specific research case can be formulated.

C Natural priority

The spatial system has both social and natural attributes. Spatial planning and design for resilience should be based on the situation of natural base layer, adhere to the bottom-line thinking, and correctly consider the relationship between urban development and natural protection. Natural base layer is the cornerstone of any complex spatial system. The principle of natural priority should be fully embodied in the process of spatial planning and design for resilience. The bottom line of natural protection should be implemented in the whole process. It is needed to reduce artificial interventions and let nature do work to create a space for harmonious coexistence between human and nature.

D Taking disturbance as a 'window of opportunities' to improve resilience

The effect of a resilient scheme can only be tested in an event that happens afterwards. For this reason, the external disturbances should be considered as an opportunity to test whether resilience can be improved or not. In particular, it is necessary to understand the advantages and disadvantages of the existing program and study the possibility of the way for a spatial system to be improved. Where there are conditions for improvement, the internal demand and external conditions can be adjusted in both space and time. Where there is no immediate improvement, experience and data can be accumulated to prepare for the next revision.

3.2.2 Based on the pre-evaluation of the spatial system

Spatial planning and design for resilience should be based on the spatial mechanism and make pre-evaluations such as the analysis of the hydrologic ecosystem, land-use suitability, potential flooding and land subsidence risk areas under the situation of climate change. The main risk area and key protection nodes should be clarified and the database should be constructed. The key contents of the pre-evaluation of the spatial system are shown in Figure 3.1.

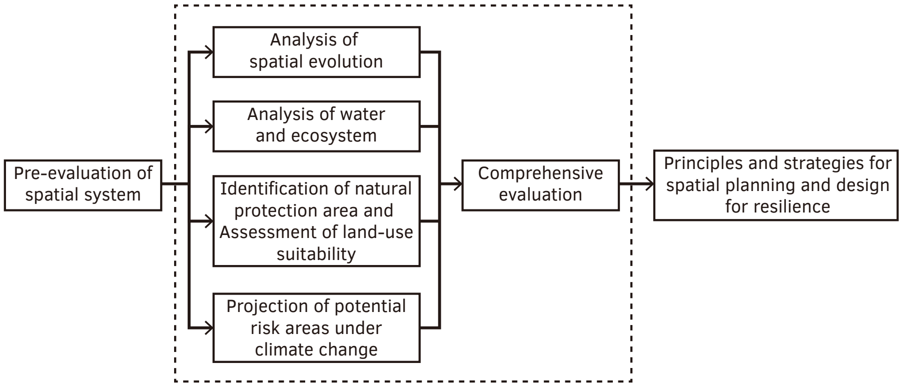


FIG. 3.1 Key contents for pre-evaluation

TOC

3.3 Organization

The objective of spatial planning and design for resilience is to generate resilient space through the processes of spatial interpretation, feature evaluation, strategy proposal, vocabulary transformation, and new scheme creation. The particularity of spatial planning and design for resilience determines the key points.

3.3.1 Build a multi-participatory working platform

Spatial planning and design involves many aspects. Multiple elements which span multiple scales involve the interests of different groups. Spatial planning and design for resilience must have a strict organization process. A multidisciplinary expert database and expert consultation system should be established. It is necessary to widely listen to the suggestions of different stakeholders and obtain suggestions from different aspects. It should improve the whole spatial system to participate in initiative and convenience. This communication contributes to the understanding of the site and providing an opportunity to learn and accumulate experience. Only in this way can the interests of different regions and different groups be taken into account, so that the new scheme can best reflect the will of the majority of people, reflect public interest, and ensure the effective implementation of the planning and design results. It is necessary to set up a cross-scale cooperation platform beyond administrative boundaries, and coordinate and promote the implementation of important blue-green strategic points, cross-border infrastructure layout and other aspects. At the macro scale, rigid control elements should be controlled by government, and at the micro scale, flexible elements should be controlled by the government, enterprises and the public.

Faced with external disturbances, planners and designers should be good at learning from the experiences of other countries in addressing disturbance, drawing lessons and taking them as an important source of wisdom for planning and design. Communication platforms and mechanisms should be established to ensure the smooth flow of information. Through talks, workshops and online platforms, stakeholders from all sides can fully express their own needs, and stakeholders can fully negotiate, so that the results of planning and design can bring tangible benefits to the public.

3.3.2 Process of spatial planning and design for resilience

Spatial planning and design for resilience is a continuous dynamic process. It has to experience phases such as investigation, analysis, arrangement, conceptual design, scheme comparison and selection, scheme implementation and so on. The process of planning and design should be organized systematically and cooperatively.
The scientific workflow of spatial planning and design for resilience should be emphasized and reflected not only in the construction of the physical environment, but also in the process of organization. Relevant departments of planning and design should clarify their responsibilities and strengthen communication. Through discussion and information feedbacks, the quality of planning and design can be constantly improved.

Different from traditional planning and design, spatial planning and design for resilience highlights the responsive process for future disturbances. The best result is that a spatial system can resist external disturbances. The second result is to reduce the disturbance's damage to the spatial system to an acceptable level. The bottom line is that the spatial system can maintain the most basic functions. Spatial planning and design for resilience is a dynamic programming process. It is necessary to acquire new knowledge through learning and discussions with experts and the public, which can become catalysts to activate new knowledge so as to propose more targeted, feasible and recognized possible schemes. After a spatial system is exposed to external disturbances, planners and designers should be good at timely summarizing the experience and lessons, and turn the experience of disturbance into the ability to further improve the level of resilience of the same spatial system.

3.3.3 Planning and design with phases

Future changes are highly uncertain. According to the length of spatial planning and design, a possible situation can be divided into short-term, medium-term and long-term. The action framework from the current situation to the overall goal is constructed, and corresponding sub-plans and sub-goals can be formulated. Short-term situations should be based on certainty and mandatory content and long-term situations can be used as a test of short-term situations. It is needed to pay attention to the connection of short-term and long-term situations for reasonable timing arrangement.

3.4 Technical route

The process of spatial planning and design for resilience follows the logic of ‘putting forward a problem, analyzing a problem, providing possible solutions, evaluating feedback’. The technical route of spatial planning and design for resilience proposed is shown in Figure 3.2.

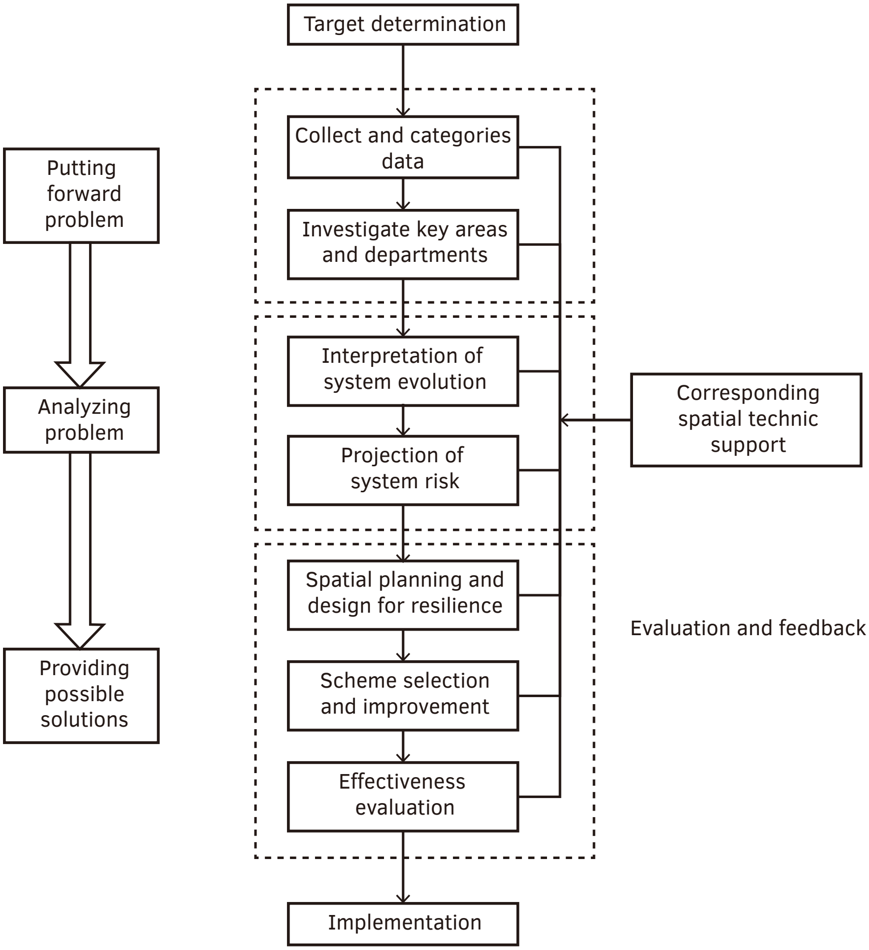


FIG. 3.2 The technical route of spatial planning and design for resilience

The first step is to collect and categorise data. It is very important to collect and sort out all kinds of documents and technical software needed for planning and design. The documents include administrative division, landform, land use, hydro-ecological environment, social and economic development, infrastructure, shipping shoreline, documents of previous planning and design, and other basic data. Technical software includes database construction, environmental risk assessment technology, scenario model analysis, GIS, RS system spatial technology analysis, spatial visualization technology, etc.

The second step is to investigate key areas and departments. Based on the study of relevant historical data, planning and design data and relevant cases, the special topic research is conducted in key areas and key departments. Through on-site surveys, interviews and multi-stakeholder consultations, planners and designers can have an in-depth understanding of the current situation, development trend and appeal of research case, and identify the key issues that can best represent the regional development and the consensus of multi-disciplinary experts.

The third step is the interpretation of the system evolution. The purpose of the step is to clarify the linkage between history and current situation, and to focus on analyzing the spatial texture and environmental characteristics. It needs to extract the important spatial elements and construct a knowledgebase that forms the graphical representation of spatial information.

The fourth step is the projection of systematic risk. Spatial planning and design for resilience emphasizes that spatial development and protection should be built on the basis of land carrying capacity. On the basis of a comprehensive analysis of the main factors which affect the spatial pattern, it is necessary to focus on the analysis of the major disturbances that affect the future spatial development, and consider the major disturbances as the target. The projection of systematic risks is the most important basic work of spatial planning and design for resilience.

The fifth step is to conduct spatial planning and design for resilience. On the basis of comprehensive system interpretation, all contents including system projection, the guiding ideology, technical route, main tasks and results need to be determined. The main spatial elements should be extracted and the driving mechanism, response speed and intensity of these control elements to the resilient target should be analyzed. The driving mechanism that plays an important role in the realization of spatial resilience should be understood. The relevant control factors can be improved to carry out spatial reconstruction. The scheme should highlight the attributes such as systematic thinking, coordinative thinking, bottom-line thinking and foresight thinking, and apply spatial resilient characteristics such as regionality, connectivity, diversity, multifunctionality, redundancy and modularization to different spatial types according to local conditions.

The sixth step is the selection and improvement of the new scheme. Spatial planning and design for resilience is a process of continuous adjustment under the guidance of spatial resilience. The complexity of the spatial system determines that the new scheme should be modified and continuously improved with the changes of society, economy and natural environment. It is necessary to compare different new possible schemes and absorb their advantages to improve the resilience of a spatial system.

The seventh step is implementation. It is necessary to put forward the scheme from supporting policies and guidance for timing arrangement. Quantifiable indicators will be selected to test the effectiveness of the new scheme for further modification and improvement.

3.5 Major work in each phase

3.5.1 Target determination

Spatial planning and design for resilience emphasizes the ability of space to address future disturbances and provides spatial support for further urbanization and natural protection. It can rely on its own robustness and adaption to maintain the core capabilities of a spatial system and enter to the new stable state as soon as possible.

The determination of target is a multi-objective decision. The relationship among spatial development, protection and land carrying capacity should be considered in the determination of research cases. Through a large number of surveys, interviews, special conferences, etc., the key contradictions can be identified and highlighted.

3.5.2 System interpretation

Understanding the spatial evolution and current state is the premise of spatial planning and design for resilience. System interpretation should comprehensively analyze the society, economy, spatial texture, and spatial pattern of the research case and study the interrelations among spatial forms, elements and environments. It needs to deeply analyze the coupling mechanism among elements, forms, subsystems to extract the key elements that have significant impact on the improvement of spatial resilience. Only by deeply analysing the performance of the existing spatial system in addressing the future condition, projecting the degree of gaps between the current situation and resilient state, and identifying the prominent hidden trouble points of the gap, can the key problems restricting the future resilient space be sorted out, so that the spatial planning and design for resilience can be more targeted and problem-oriented.

A Comprehensively analyse the dynamic evolution of the system

The evolution of space from the dimensions of time and space should be analyzed by combining the diachronic and synchronic nature of the spatial system in order to find a bridge connecting the history and the future. From the dimension of time, the life cycle of the spatial system should be studied, and its adaptation to the surrounding environment needs to be concerned. The relationship between the part and the whole system should be analyzed in spatial dimension, and the changes of its internal organizational structure should be concerned. In particular, it is necessary to pay attention to the evolution of the ecosystem and study the coupling relationship between different layers to explore key factors which impact spatial form, land use and connectivity of the blue-green network on the water and ecosystem.

B Comprehensively analyse the spatial pattern and its way of organization

The pattern of a spatial system is the result of long-term evolution and has the role of irreplaceable and multi-scale relevance. It is of great strategic significance for maintaining the health and the integrity of water and ecosystems, safeguarding hydro-ecological security to realize spatial resilience. Scientific identification of natural base layer and natural security pattern is the premise of spatial planning and design for resilience. Spatial planning and design for resilience should break away from the traditional linear and deterministic framework and pay more attention to the potential risks of the spatial system with strong uncertain disturbances. By assessing

TOC

the spatial pattern of land-use suitability, natural sensitivity and potential risks, the way to develop or protect a space in a specific region can be possibly judged. The natural security pattern and the distribution of infrastructure in the whole region should be taken into comprehensive consideration to provide a foundation for the regional spatial structure layout. The flow mechanism of 'production-confluence' of space should be studied with emphasis on the selection of key strategic points and the potential patches so as to build a robust hydro-ecological network.

C Identification of key spatial nodes

The dynamic mechanism of spatial form, land use and connectivity on the water and ecosystem needs to be studied. The important spatial nodes for realizing spatial resilience can be selected as the control elements. Through scientific selection, planning and design of key spatial nodes that are important for improving spatial resilience, the connectivity between key spatial strategic points and blue-green networks can be improved. The relationship between land use and public space can be studied and the strategic points can be taken as the entry point to enhance the resilience of a spatial system.

D Identification of land carrying capacity

Land carrying capacity refers to the comprehensive quantitative threshold under the consideration of both special geographical conditions and development needs. The factors that determine the resilient capacity include not only the supportive natural resources, but also external disturbances such as the pressure of social and economic development and climate change. The high point of land carrying capability threshold is the maximum adaptable value that the environment can provide, and the low point is the minimum level of social and economic development that the environment must ensure and the spatial system can accept. Land carrying capacity is the foundation of improving resilience. The analysis of land carrying capacity integrates land resources, land use model, hydro-ecological environment, infrastructure, population scale, development intensity, etc., especially the limiting factors of spatial threshold should be considered.

3.5.3 Main scenario projection

The projection of major scenario is the key part of the spatial planning and design for resilience. It includes information collection, motivation analysis, scenario creation and scenario assessment. Based on the existing conditions and natural base layer, the projection of main scenario needs to study the evolutionary characteristics of the spatial system and actively explores the future urbanization trends. It is the key to separate uncertain scenarios from known uncertainties and imagined uncertainties. The main scenario projection should combine the natural conditions and social and economic development trends that can be identified from a variety of possible development scenarios. It takes the main scenario as the background of spatial planning and design for resilience and applies corresponding resilient strategies and technologies based on the main scenario.

A Projection of major disturbances

Spatial planning and design for resilience should project the type and intensity of major disturbances brought by future extreme climate change according to various factors such as the natural base layer, the frequency of disasters that have occurred in history, the scope of impact and the loss caused by disasters. It is necessary to conduct systematic investigation on spatial vulnerability and focus on the lack of capacity based on the evaluation of the categories of potential risks and environmental sensitivity. The type and intensity of major disturbances that need to be prevented in the future are identified for the subsequent adoption of corresponding resilient measurements.

B Succinct main line of the scene

Succinct main line of the scene is to project and select the largest possibility of future scenarios. All kinds of spatial analysis techniques should be applied comprehensively to extract the main line of the scene. It should be good at grasping the main factors, making reasonable simplification and generalizing a number of possible future scenarios from possible events. It is needed to integrate the results of systematic interpretation, expert interview and experiential learning to eliminate the full impossible scenarios. The key point of scenario projection is to reduce uncertainty.

TOC

3.5.4 System planning and design

Facing future disturbances, spatial planning and design for resilience should provide relevant principles and strategies. Based on the characteristics of the research case, it needs to widely use resilient spatial characteristics such as regionality, connectivity, diversity, multifunctionality, redundancy, modularization, and take the improvement of spatial robustness and adaptability as the orientation. Spatial planning and design for resilience should formulate reasonable scale and staged-indicators, analyze response speed and intensity of key control elements to the target, and improve the spatial distribution and resource allocation. In the process of spatial planning and design for resilience, different types of space should be classified according to their spatial characteristics.

A Classified and multi-scale planning and design

Spatial planning and design in macro scale should emphasize the integrity of the whole system, and pay attention to the general trends that a system can develop. It focuses on regional natural protection, land-use suitability, regional integrity, and improving connectivity of large blue-green networks. It should give priority to natural protection on the whole system, pay attention to the protection of history and culture, and grasp the relationship between form and space. It is needed to identify the source-flow elements of the natural environment, important corridors behind the landscape pattern and the important hydro-ecological sources. Based on respecting the heterogeneity of landscape, the key strategic points should be found. A certain amount of margin can be required for continuous infrastructure across scales.

As an intermediary which connects macro scale and micro scale, planning and design in meso scale should be focused on connectivity and carried out under the premise of complying with the integrative requirement of macro scale. It should further implement the requirement of network connectivity at multiple levels in space. Spatial planning and design for resilience advocates mixed land-use model, promotes the transformation of spatial function and stimulates the diversity of land function. The spatial layout should not only adapt to the present moment but also leave redundancy for future changes and provide diversified choices for the future.

Spatial planning and design in micro scale should further refine the planning and design results in both macro and meso scale. It is necessary to strengthen the diversity, multi-function, redundancy and self-organization of various spaces. By improving the land use condition, elevation control and embankment design of spatial nodes, a series of main spatial characteristics of resilience presented by planning and design can be further concretized to consolidate the foundation of spatial resilience.

B Take land use, blue-green network as the framework of spatial layout

Improving land use situations and blue-green networks are the core of spatial planning and design for resilience. Land resources are scarce. Based on the results of identification of natural resources and land-use suitability assessment, reasonable land use for future can be arranged. For areas with high vulnerability and low threshold, the construction of blue-green networks should be strengthened to create a smoother hydro- ecological cycle.

C Focus on flood control and drainage

The estuary of the delta is a typical hydro-ecologically sensitive area and its flood control and drainage situation are very severe, which directly becomes the potential threat to the healthy development of the whole spatial system. It is necessary to attach great importance to flood control and drainage, and to build a resilient flood control and drainage system on the basis of fully understanding the hydro-ecological environment of the delta estuary. It is the primary task for improving resilient flood control and drainage in the delta.

3.5.5 Evaluation and feedback

It is very important to check the effectiveness of spatial planning and design for resilience. During the evaluation, five factors such as regional characteristic (based on the practice site), the technical rationality (based on the function of the regional characteristics) and artistic (form harmony based on the geographical characteristics) and practical (based on the practical demand for the regional characteristics), coordination (based on the regional characteristics of environment coordination) can be considered. They are needed to find out the shortcomings during the process of spatial planning and design for resilience, and provide modified strategies to planners and designers.

3.6 Summary

In this chapter, the implementation principle, organization, technical route and working process of spatial planning and design for resilience are described in details, which provides the implementation method for the application of spatial planning and design for resilience for further empirical research of the PRD. The main contents of this chapter are as follows:

1. The operation principle of spatial planning and design for resilience in a spatial system is proposed, which is to take 'theoretical guidance, overall association, adaptation to environment, natural priority, moderate redundancy and gradual evolution' as means, and to widely apply spatial resilient characteristics to research cases. It focuses on improving robustness and adaptability and enabling to maintain the steady operation in the face of the future disturbances.

2. The process of spatial planning and design for resilience is elaborated from the aspects of target determination, system interpretation, system projection, system planning and design, evaluation and feedback. The key content of each phase is elaborated in details. System planning and design is the most important part of the whole process. Macro-scale planning and design should focus on critical issues such as integrity of large spatial patterns, land-use, cross-regional blue-green network and coastline. Giving priority to natural process and focusing on important hydro-ecological corridors are important. As an intermediary connecting macro and micro scales, the spatial planning and design at the meso scale should implement the results of the macro's scheme. The diversity, multifunctionality and redundancy of each type of strategic space should be strengthened in micro scale's planning and design. The natural processes should be respected, and the adaptability of strategic space to climate change should be strengthened. Resilient spatial characters should be taken to enable the spatial form better adapt to the environment. The spatial layout should be moderately advanced in network and redundant elements to provide diversified options for addressing future disturbances.

3. The effectiveness of spatial planning and design for resilience should be tested and improved in practice by generating evaluation framework. Through the process of evaluation and feedbacks, resilience of a spatial system can be constantly improved.

4 Research on Spatial Planning and Design for a Resilient PRD

4.1 Introduction

The PRD is a complex socio-ecological system. This chapter responds to the real situations of sea level rise and land subsidence under extreme climate change. It attempts to apply the theory and the method of spatial planning and design for resilience proposed in chapter 2 to chapter 3. By conducting the analysis of the current characteristics and the evolution of the PRD, projecting potential water-related risks areas, and identifying the challenges and main future development scenarios of the PRD, this chapter researches on possible schemes of a spatial resilient PRD, especially from the perspectives of land use, blue-green networks and coastline.

This chapter consists of 7 sections. Section 4.2 presents research framework for conducting this research. Section 4.3 researches on spatial systems and projects future scenario of flooding and land subsidence under extreme climate change condition. Section 4.4 firstly conducts the analysis of natural protection area identification, as well as the assessments of agricultural, urban land-use suitability, then researches on the principles and strategies for resilient land use of the whole PRD. After identifying natural protection areas and appropriate population that can be accommodated, a land-use scheme for Nansha is provided. Section 4.5 firstly establishes cross-regional ecological barrier and improves a cross-regional water network of the PRD. Then appropriate selections of new regional water corridors in the PRD based on the technical assistance of the minimum cumulative resistance (MCR) model are conducted. Based on regional context, water networks in Nansha are also improved by a new possible scheme. Section 4.6 firstly divides the whole coastline of the PRD into coastline segments based on its surrounding physical conditions rather than merely administrative boundaries. The coastline function is arranged into three categories, namely areas for development, areas for controlled development and areas for protection, together with the creation of coastline buffering belt, based on coastline development suitability assessment. Section 4.7 is the conclusion.

4.2 Overall spatial planning and design framework

The technic route for providing spatial planning and design in the PRD can be seen in Figure 4.1.

- **Step one** is to comprehensively understand the situation of the PRD from spatial perspective, as a basement knowledge for planning and design action. It is important to clarify basic information such as elevation, soil, water system, traffic system and find out the changing relationship between urban and blue-green structures.

- **Step two** is to conduct scenario simulation and find out vulnerable places (especially flooding and land subsidence) in both agricultural and urban areas in the whole PRD under extreme climate change situation.

- **Step three** is to provide a possible land-use scheme for realizing spatial resilience. Land use approach and spatial resilience has a close relationship. Given regional characteristics, existing circle-layout characters and different local terrain conditions, land-use classification should be used to determine land-use strategies, land-use policies and regulations in different local areas. Based on the exploration of spatial evolution, the projection of flooding and land subsidence risk areas, the identification of natural protection area, and the assessment of agricultural, urban land-use suitability, a possible land-use scheme with the spatial characteristics of three-circle space coordination and four land-use categories is generally formed to respond to future climate change.

— **Step four** is to provide a new scheme for improving blue-green networks. Strategies for new blue-green networks and spatial resilience are also closely related, which can function as a backbone structure for the future PRD. Given the resilient spatial characteristics of network connectivity and redundancy, the measurements of creating cross-regional ecological corridors and improving cross-regional water networks in PRD are put forward, with the technic assistance of MCR model that can help select new blue-green corridors that have comprehensive least environmental cost and lowest average land resistance between aimed connecting points, when new blue-green corridors are implemented.

— **Step five** is to provide a new scheme for improving coastline quality, which includes the arrangement of the coastline function and creation of coastline buffering belt. Three categories of functions of the whole coastline, including areas for development, areas for controlled development and areas for protection are proposed with the assistance of a coastline development suitability assessment. Resilient spatial characteristics of regionality, redundancy and multifunctionality need to be taken into consideration for improving coastline quality.

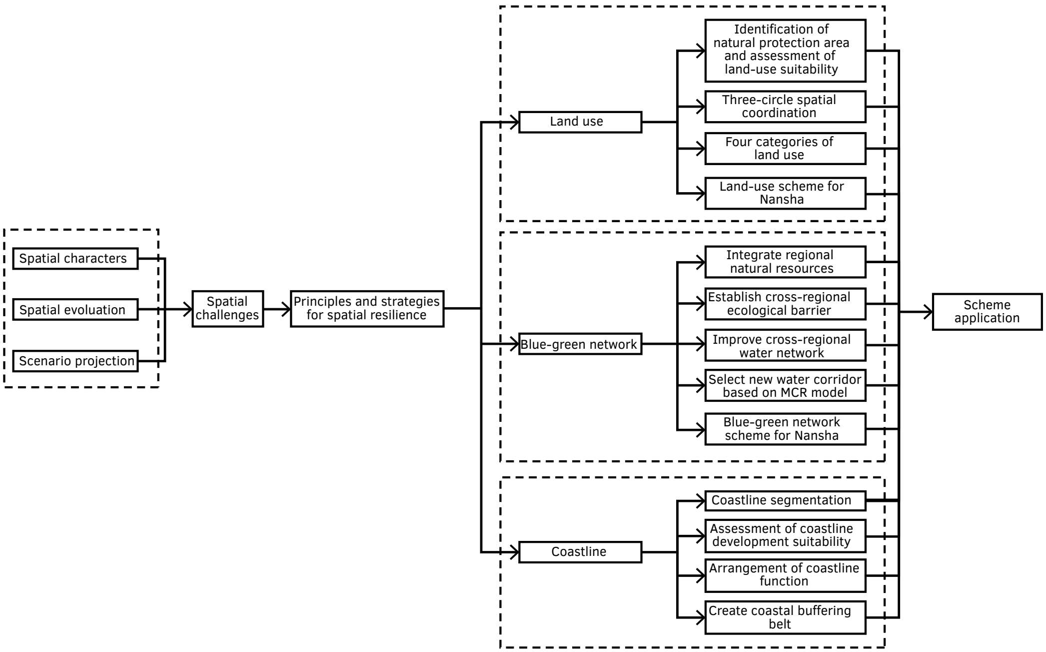


FIG. 4.1 Research technic route

TOC

4.3 Understanding the spatial system and projection of future scenarios

4.3.1 Spatial pattern of the PRD

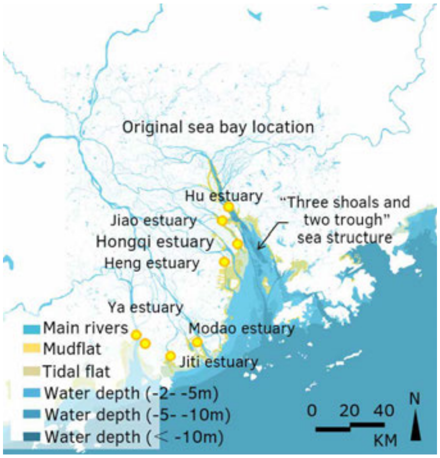
The PRD is composed by the West River sub-delta, the North River sub-delta, the East River sub-delta and the Pearl River sub-delta. Four sub-deltas shape the whole delta landscape with mutual interactive erosion processes (Chen, 2015). The west coastline of the PRD is shaped by fluvial and tidal influences, while the east coastline is majorly shaped by tidal influence. Figure 4.2 is the current spatial pattern map of the whole PRD. It can be found that there are a large number of tidal flats nearby eight estuaries. Comparatively, the size of tidal flats of the west coastline is larger than those in the east coastline. The delta coastline is continuously moving forward to the sea. Its movement speed is closely related to the continuous fluctuation of water level, dyke construction, reclamation that can affect the process of sediment accumulation. Nowadays, the average coastal moving speed is about 32.5m/a towards Lingding sea, 47.2m/a towards Huangmao sea and Modao estuary and 13.4m/a towards Lingding sea (Xu, 2014).

PRD has complex blue-green networks, as shown in figure 4.3 (left). There are nearly 100 large rivers, waterways, streams as well as thousands of tributaries, ditches in the West River sub-delta and the North River sub-delta of the PRD, with a total length of 1600 km and the average density of 0.81km/km^2. There are 5 main rivers, waterways, in the East River basin, with a total distance of 138 km and the average density of 0.88km/km^2 (Xu, 2014).

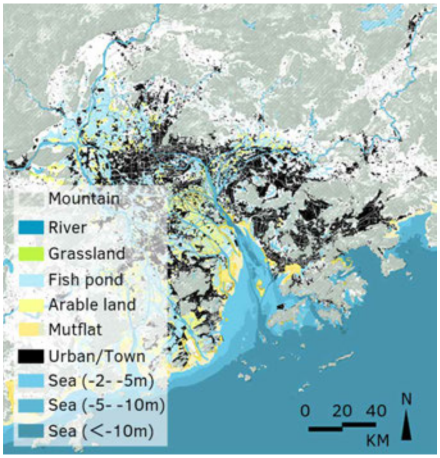
The traffic network of the PRD is centripetal as shown in figure 4.3(right). It is gathering to the central cities and principal urban agglomerations with a close traffic connection between the central cities such as Guangzhou city, Shenzhen city and the surrounding middle and small cities. Due to the circular characteristics (space can be divided into circles by the differences of landscape characteristics) of the PRD, the density of traffic network is higher in the inner circle, especially near the coastline of the PRD (Ye et al., 2011). The density of traffic network in the outer circle is relatively low with scattered pattern. Among major cities, the traffic development of Guangzhou city, Shenzhen city and Zhuhai city is mainly driven by their own urban development tendency.

TOC

As shown in figure 4.4, the digital elevation model (DEM) can be used to identify the overall elevation distribution of the whole PRD. In general, PRD has two important contour lines: 2m and 5m (Pearl River Datum as standard). The 0m-2m area mainly covers places such as Shunde city, Panyu city, Xiaolan city, Nansha in the central region, and Dongguan city in the east region. The natural landscape in the 0m-2m area is mainly influenced by the interaction between fluvial and tidal flow. The soil is soft with high salty degree. Underground water is too much for any suitable construction. The 2m-5m area cover places such as Nanhai, the main urban area of Guangzhou city, and the main urban area of Shenzhen city. The natural landscape in 2m-5m area is mainly influenced by fluvial sedimentation, with good soil quality. The area above 5 m was formed earlier compared with 0m-2m area and 2m-5m area, which mainly covers the north-western part of the PRD and the area along the most of east region.



1 Estuary map of PRD



2 Land use map of PRD

FIG. 4.2 Current spatial pattern map of the whole PRD

TOC

1 Current blue-green network

2 Current traffic network

FIG. 4.3 Current blue-green network and traffic network

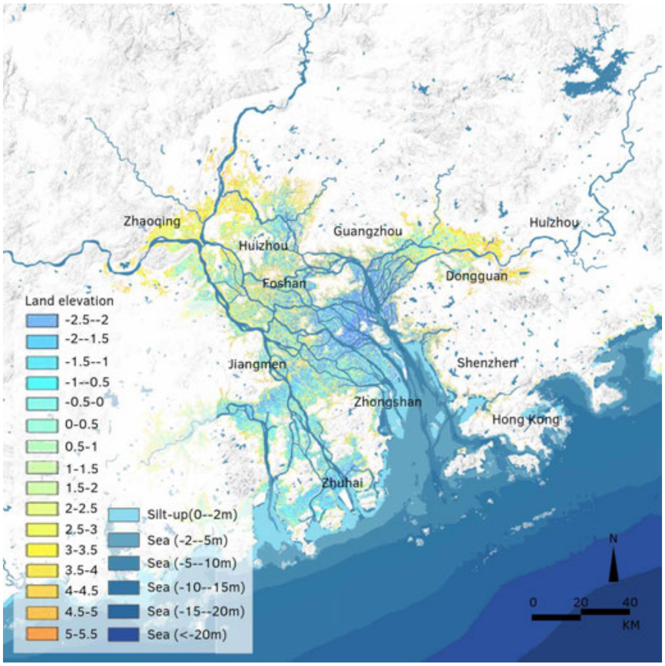


FIG. 4.4 Digital elevation map

FIG. 4.5 Four regions and its corresponding sub-regions of PRD

TOC

According to the natural environment, existing circle-layout characteristic and certain terrain condition, the PRD can be divided into four regions, namely the westside upstream region, the westside downstream region, the east region and the central region. Different regions have different spatial urban and blue-green structures. Figure 4.5 shows four regions and their corresponding sub-regions of the PRD. To understand the relationship between regions can help better understand the PRD spatial system. Detailed spatial analysis, the calculations of division of four regions and their relationships can be found in Appendix C-1.

Generally, current spatial pattern have the following spatial characteristics.

- Because of the development gaps between Guangzhou city, Shenzhen city, Zhuhai city and other cities, the urban structure in the PRD presents the spatial characteristics as 'dense and compact in the north and east area, sparse and loose in the south and west area'. The central cities play important guiding roles in the development of future urban structures. Guangzhou city and Shenzhen city are always in dominant positions, resulting in the strongest connection between the westside upstream region and the east region. The 'Guangzhou-Shenzhen express' has always been the most important socio-economic axis in the PRD. Currently, the competitions among the 'Guangzhou-Shenzhen express', 'Hu estuary Bridge' and 'Zhuhai-HongKong-Macao' Bridge have greatly promoted socio-economic exchanges between the east coastline and west coastline across the Pearl River Estuary.

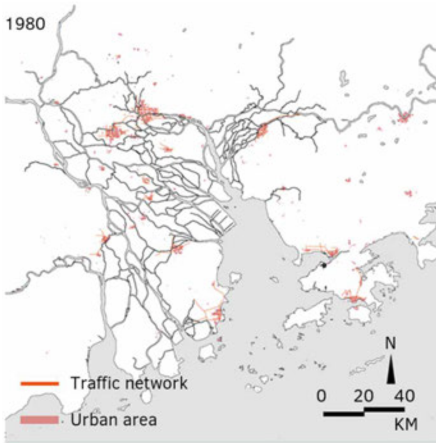
- Due to the existing circle-layout characteristics of blue-green network barrier, blue-green network connectivity can be described as 'strong and dense in the outer circle, weak and sparse in the inner circle'. The previous natural mechanism of the evolution of the blue-green network has been impacted by humans. The blue-green connections of 'Zhaoqing-Guangzhou', 'Dongguan-Huizhou', 'Zhongshan-Zhuhai' remain better than others, which can be regarded as the radiation corridor of the water and ecosystem services in the PRD. Some key hydro-ecological corridors between 'Guangzhou-Foshan', 'Guangzhou-Zhongshan', 'Zhuhai-Jiangmen', 'Dongguan-Shenzhen' have been converted into urban areas, which results in a lower degree of connections.

4.3.2 Analysis of spatial evolution

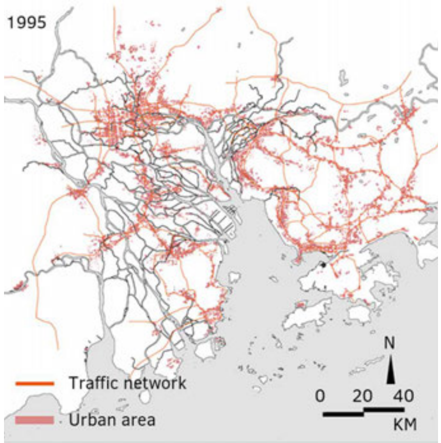
Before 1980, the spatial structure and the land-use of the PRD were dominated by agricultural patterns. The size of dry farmlands, fishponds accounted for 86.3% of the total lands. Fishponds, together with the surrounding dykes, ditches became the typical cultural landscape in the ancient PRD, which could provide the functions of regulating climate, growing fish, and storing water (The Editorial Board of Agricultal Chronicles of P.R.D, 1976). The regional activity of building dykes for improving polder areas began in Tang Dynasties during 600AD-900AD. Dykes and polders were regarded as unique elements of creating spatial security of agricultural areas by defending severe floods in the PRD. In order to keep away from the flooding risks, the settlements were gathered on highlands. During Qing Dynasty (1650AD-1912AD) with the further expansion of population, polder reclamations with dyke system and the extension of 'mulberry-fish pond' spread to the whole PRD. After the Opium War in 1840, Hong Kong became the hub for the import of Western technology and their goods into the mainland of China. PRD has transformed from 'Guangzhou-Macao' center to 'Guangzhou-HongKong' center. Guangzhou city has become a comprehensive economic center of industry, commerce, trade, finance and transportation.

Since the 'reform and open-door' Policy in 1978, industry and transportation have greatly changed the development model of the urban spatial structure in the PRD. With the acceleration of urbanization in the PRD, a large number of traditional farmlands, fish ponds have been transformed into urban space, which causes a declining traditional water-oriented delta spatial structure. In the early stage from 1980 to 1995, the PRD made full use of its geographical advantages to absorb the western capital and their technology from HongKong and Macao capital. The export-oriented industry and the rapid development of special economic areas like Shenzhen city and Zhuhai city led to the rise of a large number of small and middle-sized cities. In the middle stage from 1995 to 2005, the PRD focused on its fast urbanization. The metropolitan area in the inner circle of the PRD has been linked together with the formation of the east and the west wing of the PRD's metropolitan areas. Since 2005, driven by the factors of heavy industry and traffic network, the spatial structure of metropolitan areas in the whole region has been moving from the hinterland to the coastline. With the increase of urban space, the remaining lands for future development decreased.

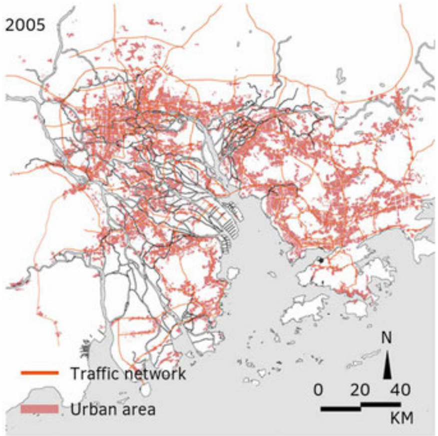
According to the above important historical time spots, Figure 4.6 and Figure 4.7 show overall spatial evolution maps of both urban and blue-green system from 1980. Appendix C-2 shows detailed maps of this spatial evolution in each sub-delta in different periods, and indicators represent this evolution process. By comparing maps, several discoveries of spatial interaction between urban and blue-green systems can be identified during spatial evolution.



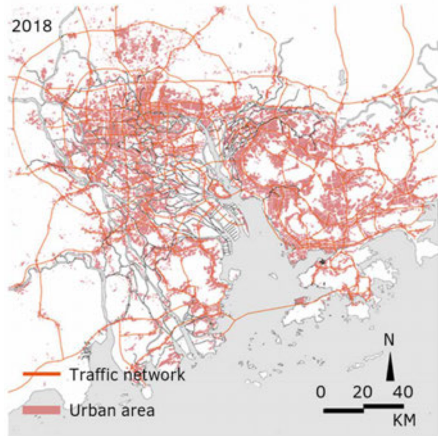
1 PRD urban pattern in 1980



2 PRD urban pattern in 1995



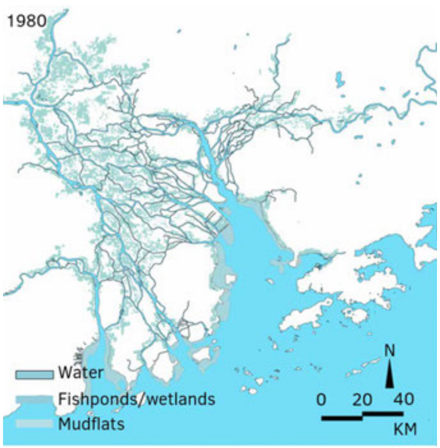
3 PRD urban pattern in 2005



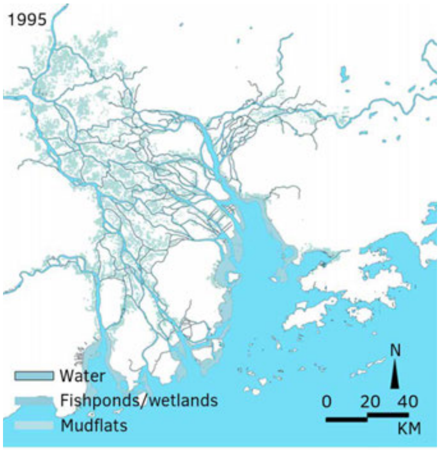
4 PRD urban pattern in 2018

FIG. 4.6 Spatial evolution of urban pattern

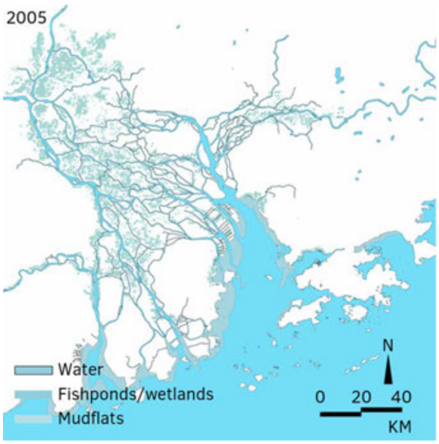
The relationship between urban and blue-green structure has been shifted from mutually dependent to relatively exclusive. Large-scale urban areas make the fragmented blue-green space expand further from the inner circle to the outer circle of the PRD. Before 1980, the West, North, East and the Pearl River were the core corridors to guide the surrounding blue-green space. Blue-green space in the outer circle could provide stable water sources and fertile soils for the development of urban areas in the inner circle. With the rapid development of urbanization, the number of large-scale blue-green corridors that originally connect the inner and the outer circle became less. Lots of marine resources were occupied by disordered coastal reclamations which negatively impacted on the water exchange, which scarified lots of valuable mudflats and tidal flats. All estuaries became congestion.



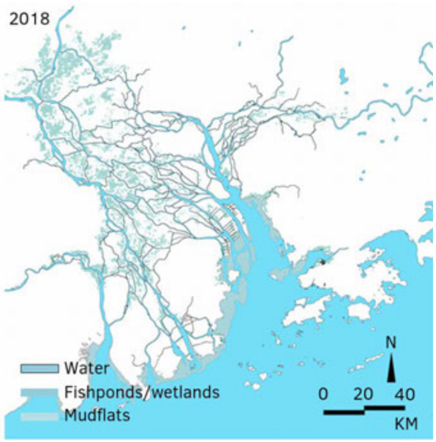
1 PRD blue-green pattern in 1980



2 PRD blue-green pattern in 1995



3 PRD blue-green pattern in 2005



4 PRD blue-green pattern in 2018

FIG. 4.7 Spatial evolution of blue-green pattern

In the west upstream region, Guangzhou city, Foshan city and Zhaoqing city are all famous historical cities. The main characteristic of the evolution of urban structure in this area is ‘circluar- spread’ sourced from Guangzhou city and Foshan city with a radiative traffic network to other adjacent regions. In the long history of development, many satellite towns shown in WU-5, WU-10, WU-9, WU-12 in

TOC

figure 4.5 have been formed around Guangzhou city, Foshan city and Zhaoqing city. Excessive sand mining of the North River causes the increase of its runoff and sedimentation diversion ratio, which leads to irregular pressures and generating the need for flood defense. For instance, due to the influences of local projects such as sand mining and dyke construction in the North River and the Pearl River, the runoff and sedimentation distribution ratio of the North River has increased by almost 40% from 1980 to now, which further caused negative fluvial influence to Guangzhou city and Foshan city waterfront (Wu et al., 2012). Lots of natural streams inside cities such as WU-1, WU-13, WU-9, WU-11 in figure 4.5 are broken. For instance, from Baiyun Mountain, Maofeng Mountain, Danan Mountain to the Pearl River and the North River, some original large-scale hydro-ecological corridors of WU-12, WU-13 in figure 4.5 are fragmented and blocked.

The west downstream region has formed a highly 'spotted-shaped' urban structure. Compared with other regions, the rate of urban expansion in the westside downstream regions is lower. Due to too many changes of dominated urban function, Zhuhai City resulted in the bottleneck of development from 1995-2005, which caused relatively slow urban sprawl of WD-15, WD-16 in figure 4.5. Because the development of enterprises in Zhongshan City was relatively fast, the urban areas were mainly constructed surrounding industrial areas such as WD-11, WD-12 in figure 4.5. The forest, grassland, farmland, fish ponds, silt-up area in surrounding areas of the West River and the North River are replaced by a large number of impervious urban lands. Thus, the blue-green structure was seriously broken.
The southwest coastline was largely reclaimed. The situation of reclamations was more prevalent in Modao estuary and Jiti estuary of WD-18, WD-17 in figure 4.5. Mangroves near downstream reaches, as well as estuaries were destroyed, which led to a decreased biodiversity. It can be projected that in the future, the silt-up areas alongside offshore will continue moving outward to the sea, which can cause an even narrowed estuary.

The east region has formed a highly 'linear-shaped' urban structure. In the early stage of the 'Reform and Open-door' period, the regional infrastructures in the east region were relatively weak compared with those in other regions. Therefore, stronger land-use policies and regulations play an essential role in urban development. Driven by the policies, Shenzhen City soon became another super center of the PRD. Compared with other regions, there are more valuable green patches in the east region, which mainly occurred in the mountain edge and important ecological corridors of E-30, E-35 in figure 4.5. Mangroves were destroyed especially in the west coastline of Shenzhen city. Excessive water and congested sediment also impair the navigation of large ships in E-18, E-24 in figure 4.5.

The central region is dominated by the development of port. The marine industry is the primary production of the central region. The decrease of farmlands and the growing urban areas were followed by the establishment of regional infrastructures. Because of the constructions of Nansha port and Guangzhou Metro Line 4, a more connective traffic network was established which generates a stable backbone for the development of Nansha of C-1 shown in figure 4.5. There was a large amount of 'mesh' agricultural texture in the north and west and 'linear shaped' agricultural texture in the south. The scattered green pattern, wetlands constitute the characteristics of the blue-green structure in the central area (C-1 in figure 4.5). Because of port expansion and land reclamations on the south of Wanqingsha, Longxue sub-areas, the original blue-green structure have been gradually occupied (C-1, C-4 in figure 4.5). The silt-up area was moving outwards to the sea.

4.3.3 Projection of comprehensive risk areas caused by climate change

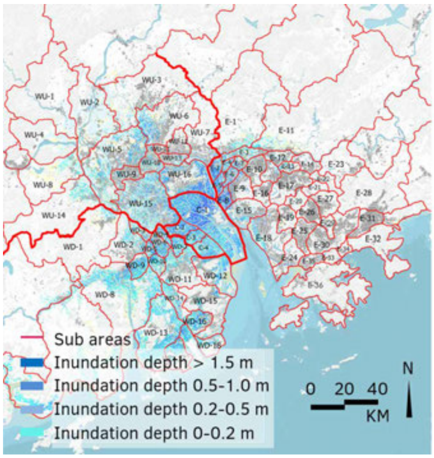
The analysis of spatial evolution of the PRD shows that rough land uses and the occupations of the water environment can cause the inner vulnerability for the spatial system. Future climate change can make the spatial system of the PRD more vulnerable especially in terms of flooding and land subsidence (Han et al., 2010). According to the monitoring records of more than 40 meteorological stations that are distributed throughout the PRD from 1954 to 2008, the average temperature of the PRD increased by 0.45°C with the rate of 0.08°C/ 10a in the past 55 years (Global Water Partnership China, 2016). The rate of the rise of temperature in the PRD is higher than the rate of global situation. Under the situation of rising temperature, three related climate change factors need to be mentioned for projection.

- An observation report conducted by the Oceanic Administration of Guangdong Province in 2007 showed that the sea level in the PRD has generally risen by 50-60 mm over the past 30 years, with an average rise rate of 2.5 mm/a (Tang et al., 2009). It can be seen that the rate of sea level rise in the PRD is consistent with the rate in the global situation. Based on this trend, the sea level of the PRD will rise respectively by 24-38mm, 72-114mm, and 192-304mm in 2030, 2050, and 2100.

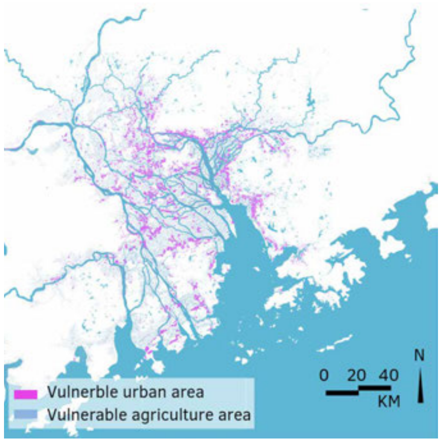
- From 1956 to 2008, the average fluvial discharge of the West River, the North River and the East River increased by 489 million m^3/10a, 443 million m^3/10a, and 200 million m^3 /10a (Global Water Partnership China, 2016). Adding those numbers to current river discharges, the average river discharges of the West, North and the East River are predicted to increase to 10248m³/s, 2332.06m³/s, and 1712m³/s in 2100.

— The formation of the PRD is driven by three groups of geographic faults, which form multiple land areas with different vertical land subsidence speeds. The average rate of land subsidence in the whole delta is around 2 mm/a. The Wanqingsha area and the East River area remain the fastest with a rate of 2.4 mm/a. There is also an area with a rate of 7 mm/a in Doumen, Zhuhai (Dong, 2012).

Figures 4.8 presents the simulations of the potential vulnerable areas of the PRD caused by the above-mentioned climate change factors. The above-mentioned climate change factors of fluvial discharge, rising sea levels, and land subsidence will cause some serious water-related issues which negatively impacts on the current spatial distribution. The results of projections illustrate that the influenced agricultural area will increase by 53.4%, while the influenced urban area will increase by 25.4%. According to locations, most of the inner coastline areas where land elevations are between 0.5-2.0m above the Pearl River Datum will be largely affected.



1 Inundation depth map of PRD



2 Vulnerable areas of PRD

FIG. 4.8 Potential vulnerable areas of the PRD

4.4 Research on the principles and strategies for resilient land use

4.4.1 General principles

Long-term spatial resilience of the PRD is closely related to the future land-use situation. Land use that conforms to natural conditions and adapts to hydro-ecological structure can possibly avoid being exposed to natural disasters such as serious flooding and land subsidence. From the perspective of resilience, the strategies for new possible land- use schemes should fully reflect the regional natural elements that need to be considered in priority. Because the PRD is located on the edge of the sea-land transition area, the land-use scheme needs to take more considerations for natural protection, and to increase the control of the prohibited construction areas and restricted construction areas. Based on the resilient spatial characteristic of regionality, new possible land-use scheme for the whole PRD should combine with the results of both natural protection area identification, and the assessments of agricultural and urban land-use suitability. The new possible land-use scheme can improve current land-use situation according to local land conditions. Land- use classification should be used. It is important to reasonably control the intensity of construction lands in coastal areas, and advocate a variety of mixed and compact land -use measurements.

4.4.2 Natural protection area identification and land-use suitability assessment

Natural protection area identification and land-use suitability assessment are the fundamental basis for creating possible future land- use schemes. As a basis, analysis for applicable urban and natural resources in each region can be seen in Appendix C-3.

Rational land-use schemes can contribute to reducing spatial vulnerability and increasing the balance between natural protection and urban development. According to the evaluation results, the land- use policies, controlling measures and models can be formulated which can also be helpful to deal with the problems of improving collaboration among sub-delta areas.

Natural protection area identification and land-use suitability assessment can be supported by ArcGIS software that overlaps multiple objective-related spatial indicators into a map and provide comprehensive land- use values. After converting raster data, checking geographic coordination, calculating buffer distances, and inputting calculative values of each indicator, a comprehensive weighted calculation of land-use suitability can be conducted. Figure 4.9 is the outcome of natural protection area identification. It is based on the database of 2015 digital elevation (DEM) and 2018 Navionics ChartViewer Digital Ocean Contour Map, 2018 blue-green digital map (grid resolution of 30m). Natural protection areas are overlapped with potential blue-green patterns that include large ecosystem, coastline tidal flats, large simulated natural water runoffs.

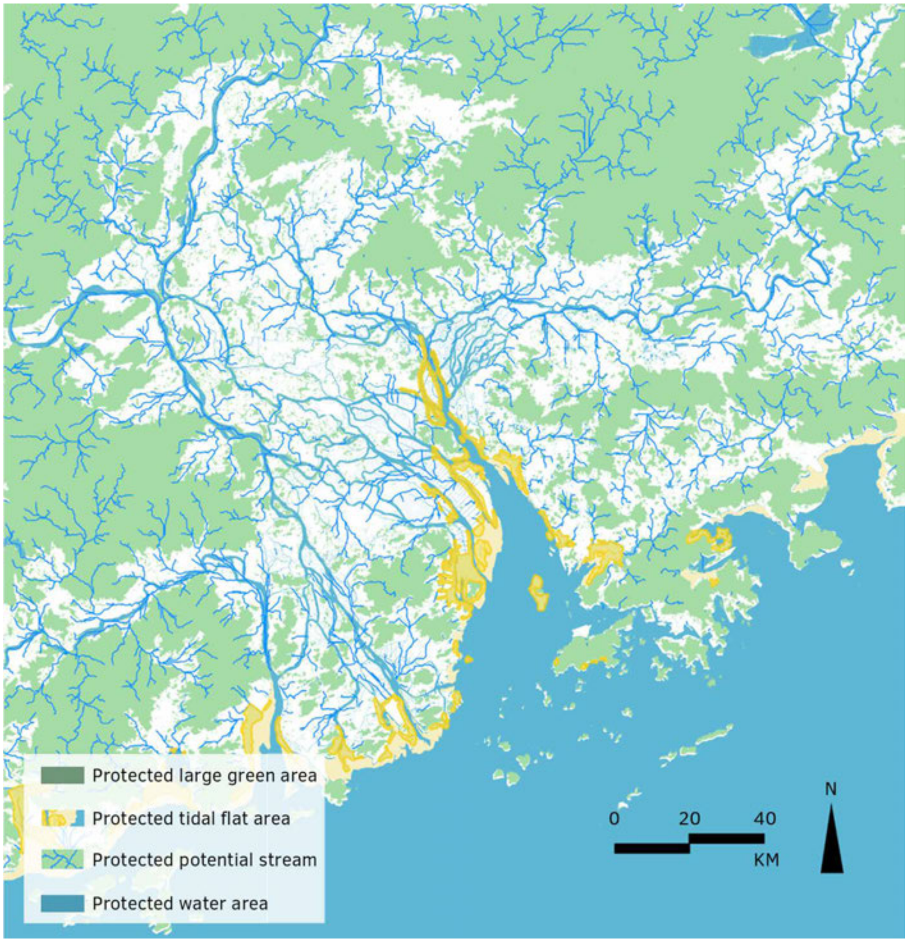


FIG. 4.9 Natural protection area identification

Figure 4.10 is the outcome of the assessment of land- use suitability for agriculture land use. It is based on the database of 2015 digital elevation (DEM) and 2018 Landsat 8.0 land use map (grid resolution of 30m). Seven indicators that are related with resilient agricultural land use are selected such as land elevation, slope, soil conditions, water resource, temperature, soil salinity, and potential comprehensive risk area. By giving weight of indicators proposed by local experts, a comprehensive evaluation of agriculture land- use suitability can be provided as clues for future agriculture land use. Table 4.1 shows the criteria and relative values of each indicator.

Figure 4.11 is the outcome of land-use suitability assessment for future urban land use. It is based on the database of 2015 digital elevation (DEM) and 2018 Landsat 8.0 land use map (grid resolution of 30m). The evaluation of land use suitability here selects eight indicators such as land elevation, slope, soil conditions, buffering area of blue-green network, buffering area of transportation network, natural resources, urban resources, and potential risk areas. By giving weights of each indicator proposed by local experts, a comprehensive evaluation of urban land-use suitability can be provided. Table 4.2 shows the criteria and relative values of each indicator.

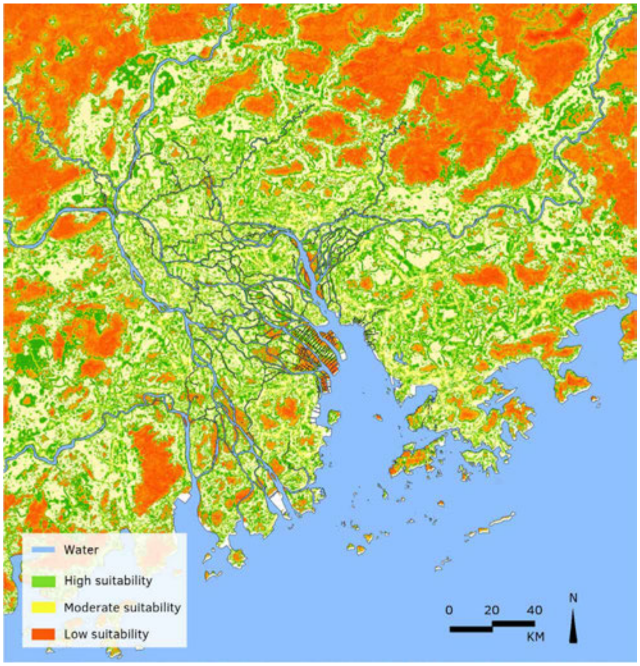


FIG. 4.10 Land-use suitability assessments for agriculture lands

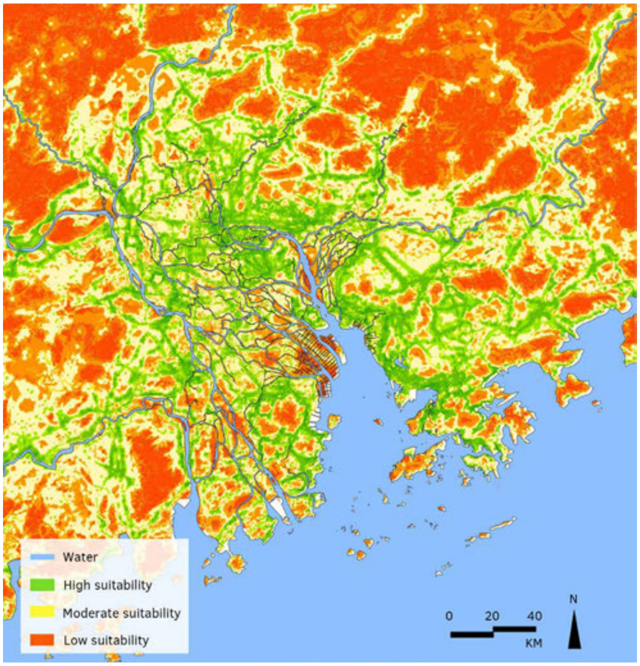


FIG. 4.11 Land-use suitability assessments for urban lands

TOC

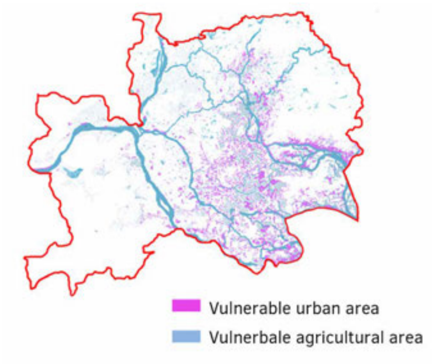
TABLE 4.1 The assessment indicators of the agricultural land-use suitability in the PRD

Indicator	Weight	High suitability	Moderate suitability	Low suitability
Elevation (Based on Pearl River Datum)	0.16	5-100m	2-5m,or 100-150m	Below 2m, or above 150m
Slope	0.10	Slope between 0-5 degree	Slope between 5-15 degree	Slope above 15 degree
Soil condition	0.14	Forest soil	Peat soil	Clay, salty clay
Water resource (Annual precipitation)	0.12	800-1000mm	400-800mm	Less than 400mm or More than 1000mm
Temperature	0.16	25-30°	20-25°	Lower than 20°or higher than 30°
Soil salinity	0.12	0.0-3.0	3.0-6.0	More than 6.0
Potential flooding and land subsidence risk area	0.20	Areas are not in potential comprehensive risk areas in figure 4.8	Areas in the potential comprehensive risk area of figure 4.8 with inundation depth 0-0.5m	Areas in the potential comprehensive risk areas of figure 4.8 with inundation depth 0.5-1.0m

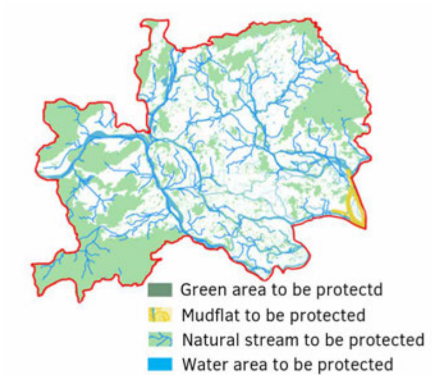
TABLE 4.2 The assessment indicators of the urban land-use suitability in the PRD

Indicator	Weight	High suitability	Moderate suitability	Low suitability
Elevation (Based on Pearl River Datum)	0.11	5-100m	2-5m,or 100-150m	Below 2m, or above 150m
Slope	0.08	Slope between 0-5 degree	Slope between 2-20 degree	Slope above 20 degree
Soil condition	0.10	Forest soil	Peat soil	Clay, salty clay
Blue-green network and buffering area	0.17	500-1000m	1000-2000m	0-500m (will be frequently flooded), above 2000m
Traffic network and buffering area	0.11	0-500m	500-2000m	Above 2000m
Natural resource	0.11	0-250m	500-2000m	Above 2000m
Urban resource	0.13	0-500m	500-2000m	Above 2000m
Potential flooding and land subsidence risk area	0.18	Areas are not in potential comprehensive risk areas in figure 4.8	Areas in the potential comprehensive risk area of figure 4.8 with inundation depth 0-0.5m	Areas in the potential comprehensive risk areas of figure 4.8 with inundation depth 0.5-1.0m

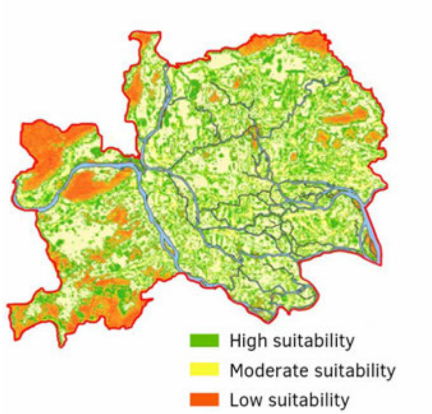
In order to further refine the assessment results in each sub-region, Figure 4.12 to Figure 4.15 show the land-use assessment results of each sub-region. Table 4.3 - Table 4.6 show the proportion lands that are suitable for agricultural and urban development in corresponding regions of the PRD.



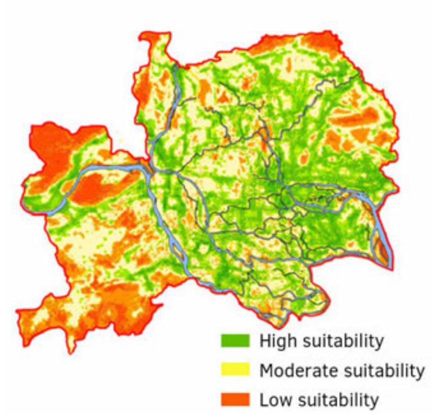
1 Vulnerable area



2 Natural protection area



3 Land use suitability for agriculture

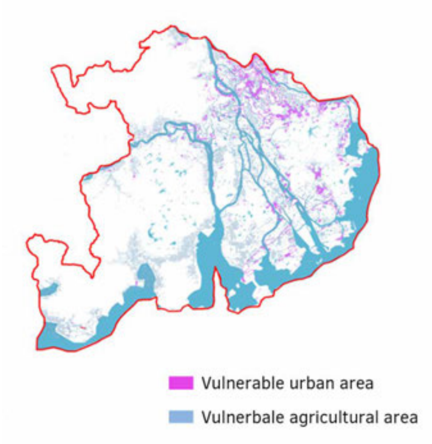


4 Land use suitability for urban

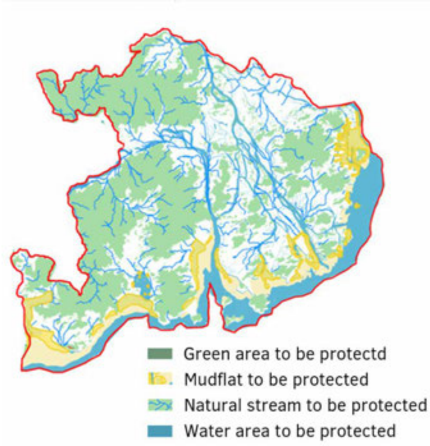
FIG. 4.12 Land-use assessments in the westside upstream region

TABLE 4.3 Proportion of land-use suitability in the westside upstream region

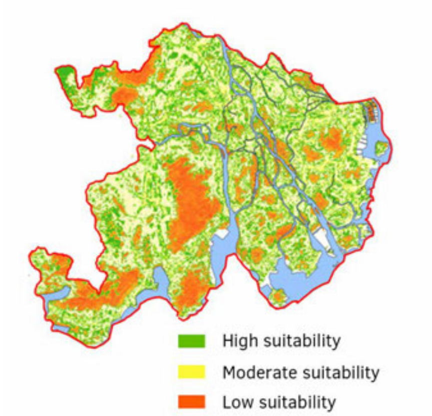
Item	High suitable	Moderate suitable	Low suitable
For agricultural land use	43.6%	32.6%	23.8%
For urban land use	31.9%	39.6%	28.5%



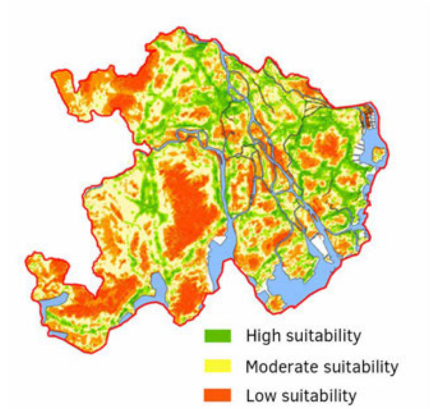
1 Vulnerable area



2 Natural protection area



3 Land use suitability for agriculture

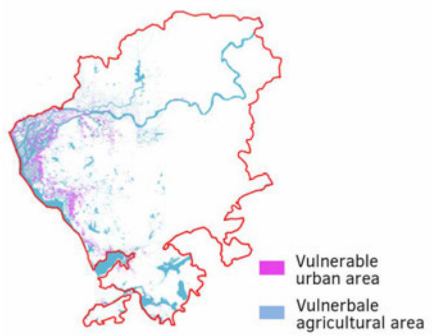


4 Land use suitability for urban

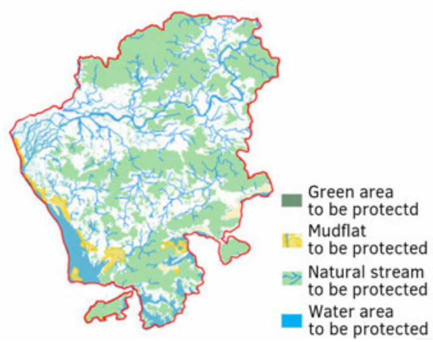
FIG. 4.13 Land- use assessments in the westside downstream region

TABLE 4.4 Proportion of land- use suitability in the westside downstream region

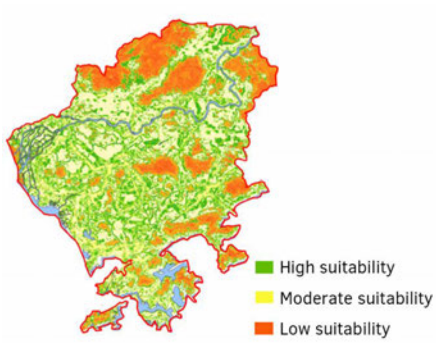
Item	High suitable	Moderate suitable	Low suitable
For agricultural land use	31.6%	29.6%	38.8%
For urban land use	27.9%	25.6%	46.5%



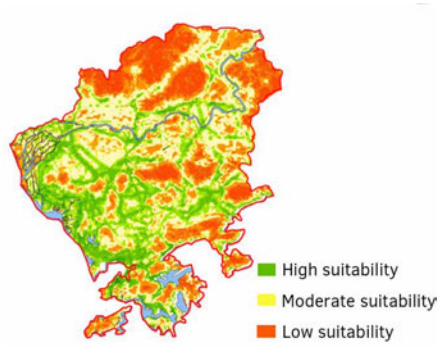
1 Vulnerable area



2 Natural protection area



3 Land use suitability for agriculture

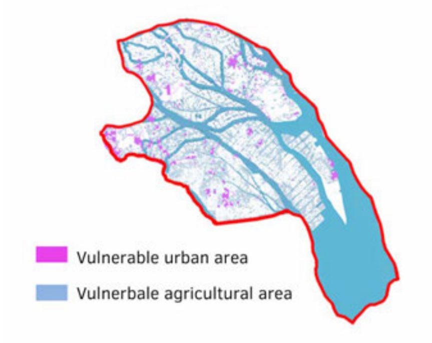


4 Land use suitability for urban

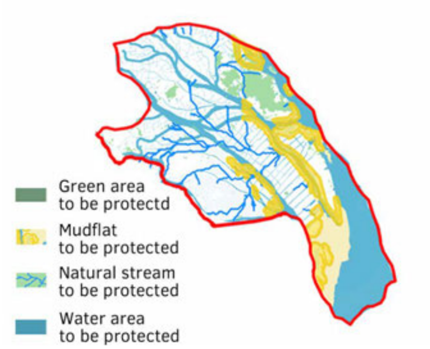
FIG. 4.14 Land- use assessments in the east region

TABLE 4.5 Proportion of land- use suitability in the east region

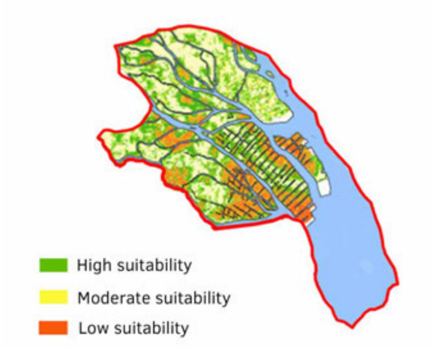
Item	High suitable	Moderate suitable	Low suitable
For agricultural land use	21.6%	29.2%	49.2%
For urban land use	33.4%	25.0%	41.6%



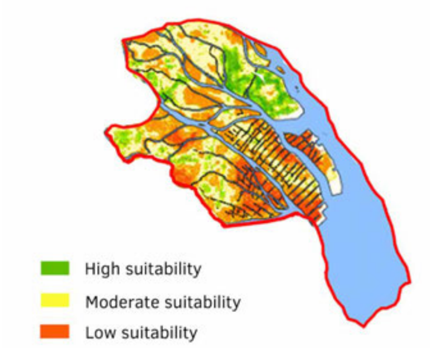
1 Vulnerable area



2 Natural protection area



3 Land use suitability for agriculture



4 Land use suitability for urban

FIG. 4.15 Land- use assessments in the central region

TABLE 4.6 Proportion of land-use suitability in the central region

Item	High suitable	Moderate suitable	Low suitable
For agricultural land use	51.6%	21.2%	27.2%
For urban land use	18.6%	23.5%	57.9%

In order to make the spatial system of the PRD more robust for future climate change and fast urbanization, the superposition of the results of above evaluations should be based on the following principles.

- When there are contradictions of different suitable land use in a certain area, the results of natural protection area identification should have priority to the future land use.

- When there are ambiguities in the division of agricultural and urban lands, comprehensive consideration should be given to regional characteristics, potential risk, soil and water conditions, and future functions of the area.

4.4.3 Possible land-use scheme for the whole PRD

Based on the results of above evaluation, the possible land- use scheme needs to actively exert the self-organized ability of the ecosystem and water system and restriction on excessive flow by monitoring and controlling important ecological-hydrological strategic points. According to the results of natural protection area identification and the assessment of land- use suitability, land- use classification should be utilized to determine strategies, policies and regulations, and the integration of all sub-regions should be promoted. Based on the above considerations, the overall protection and development pattern is shown in Figure 4.16 and the overall possible land- use scheme is shown in Figure 4.17.

On the whole, the spatial axis connection between the east coast and the west coast is formed based on the prototype of ‘point and axis’. Based on the current situation of Guangzhou city and Shenzhen city, the east wing focuses on the development of ports and green corridors. The west wing will take benefits from the wet plains developing into a blue necklace with water sensitive ecological agri-aquaculture and flood storage, complemented with strong urban hubs that benefit from transit-oriented development. It needs to rely on the development dividends brought by the axis of the Guangxi-Zhuhai Expressway in the west, the coastal expressway in the southwest, the Guanghui Expressway in the north, the Guangdong-Hong Kong-Macao Bridge in the south, the Guangdong-Shenzhen Coastal Expressway in the east, and the Pearl River Delta Expressway in the outer ring. It is important to rely on the road axis constructed in different periods and make Nansha District a new center with strong innovation and radiation capabilities, cohesion and expansion. Alongside Pearl River Estuary, it is important to strengthen natural resources’ supply and ecological compensation. Through increasing the density of road network and public service systems, the center-edge point aggregation and diffusion effects can be improved. Guangzhou city, Shenzhen city, Foshan city, Dongguan city, Zhongshan city and other cities should strictly control the newly added construction lands. Revitalization can be the main choice for spatial development in these cities.

Based on the results of the assessment of comprehensive flooding and land subsidence risk area, natural protection area identification and land-use suitability assessment, as well as the circle layout characteristic of the territory, the strategies of ‘three-circle spatial coordination’ and ‘four land-use categories’ are proposed in figure 4.17.

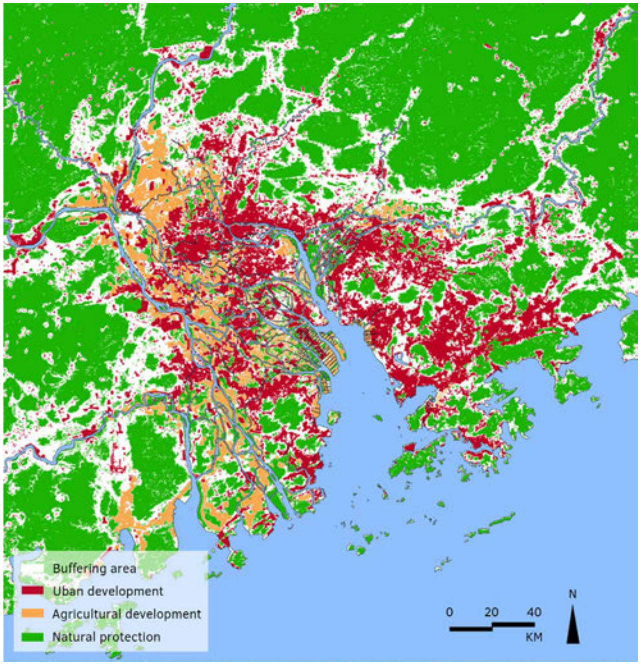


FIG. 4.16 Overall protection/development pattern

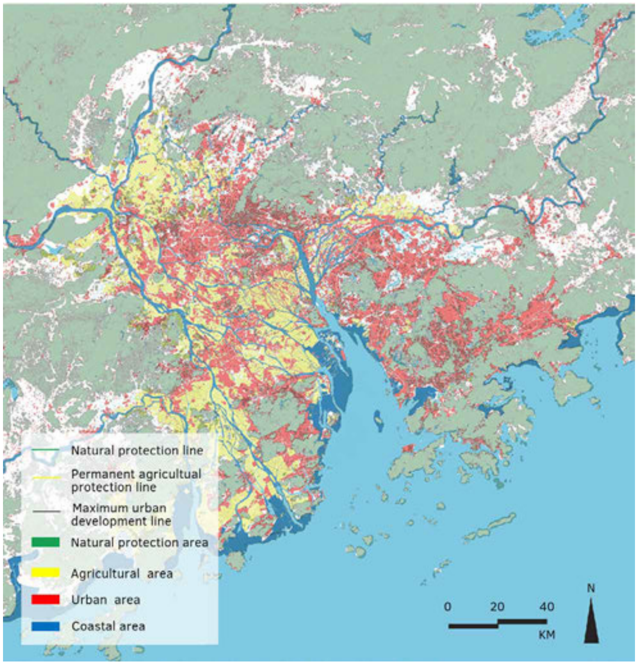


FIG. 4.17 Overall land use scheme

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A Three-circle spatial coordination

New land-use schemes needs to consider both natural and urban spatial resources. The development of the PRD is influenced by the difference of natural resources and has formed results in three-circle spatial differentiation characteristics. Therefore, a new land- use scheme is suggested with the consideration of three-circle spatial differences. The first circle is the coastal circle. It is necessary to make full use of the advantages of sustainable ports to construct the coastal protection belt. The biodiversity, coastal protection and brackish water interaction should be well considered. The second circle is metropolitan development circle, which is located between the coastal circle and the natural protection circle in the mountainous area. This circle provides the most mutual feedings between the urban development space and the blue-green space. Land-use regulation should focus on the construction and restoration of urban internal ecological corridors and opening green space. It is necessary to conform to the blue-green spatial texture and control the urban disorderly sprawl rate. The third circle is the natural protection circle of large and high valued reservoirs and mountainous regions, which are important for water storage and soil conservation.

The socio-economic and cultural resources in the PRD have resulted in the differentiation characteristics between urban and rural space. The 'Guangzhou-Foshan-Zhaoqing' metropolitan and the 'Shenzhen-Dongguan-Huizhou-HongKong' metropolitan have many large urban resources, well-developed infrastructures, and well-developed urban functions, but they lack land resources. These areas should consider the strategy of urban-rural renovation and avoid continuous actions of urban sprawl. Attention should be paid to the construction of hydro-ecological corridors inside the city, and the implementation of the restoration of small river corridors and the construction of green open space in the city. There are many current ecological-hydrological corridors in the 'Zhuhai-Zhongshan-Jiangmen' metropolitan, especially the West River and the North River which have many capillary corridors that can provide important regulation effects. Therefore, while increasing the service density of public facilities, it is necessary to focus on building blue-green structures with self-organization capabilities.

B Four categories of regional land use

The land-use scheme suggests to divide the land use of the whole PRD into four categories, with different land-use strategies based on the understanding of terrain condition, land characteristics, collaborative effects between sub-deltas and long-term protection and development process. These four categories are natural protection area, agricultural development area, urban development area and coastline area.

- **Natural protection area**

  The land-use scheme suggests that natural protection areas should be concentrated along the West River and the North River, coastline, estuaries, as well as the outer circle mountain. Several measurements need to be taken for long-term natural bottom-line operation. It is necessary to take natural geographic boundaries as research units, take large blue-green patches as the core elements and formulate corresponding construction regulation according to environmental capacity, resource carrying capacity. It is important not only to restore the natural shape of the river and green space, but also to solve the problem of disordered texture caused by urban squeezing. Natural protection areas should play their roles in ecological conservation, biological maintenance, and hydrological regulation. It is wise to pay attention to nature-based solution and advocate the conversion from dyke engineering to work with nature. It is necessary to strengthen the protection of coastal landscapes, take into account the diversion ratio of natural coastlines and artificial coastlines by controlling the length of the building that can occupy the coastline. It is important to strengthen protection measures for the eco-environmental area near the coastline and to make compensations for excessive reclamations in order to increase the capacity of the tidal storage by estuaries.
  As an inside natural protection area, the Pearl River Estuary is the first barrier to be protected. The land-use scheme suggests focusing on the sea-land transition environment, protecting the existing wetlands, building a coastline protection belt and promoting the biodiversity of the bay area.

- **Agricultural development area**

  The land-use scheme suggests that agricultural development area should be distributed in between natural protection area and urban development area, which can not only function as a buffering area for further utilization, but also provide traditional cultural landscape of ‘Mulberry-fish pond’. From the evaluation results of agricultural land-use suitability, Foshan city, Dongguan city, Zhongshan city, Nansha are suitable for agricultural development. According to land-use suitability assessment, different kinds of crops should be cultivated in order to ensure food provision service for the PRD.

  Specifically, the suitable agricultural areas in the westside upstream region are dominated by the current inter-city wasteland. The soil and water condition are suitable for Foshan city, Shunde and other places to strengthen the development of fish pond agriculture and advocate for a ‘fish-mulberry’ circular agricultural economy near the fringe agricultural land of Guangzhou and Foshan towns. It is important to improve farmland infrastructure conditions and raise farmland standards. The suitable agricultural land in the westside downstream region dominates in large areas of undeveloped fishpond, which can be used as the core lands for cultivating and fishing. It is important to strengthen the protection of fish ponds along Doumen, Xinhui, Qijiang and Zhongshan city areas, and form a modern standard agricultural concentration area with concentrated splicing, completed- infrastructure and valuable travelling place. The suitable agriculture land in the east region is mainly located along the East River. It is necessary to ensure that the farmlands in the basic protection areas should not be decreased for promoting the cultivation of waste lands. The suitable agriculture lands in the central region are located in Nansha, Wangqingsha. Some low-lying areas should be reserved as useful supplements to agricultural land and urban landscape in the future.

— **Urban development area**

The land-use scheme suggests that urban development areas can be concentrated in high-valued lands along the existing large cities like Guangzhou city, Shenzhen city, Zhuhai City. It is important to properly increase the density of traffic network and provide as many types of public facilities as possible, and rely on the advantages of public services, infrastructure and facilities to increase the proportion of the commercial finance, trade fairs and corresponding business. It is necessary to coordinate urban development area with the natural protection area, to scientifically insert parks, lakes to the existing urban lands in order to create attractive landscape for future residence. Based on factors such as topographical conditions and environmental capacity, it is necessary to change the development model from 'extensive' to 'intensive'. For port areas, the south side of offshore areas should focus on coordinating the construction of ports and reclamations of islands. The outline of port, as well as its related logistics layout, should be coordinated with the dynamics of sedimentation and erosion of the sea.

The suitable urban lands in the westside upstream region rely on the existing cities of Guangzhou, Foshan city and Zhaoqing city and combine with the existing road network. The suitable urban lands in the westside downstream region are centered on Wugui Mountain, along Zhongshan—Xiaolan—Shunde axis and along the Zhuhai coastline on the eastern side of Wugui Mountain. The suitable urban lands in the east region are dominated by the corridors along the main rivers in Dongguan city and Shenzhen city, as well as on both sides of Yangtai Mountain and Yinping Mountain. In the future, new construction lands should be strictly controlled due to limited land resources. The suitable urban land in the central region is mainly concentrated in the North of Nansha. Relying on the port and navigation of the Pearl River Estuary, it is important to coordinate the development of port, industry and city. The urban structure in the future is suggested to transform from scattered to networked, which can create a modern service industry basement and an advanced manufacturing basement with inland backing.

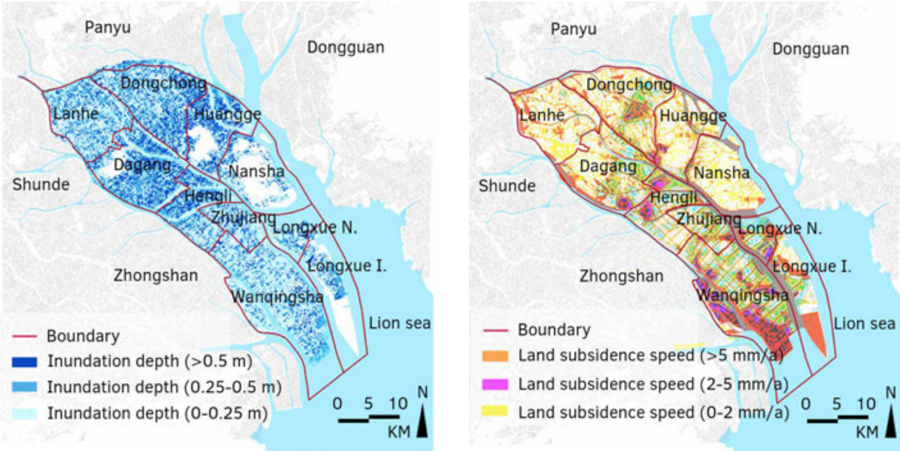
TOC

- **Coastline area**
  The land-use scheme suggests that coastline area should be mainly distributed at the estuaries and coastline areas in cities, which are important spaces for fluvial-tidal interactions in the PRD. Because of its specific condition, several measurements need to be taken for long-term operation. It is important to address the relationship between construction, industrial development, and natural protection and pay attention to the repair and maintenance of offshore mangroves. It is important to protect marine islands and improve marine resources, reasonably control the proportion of various types of shorelines and scientifically allocate the use of productive, living and ecological water. According to the differences of water depth, deeper water can be used for production-oriented shoreline function, while the shallower water can be used for life and hydro-ecological shoreline functions.

4.4.4 Possible land-use scheme in local context — Nansha as an example

Combining above research results, Nansha is selected as the key research case at the lower scale. Nansha is located at the junction of three metropolitan circles of the PRD, and is the geographical center of the PRD (Planning bureau of Guangzhou city, 2013). In Nansha, the North River and the Pearl River flow into Lion Ocean and Lingding Ocean through Hu, Jiao, Heng and Hongqi estuaries. Detailed land-use situations of Nansha District are shown in Appendix C-4 (Bureau of statistics of Guangzhou city, 2018).

Addressing 200-year floods and 0.50m sea level rise in the future, the projection of future flooded areas and land subsidence areas in Nansha is shown in Figure 4.18, and the distribution of vulnerable areas formed by the results of the assessment of vulnerability degree that is over-layered by inundation depth and land subsidence speed, is shown in Figure 4.19.



1 Inundation depth map in Nansha

2 Land subsidence map in Nansha

FIG. 4.18 Flooding and land subsidence areas in Nansha

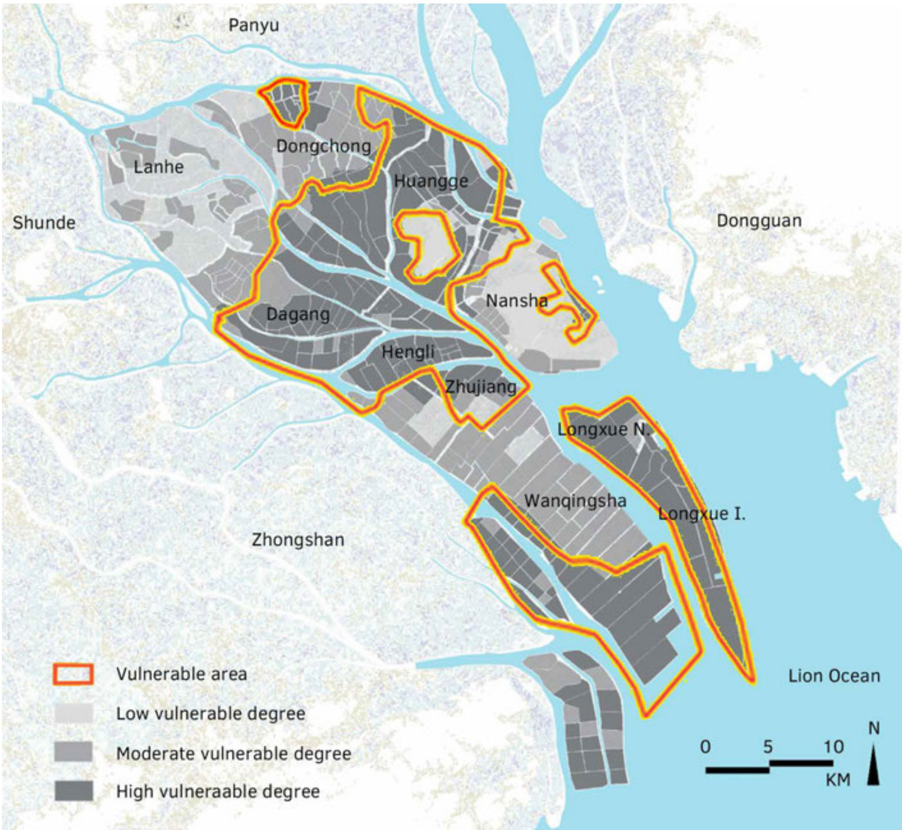


FIG. 4.19 Vulnerable area in Nansha

A Identifying the natural protection area and appropriate population that can be accommodated

Nansha is surrounded by water on four sides, which is the lowest area in the PRD. Climate change has brought great challenges to the future urbanization of Nansha. Based on the projection of flood inundation depth and land subsidence, it can be found that the most seriously affected areas of flooding and land subsidence risk are Dagang, Hengli Island, Wanqingsha and Longxue North. Under extreme climate change condition, the tides would pass over the existing dyke.

A resilient rational land-use scheme needs to concern two aspects. The first is to identify natural protection areas. Natural protection area refers to the lands that need to be protected in order to improve long-term hydro-ecological effects. Figure 4.20 shows the assessment results of the identification of natural protection areas. It can be seen from the Figure 4.20 that large waterways, Huangshan Lu Mountain, Eighteen Arhats Mountain and large areas of tidal flats near Jiao Estuary belong to natural protection areas. At the same time, considering the inundation depth of flooding and the speed of land subsidence, some lands in Wanqingsha, Longxue, Dagang, Hengli Island and other places can be converted partly into natural space to buffer the negative impact of extreme climate change. Any constructive activities in the natural protection area are prohibited.

The second is to determine the maximum population that can be accommodated in the future. Nansha began the rapid urbanization construction in 1993. With rapid urbanization the population greatly increased. Based on that, the attributes of natural protection areas cannot be converted into other types of land use. The land-use situation is simulated by using the FLUS, Markov - CA chain and ArcGIS software under different population figures of Nansha in order to find out 'tipping points' of land use, and subsequently to determine the maximum amount of population.

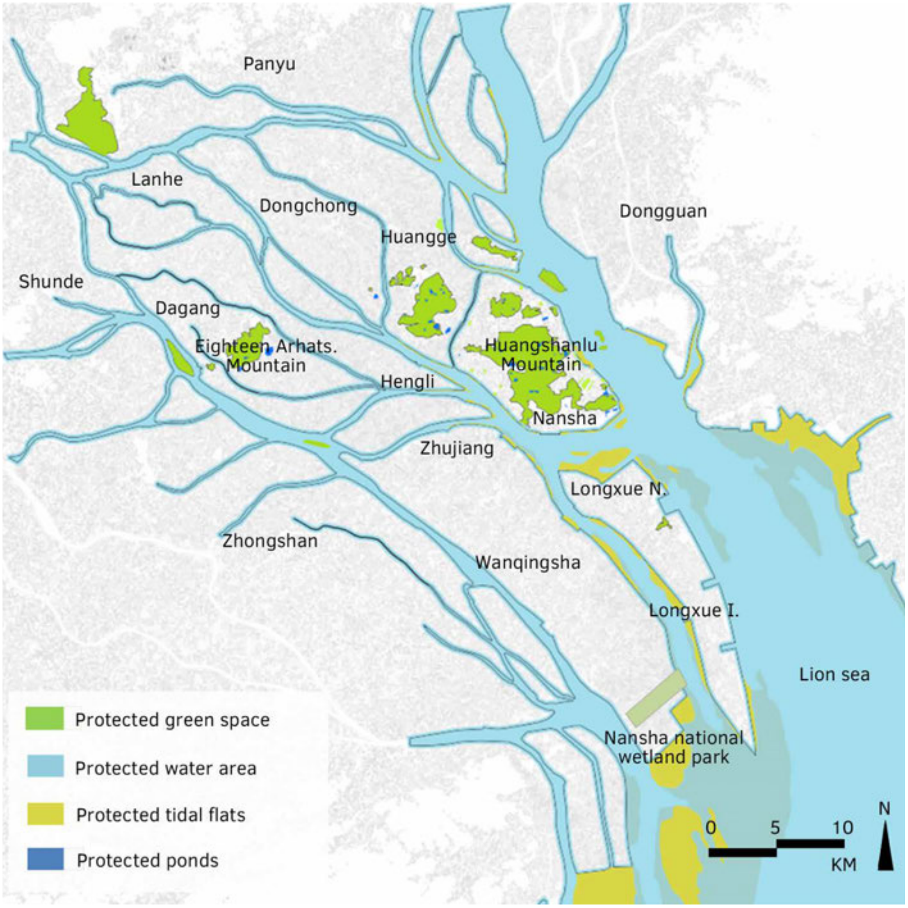


FIG. 4.20 The identification of natural protection area in Nansha

Based on current population number of Nansha and pre-setting a strict natural protection area in figure 4.20, land-use scenarios under different population numbers from 0.8 million to 3.8 million are simulated in order to form a possible future land-use evolution pathway. Figure 4.21 represents 6 major land-use scenarios. The current vulnerable areas can be explored as urban construction lands if the land carrying capacity of these areas can be greatly improved by strengthening flood control and drainage measures in advance.

The outcome of simulated land use shows that the sub areas of Nansha, Hengli, Dagang, Huangge, Dongchong, Lanhe, Zhujiang will be further developed, one after another when population increases. Wanqingsha and Longxue will be the last sub areas to be developed.

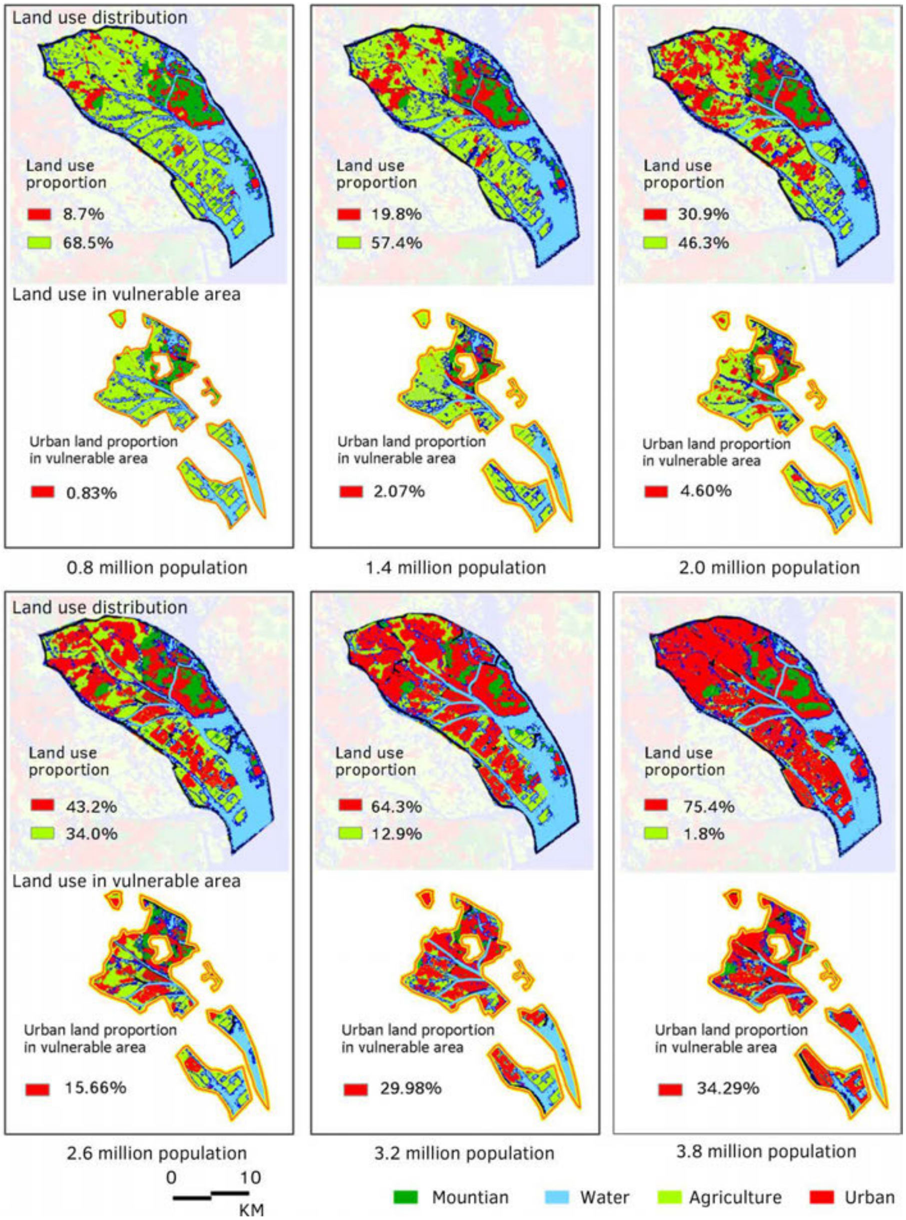


FIG. 4.21 Land use distribution when population increase

The size of urban areas will account for 0.83% in vulnerable areas when the population reaches 1.4 million. Urban areas will mostly expand in Dagang, Lanhe sub areas that located in the north part of Nansha. At that time, there are still sufficient lands for urban development. When the population reaches 2.0 million, the first 'tipping point' occurs. The size of urban areas will account for 4.60% in vulnerable areas. The north and the west part of Nansha will be largely occupied so that urban areas will expend into current vulnerable areas in a fast speed. When the population reaches 2.6 million, the size of urban areas will account for 15.66% in vulnerable areas and the current available lands for further construction mainly remains in Wanqingsha sub area.

When the population reaches 3.2 million, the second 'tipping point' occurs. The size of urban areas will occupy 29.9% in vulnerable areas, which leads to higher requirements for flood control and drainage systems on Hengli Island, Zhujiang, Huangge sub areas. Under this circumstance, waterfronts of main waterways will be largely squeezed. When the population reaches 3.8 million, the size of urban areas will occupy 34.3% in vulnerable areas, in which the remaining lands excluded strict natural protection areas of Nansha. Under this circumstance, urban areas will only expand at the expense of occupying prohibited natural protection areas or reclaiming sea areas.

Based on above simulations, it is possible that 2.0-2.6 million can be an appropriate population number for Nansha for long-term development. Land use for supporting 2.0-2.6 million is beneficial to provide buffering areas between different urban groups. The pressure for flood control and drainage system will be moderate. The theoretical maximum population number can be 3.8 million. If the population number exceeds 3.8 million, the natural bottom line will be broken and turn the whole Nansha into a vulnerable system.

B Suggestions for future land use

Nansha has relatively flat landform, convenient traffic and sufficient nature resources. The main reason that causes massive vulnerable lands is its low elevation condition and insufficient connection of water network. In the future, if Nansha needs to be constructed in its current vulnerable areas, it is necessary to first take measures to improve flood control and drainage for fundamentally addressing the hidden flooding and land subsidence dangers. This is also the main reason why the next chapter takes flood control and drainage as an important task for improving the spatial resilience on Hengli Island.

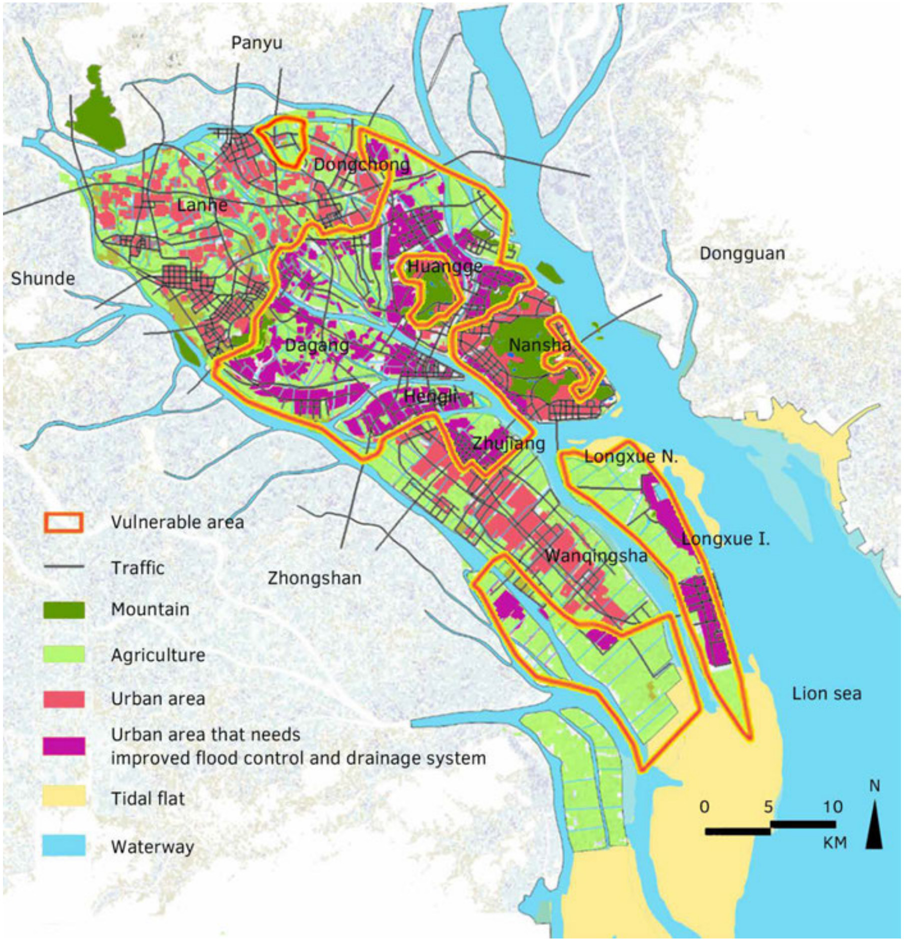


FIG. 4.22 Land-use scheme for 2.3 million populations

Based on above analysis, Figure 4.22 shows a possible resilient land-use scheme for accommodating 2.3 million populations.

The land-use scheme takes natural protection areas as 'an impenetrable bottom line'. Strict land protection is implemented. Dangerous buildings in natural protection areas should be removed and converted to natural areas. For instance, in Dahu Island, Longxue Island, Dangang, Wanqingsha, some old factories with large hydro-ecological damage and low socio-economic value can be transformed into cultural landscape in natural protection area. Natural protection areas can provide multiple functions such as leisure, tourism and cultural education service functions to increase the sense of belonging of citizens to the delta landscape.

Future urban area can be divided into two categories. One is the area with suitable geographic conditions, natural conditions and high altitude. Priority development is recommended for such areas to meet the needs of a growing population. The other is those vulnerable areas that the traffic, geology, resources and other conditions are suitable for urban development, but altitude is low and the current flood and drainage capacity is weak. For example, Hengli Island, Zhujiang and Huangge can be included in these areas. For these areas, it is necessary to fundamentally address the issue of flood control and drainage, and to improve the suitability of lands before urban construction can be carried out in these areas. In the future, efficient, compact and multifunctional land-use model should be adopted to set aside enough buffer space between urban groups and provide land conditions.

The land-use scheme integrates the spatial texture between the natural protection areas and the urban development areas. The boundary between urban space and natural space should be more organic. For example, in the north of Nansha, the urban areas will be more 'dispersed' according to the high hydro-ecological value and the distribution of point-like water storage. In the south of Nansha, the urban areas will form a more compact spatial texture due to the high elevation of the land. At the same time, more buffer space should be set aside around the coastline to prevent tidal effects.

4.5 Research on the principles and strategies for regional blue-green network

4.5.1 General Principles

The regional blue-green network is the framework for the spatial organization of the PRD. It runs through the relationship between parts and the whole region. From the perspective of resilience, the blue-green network strategies should fully reflect the principle of network connectivity. In response to the challenges of degradation of rivers, branches, waterways, tributaries and congestion at estuaries, it is necessary to integrate regional natural resources and focus on creating cross-regional ecological corridors and water corridors. It is possible to reconnect crucial cross-regional rivers and tributaries by adding new passing water channels in the upstream location close to important cities, to improve the spatial resilience of the PRD.

4.5.2 Integrate regional natural resources

The PRD has dense river networks and abundant water resources. It is necessary to coordinate regional natural resources and strength the corridors from the whole region's perspective. The PRD and the neighborhood places in the adjacent provinces should be regarded as an integrated system and strengthen the blue-green corridors that can cross from the north to the south and from the east to the west, to form a spatial safety natural base layer.

It is necessary to collaborate efforts to promote the protection of water resources and water pollution control across provinces such as the East River, the Han River and the North River. The Nanling Nature Reserve, the West River upstream, the East River upstream, the Han River upstream and offshore natural reserves should be further strengthened and coordinated with surrounding cities, focusing on the co-construction of nature reserves and ecological function areas to jointly govern areas with prominent ecological and environmental problems. A coordinated belt of cross-provincial ecological and hydrological co-construction area has to be built to improve social and economic development.

It is important to coordinate the development of water resources in the West River basin to promote shipping and build a golden waterway. It is necessary to strengthen the joint protection of water sources of reservoirs at all levels. It is also necessary to strengthen the protections of natural forest and grass resources, wetlands and important ecosystems and cross-provincial ecological protection and restoration.

4.5.3 Establish cross-regional ecological barrier of the PRD

Natural base layer should be respected by breaking through the administrative boundaries that cause unfairness and competition among regions to ensure the coordinative function of the whole ecosystem and create sufficient 'flow space' for smooth crisscross landscape flows. Coordination should be taken across boundaries, especially in 'social-economic-ecological' space occupied by multiple elements. It is necessary to actively exert the self-organized ability of the ecosystem and prevent the excessive flowing by monitoring important ecological-hydrological strategic points.

The PRD has sufficient natural resources that can be connected to shape a healthy water system and ecosystem. Relying on the mountainous terrain, the outer ecological corridors can utilize large natural reserves such as mountains, reservoirs, forest parks and wetlands to strengthen natural purification and natural regulation functions.

An urban ecological corridor needs to be prepared from both construction and remediation. It is important to strengthen the construction of existing ecological corridors, the restoration of river corridors and green open spaces by reducing the reclamation and landfill of mountains and water bodies. It has to reasonably control the number of hard paving and gray infrastructure, and reduce the impact of hard pavement on ecological land by reasonably adjusting the elevation, land conversion and vegetation allocation. It is important to improve the vertical and horizontal processes in the 'natural-agricultural-urban' environment. If necessary, artificial beaches and silt-up areas can be carried out together with the shaping process from the marine environment. It is necessary to strengthen the protection of coastal landscapes and take into account the ratio of natural coastlines and artificial coastlines.

Based on assessment of natural protection areas shown in Figure 4.9, a possible ecological barrier map is shown in Figure 4.23. The outer circle is suggested to be dominated by various ecological functional corridors, and important natural reserves are set up to consider the advantages of natural reserves, forest parks, natural heritage, and wetlands. These spaces can provide functions such as biodiversity protections and soil-water conservation. Based on the assessment of high-valued nature resources, it is possible to construct ecological corridors in Yunwu Mount- Tianwu Mount Connection, Qiwei Mount-Loubei Mount Connection, Qingyun Mount and Jiulian Mount in order to radiate the advantages of large natural resources in the outer circle to the core area of the PRD. On the south side of the PRD, disordered reclamations have to be restricted. From west to east, circle-layout protection pattern can be consisted of Maofeng Mount, Tianwu Mount, Gudou Mount, Huangyang—Helan Mount, Daluo—Feilai Mount, Maofeng—Baiyun Mount, Fenghuang—Yangtai Mount. It is important to construct HongKong Maipu wetland, Shenzhen city Back Bay, Dongguan Jiaoyi Bay, Zhongshan Qi'ao Island, Zhuhai Hengqing Island and other places as the southern marine ecological protection corridor, and use marine power to carry out artificial beach breeding.

The westside upstream region needs to protect the mountains on the west, north, and east sides, and connects the scattered parks within the city through urban greenways. The upstream tributaries of the Pearl River need to be strictly protected. It is necessary to improve the hydrological bifurcation point of Sixianjiao, and increase the joint remediation of Lubao River and Baini River at the junction of the Pearl River and the North River. It also needs to protect natural runoff on both sides of large mountains such as Tianlu Mount and Maofeng Mount, and improve the allocation of water resources of the North, West and East River. It is necessary to protect the large tidal flats on the side of Hu estuary as a buffer place to reduce the tidal impact on Guangzhou City.

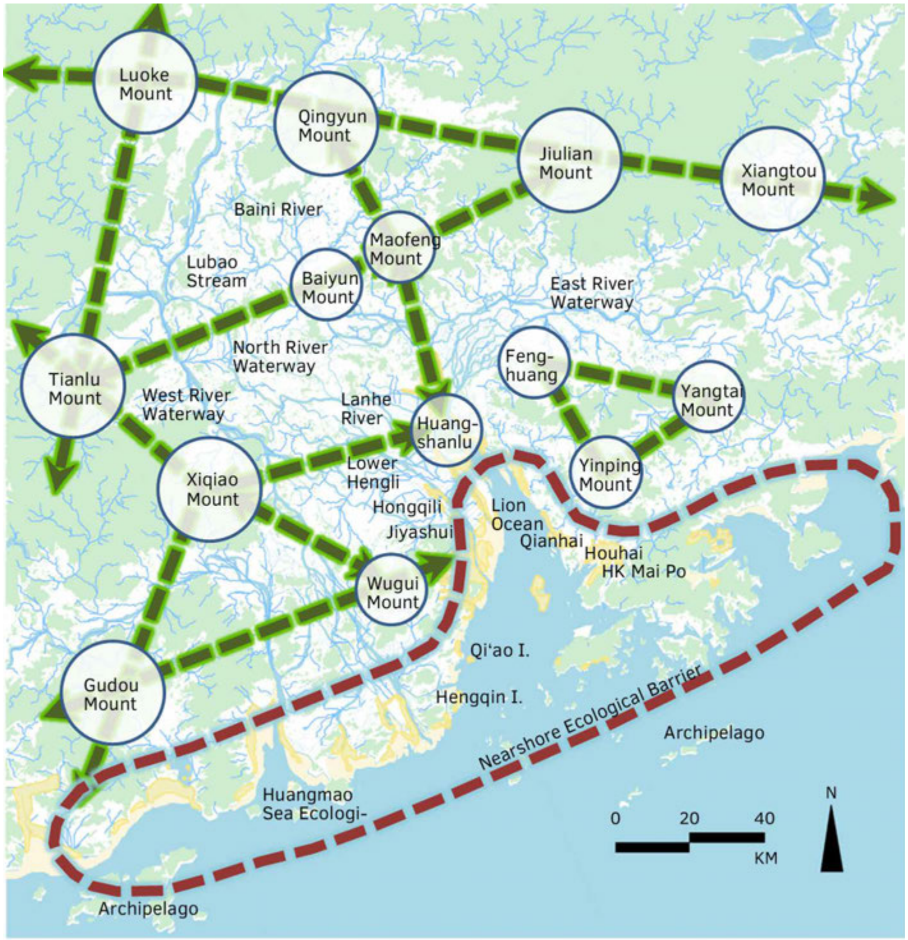


FIG. 4.23 Possible ecological barrier

The westside downstream region should protect Gudou Mount, Xiqiao Mount, Tianlu Mount and Wugui Mount. The large natural runoff from Wugui Mount and Xiqiao Mount to the West River should be connected. It is important to strengthen the protection measures of coastal ecological environment areas and repair the Modao estuary in order to increase the bay capacity and tidal volume. The protection of Huangmao sea ecological reserve should be strengthened to ease the trend of further narrowing the entrance. The islands scattered around the lower reaches of the West Bank should be protected. It is necessary to focus on the construction of ecological systems such as islands, marine reserves, coastal wetlands, mangroves, and coral reefs. If necessary, artificial beach cultivation could be carried out.

The east region should protect Qingyun Mount and Lianhua Mount, forest park, wetlands and other large nature reserves, which can be used as bases for ecological corridors. The coastal beach on the west side of Shenzhen city, especially the mangroves around Qianhai and Houhai should be protected and the polymerization effect of similar land use utilized by combining diversified aquatic ecological land-use patterns. Plaques with different scales and different types of habitats can be inserted appropriately.

The central region is suggested to increase the natural protection of Nansha Shuangshanlu Mount and Eightenn Arhat Forest Park. By protecting large-scale natural runoff, the connection between Lanhe waterway, Shanghengli waterway, Hongqili waterway and Jiao waterways can be strengthened. Valuable tidal flats need to be protected alongside Jiao estuary, Hongqi estuary and Heng estuary to reduce the negative impact from sea level rise to Nansha Island. The water networks should be increased in Hengli Island, Shunde and other sites to improve the connectivity of the current water network.

4.5.4 Improve cross-regional water network of the PRD

Improving cross-regional water network is an important foundation for improving spatial resilience of the PRD. Figure 4.24 shows the spatial distribution map of current water networks of the PRD.

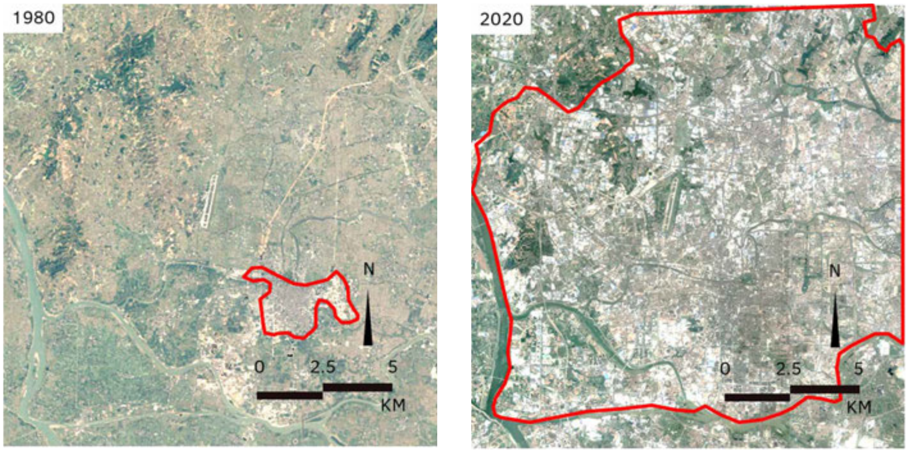
It can be found in the figure that the PRD has well-developed water networks and river channels. However, the estuaries of some river sections have become smaller due to sea reclamations, which have severely affected the discharge of upstream water systems during extreme precipitation and caused great pressure on flood control and drainage in surrounding important cities. It is believed that current water network of the PRD needs to be improved, based on the analysis of spatial evolution, topography, runoffs and estuary environment.

FIG. 4.24 Current spatial distribution of water system and its improved scheme

A Three rivers with problems

1 Location 1—The North River (branches) in the westside upstream region

The North River in the westside upstream region and its tributaries have an important influence on the formation of Guangzhou—Foshan—Zhaoqing metropolitan area, and the formation of Guangzhou—Foshan agricultural areas and their related irrigation system.



1 Urban areas in 1980

2 Urban areas in 2020

FIG. 4.25 Spatial evolution in the North River in the westside upstream and surrounding urban areas (inside redline areas are urban areas) (Source: Author revised based on google map)

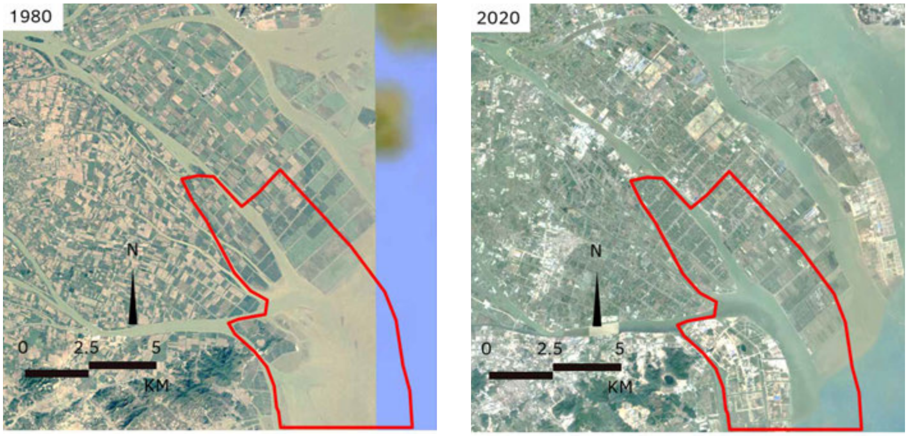
Figure 4.25 shows the spatial evolution of the North River in the westside upstream and surrounding urban areas from 1980 to 2018. The core urban areas have expanded more than ten times with dramatically increasing population, which leads to a deteriorated spatial relationship between urban areas and water. On the one hand, in the past 40 years, the phenomenon of sand mining in the upstream of the North River has resulted in an imbalance runoff and sedimentation diversion ratio between the upstream of the North River and the upstream of the West River. The diversion ratio change of the West River and the North River from 7:3 in 1980 to 6:4 in 2018 make the average water flow in the upstream of the North River increase by nearly 40% in 2018, compared to that of 1980. The situation is serious in the North River and the Pearl River because dykes alongside rivers restrict fluctuating water flow, which impair water dynamic. On the other hand, the formation of the 'Guangzhou—Foshan—Zhaoqing' metropolitan has led to a large number of surface runoffs in this area being blocked and channelized, which results in a significant

TOC

increase in the amount of water passing in the upstream of the North River. The potential flooding spots in urban areas alongside the North River, especially Foshan city and Guangzhou city waterfront, Shawan waterway and Lanhe waterway in Nansha have increased significantly. Therefore, there is an urgent need to reduce the amount of passing water and sedimentation in both the upstream of the North River and its tributaries to reduce the pressure of flooding in surrounding important urban areas.

2 **Location 2—The West River in the westside downstream region**

The West River is the river that has the largest amount of passing water and sand volume in the PRD. The main entrance from the West River to the sea is through Modao estuary. Over the past 50 years, disordered reclamations have led to a sharp reduction of the size of Modao estuary, which caused heavy water congestion (Figure 4.26).



1 Urban areas in 1980

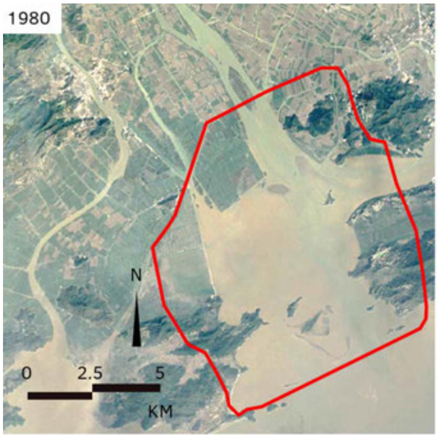
2 Urban areas in 2020

FIG. 4.26 Spatial evolution of Modao estuary (inside redline area is Modao estuary)
(Source: Author revised based on google map)

Situations of water backtracking and tidal intrusion have occurred normally, which leads to the fluvial flooding of the West River that can pose potential threats to the development of the surrounding Jiangmen city. Under the extreme climate conditions, huge fluvial flooding seriously impacts on the waterfront of Jiangmen City and further increases the pressure of flood control. Therefore, it is necessary to add a new passing water corridor between the downstream of the West River and the Tan River to relieve the flooding pressure of both the downstream of the West River and its tributaries, to ensure the flood safety of nearby Jiangmen city.

3 **Location 3—Waterways in Nansha**

Parts of branches (tributaries) of the West River and the North River converge in Nansha and form the Shawan waterway, Hongqili waterway and Jiaomen waterway. In the past 20 years, due to the erosion and sedimentation of Hongqi estuary, the development of Nansha Port and the reclamation of Wanqingsha sub-area, Hongqi estuary, Heng estuary have been seriously silted, which have affected navigation and flood storage capacity (Figure 4.27).



1 Urban areas in 1980

2 Urban areas in 2020

FIG. 4.27 Spatial evolution of Hongqi estuary (inside redline area is Hongqi estuary)
(Source: Author revised based on google map)

The water storage volume of Hongqi waterway in 2018 decreased by 23.46% compared with that in 1980, which resulted in unsmooth water passing and continuous flooding. Therefore, it is necessary to add another water passing corridor to divert excessive water from Hongqili waterway to Lanhe waterway in order to reduce the flooding pressure of Hongqi estuary.

B Improved scheme for water network

For addressing the above problems of river location 1 to river location 3, it is necessary to discover important hydrological strategic points and reconnect important rivers (branches) by adding new passing water corridors in the upstream location of important nearby cities, which will play an important role in improving the spatial resilient PRD. By the interconnection of water networks, the allocation of water resources of the West, North, East River and the Tan River can be improved to keep the diversion ratio within a reasonable range to ensure the flooding safety to surrounding important cities. It is very important to add passing water corridors as excessive water retentive buffering lands, based on current forest land, lakes, wetland, and tidal flats on both sides of the river banks.

Based on above principles, the improvement scheme of new possible water networks is proposed in Figure 4.24, in which the new passing water corridors is shown in the red dotted lines of AB, CD, EF.

1 Regional analysis shows that Point A and point B are both important hydrological points of the westside upstream region. The current status of the connection between point A and Point B is insufficient and cannot keep the runoff and sedimentation diversion ratio between the North River and the Pearl River within a reasonable range. According to the results of spatial evolution in the above sections, main parts of Foshan City around line AB are under the pressure of fluvial flooding both from the upstream of the North River and the Pearl River. For long-term development, it is necessary to add a new water corridor to connect line AB. It is suggested that based on terrain condition, when the flooding control pressure in the Pearl River and Guangzhou City poses a serious threat to safety of downstream cities, the sluice at point B can be opened so that the water can flow from point B to point A, and reduce the potential flooded area of Guangzhou city waterfront. When the flooding control pressure in the upstream of the North River, Foshan city and Shanshui City poses a serious threat to the safety of downstream cities, the sluice at point A can be opened so that the water can flow from point A to point B and reduce the potential flooded area of the upstream of the North River, Foshan city and Shanshui city.

2 Regional analysis shows that Point C and Point D are both important hydrological points of the westside downstream region, which can effectively provide as basic points for connecting the downstream of the West River. It is important to connect line CD. Combined with the existing Nanhua conservancy project, a sluice can be established at point C. When the flooding control pressure of the West River and its tributaries in downstream is increasing, the sluice at point C can be opened to make

the water flow from point C to point D. The connection of line CD can reduce the impact of Jiangmen City's waterfront and the negative water effects from the fast reclamations of Modao estuary.

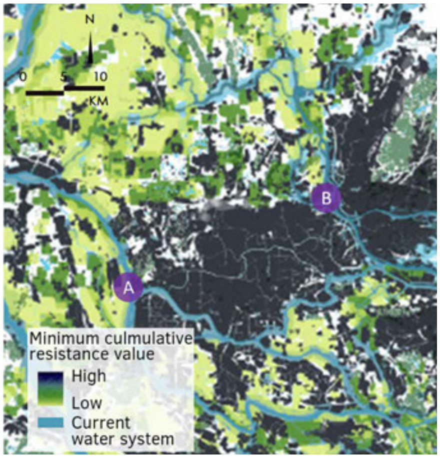
3 Regional analysis shows that Point E and Point F are both important hydrological points of the central region of the PRD. It is important to connect line EF to redistribute runoff and sedimentation diversion ratio between Hongliqi waterway and Jiaomen waterway. Line EF creates a possible new water corridor that can transport excessive water which originally comes to Hongqi estuary and to Jiao estuary so as to reduce the phenomenon of congestion of Hongqi estuary. This will enable the entire Nansha, Hengli Island to have a better buffering capacity in the future when addressing both fluvial and tidal floods caused by extreme climate.

C The Selection of New water corridor based on minimum cumulative resistance model (MCR)

The principle for the selection of new water corridors should be based on topography, soil, water and current land-use conditions. Minimum cumulative resistance model (MCR) could be applied to form new water corridors that can provide comprehensive least environmental cost and lowest average land use resistance between aimed connecting points when new blue-green corridors are implemented, based on the situation of existing blue-green network.

1 **Westside upstream region**
The objective of the new line AB water corridor is to alleviate the flood control pressure in Guangzhou city and Foshan city waterfront and improves the quality of space. Figure 4.28 shows three possible options based on the simulation of MCR model. The advantages and disadvantages of possible new water corridor can be seen in Table 4.7.

Based on above analysis, it is proposed that existing water corridor 3 and newly added water corridor 1 should be established at the same time. In this way, on the one hand, a large number of floodable areas can be combined around water corridor 1 to buffer and store the excess incoming water of the North River and the Pearl River in extreme climate condition, and realize the flexibility of the connection of the North River and the Pearl River by current nearby natural areas. On the other hand, it can increase the vitality of Foshan City and promote the quality of public space by rehabilitating existing water corridor.



1 MCR model

2 Option of new water corridors

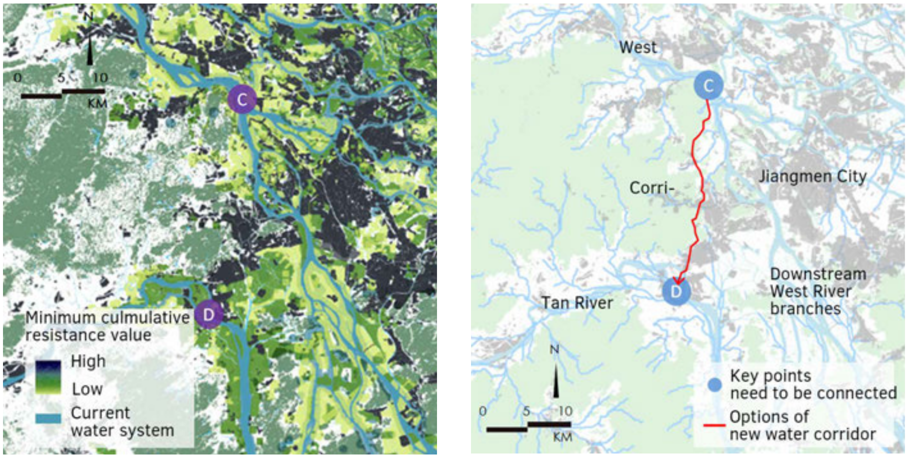
FIG. 4.28 Options of new water corridors based on MCR model

TABLE 4.7 Analysis of possible new water corridor in line AB

Options	Advantage	Disadvantage
Water corridor 1	– This water corridor will not pass through Foshan city so as to reduce the impact of potential floods caused by new water corridor on Foshan city. – This water corridor will pass through existing natural areas so that new nature reserves can be combined conveniently – A large floodable area can be combined with original low-lying and sufficient reserved areas.	– The length of water corridor path is relatively longer. – During the construction process, some animal habitats may be destroyed
Water corridor 2	– The length of water corridor is the shortest and the cost for construction is low. – The terrain is suitable to be rivers and the water flow can be relatively stable after construction	– This water corridor will pass through the current urban-rural edge areas. – If urban is expanding in the future, the requirements for water protection and water purification will be increased.
Current water corridor (Foshan city waterway)	– It only needs to be modified by increasing the width, depth of current waterway to increase the water storage capacity. The reconstruction cost is smaller. – The renovation of current waterway can further promote the urban vitality of Foshan City's waterfront.	– This water corridor will pass through the main urban area of Foshan City. Higher flood control standards are required that make it necessary to build large hard dykes alongside the waterfront to protect Foshan City.

2 Westside downstream region

The objective of new line CD is to connect the West River downstream branches and the Tan River in order to transport excessive water from the West River downstream branches to protect Jiangmen City’s waterfront and alleviate runoff and sedimentation congestion of Modao estuary. Figure 4.29 shows the selection of a new water corridor based on the simulation of MCR model. It forms a new vital axis of urban public space along Gudou Mountain. The spatial quality of the landscape space between the West River and the Tan River can be improved. The creation of this new water corridor can also provide opportunities for the development of new towns on the north and west sides of Jiangmen City.



1 MCR model

2 Option of new water corridors

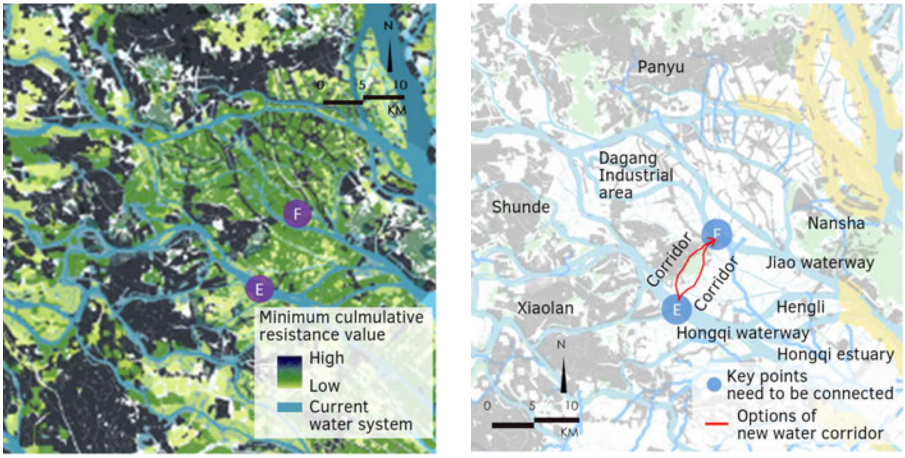
FIG. 4.29 Option of new water corridor path based on MCR model

3 Central region

The objective of new line EF is to make use of existing abundant water resources in Nansha and to connect Hongqi waterway and Jiao waterway. Under extreme climate condition, excessive water can be moved from new water corridor EF which can reduce the congestion phenomenon of Hongqi estuary.

TOC

Figure 4.30 shows two possible water corridors based on MCR model. The advantages and disadvantages of possible new water corridor can be seen in Table 4.8. Considering the future urban development trends of Nansha and the core area of Hengli Island, it is recommended to choose water corridor 2. On the one hand, water corridor 2 can avoid water pollution from industrial areas along water corridor 1. One the other hand, it can also form a new spatial axis in conjunction with the surrounding Forest Park, Binqili waterway and Tanzhouli waterway to increase the spatial quality of the Nansha and Hengli Island in the future.



1 MCR model

2 Option of new water corridors

FIG. 4.30 Options of new water corridors based on MCR model

TABLE 4.8 Analysis of advantages and disadvantages of new water corridor in line EF

Options	Advantage	Disadvantage
Water corridor 1	– This water corridor has shorter connection distance and low construction cost – The surrounding inner-rivers' texture is relatively suitable for connecting new water corridors	– Water corridor will pass through Dagang industrial area,Changan and Shakeng Industrial areas, which will cause polluted water quality
Water corridor 2	– It can be combined with current waterways to bring a positive impact on the future development of the central area of Nansha and Hengli Island.	– Affected by traditional fishpond texture, the current surrounding inner-rivers' texture is more tortuous for connecting new water corridor

4.5.5 Improve blue network in local context—Nansha as an example

Urbanization and climate changes are typical characters in Nansha. Therefore, improving blue networks in Nansha is necessary for future development. The specific steps are as follows.

- **Step one** is to identify vulnerable areas. Vulnerable areas will be the target places for taking measurements. According to the specific condition of Nansha, it will be exposed to flooding and land subsidence to a large extent. The places with more inundation depth and faster land subsidence speed can be regarded as vulnerable areas.

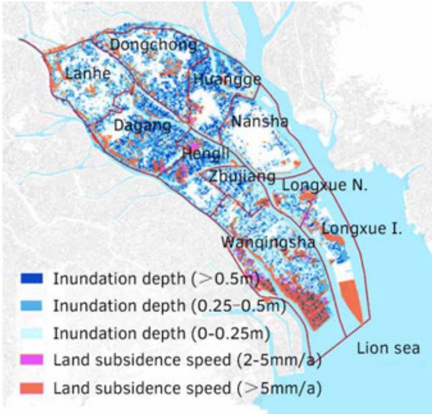
- **Step two** is to assess the connective degree of existing water system. The indicator of spatial integration is selected for assessment. The higher the indicator of integration is, the better the accessibility of blue-green networks, which infers that the flow of these areas can be smoother. By overlaying the assessment results of vulnerable areas and spatial integration degree, places that are located in both high vulnerable areas and low spatial integration degree can be identified.

- **Step three** is to find out low elevation points that have potentials to be turned into large water storage space. It is necessary to use the MCR model that is based on minimum cumulative resistance of land between targeted low elevation points to form an improved water network.

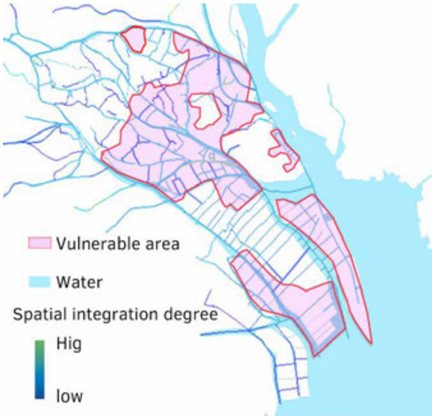
- **Step four** is to build new blue corridors such as inner-rivers and branches based on MCR value.

The outcomes of above four steps are shown in figure 4.31.

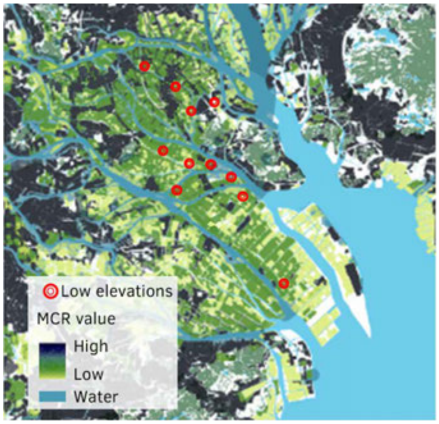
It can be seen that under the impact of climate change, the vulnerable areas caused by flooding and land subsidence perspective are largely located in Hengli, Dagang, Huangge, Wanqingsha and Longxue. The average inundation depth in these places is more than 0.25m, and the subsidence speed is 2-5mm/a. The phenomenon of water backtracking and salty tidal intrusion occurs frequently, which poses threats to the future urban development of these areas. In addition, the current spatial integration of existing water system is insufficient in these vulnerable areas, which results in insufficient water storage and unsmooth water circulation.



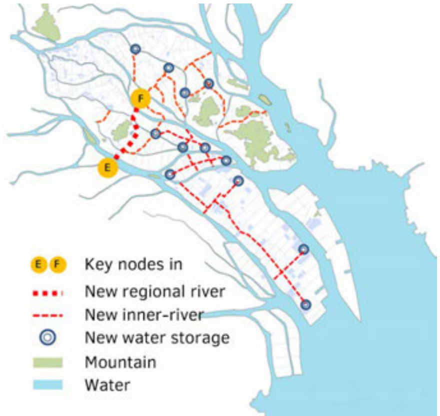
1 Step 1: Identify vulnerable area



2 Step 2: Assess existing water system



3 Step 3: Find out low elevation points and establish MCR model



4 Step 4: Reconnect water system by adding new inner-rivers and new water retentions

FIG. 4.31 Steps of improving and reconnecting blue network in Nansha

Based on the above spatial analysis, current blue networks in Nansha can be possibly improved by using the following principles:

- Make full use of the low elevation points distributed in areas to form large water storage spaces for absorbing the potential excessive water.
- Improve network integration in vulnerable areas. Maintain the flow route of the original main waterways and the status of large mountains.
- Reduce the channelization of organic streams and reduce the reclamation of sea.
- Connect the current important but discontinuous or blocked inner-rivers.

— Digging new water corridors based on MCR model by fully combining the existing topographic and geomorphic conditions, soil conditions and spatial texture, wetlands, lakes and beaches.

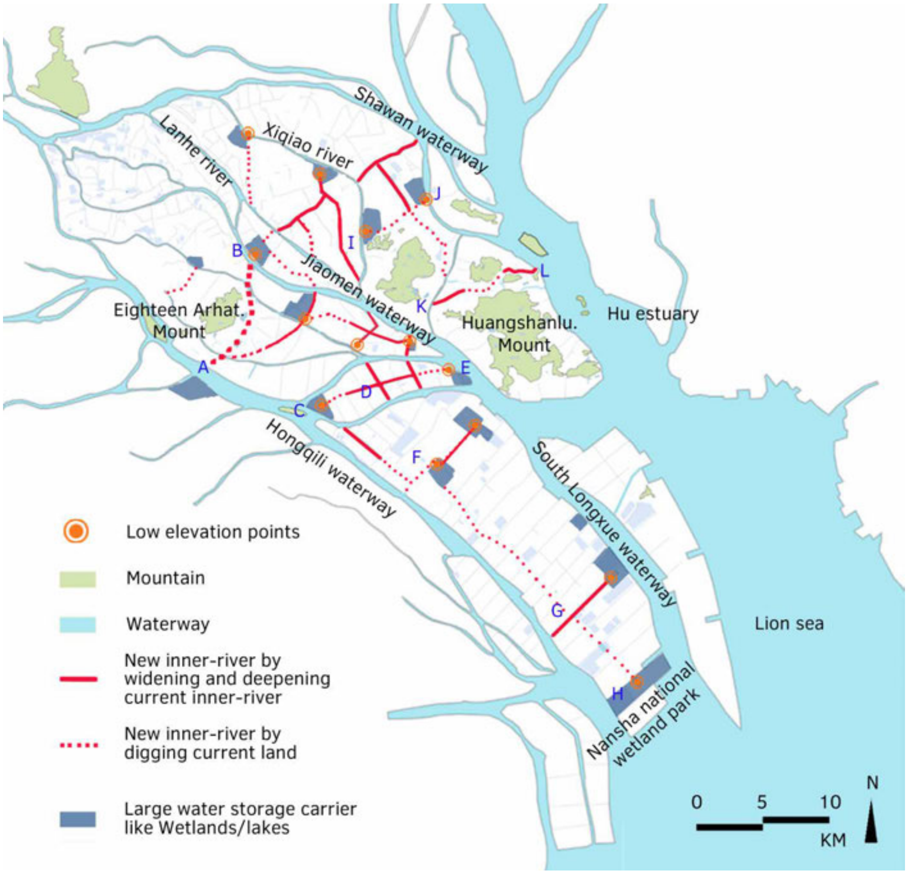


FIG. 4.32 New blue networks in Nansha

Figure 4.32 is a possible conceptual scheme of the future blue network in Nansha by adopting the above measures. In this new blue network, the water system network is composed of three types of water, which serve as the framework for future space development. The first type of water consists of large regional outer waterways that need to be protected. For example, Shawan Waterway, Hongqili waterway, Shanghengli waterway, Xiahengli waterway, Jiaomen waterway and Longxue South waterway can be included. These waterways serve as transportation carriers connecting the hinterland of the PRD with the estuary for realizing the connection of Nansha with the East River, the West River and the PRD. Construction on water and dredging of riverbeds should be prohibited if encroachment on waterline is required. The second type of water is formed by connecting, widening or deepening the current blocked inner-rivers such as FGH, IJ and KL shown in the figure 4.32. The third type of new water is based on the MCR model and consists of newly digging inner-rivers, such as AB and CDE shown in the figure 4.32.

In addition to the improvement of the above water corridors, large ecological patches such as Huangshan Lu Mountain, Shibaohan Mountain and Nansha Wetland Park also need to be included into strict protected areas. Nansha Wetland Park can buffer the salt water and purify the estuary. It is needed to restore the natural landscape around the entrance, protect the tidal resources, promote the restoration of mangroves, and ensure a good living and breeding environment for terrestrial and aquatic organisms.

The blue-green networks can be beneficial in addressing extreme climate conditions with its high spatial connectivity and modular water storage carriers. In normal days, the operation mechanism of the water network will conform to the dynamics of the natural base layer. Based on the principle of working with nature, sluices at each junction point of inner-rivers can be opened to smooth the water circulation by gravity. The new connective inner-rivers can function as central leisure places. When flooding occurs, large water retentions like wetlands, lakes of low elevation in each sub areas can absorb excessive water from nearby waterways. New inner-rivers can function as transportation carriers which can adjust diversion runoff and sedimentation ratio between important waterways.

For instance, inner-rivers AB and CDE shown in Figure 4.32, which is located in Dagang and Hengli sub-areas, can transport water from Hongqili waterway to Jiaomen waterway to reduce the congestion pressure of Hongqili waterway and Hongqi estuary that will cause serious water backtracking to Nansha. New digging inner-river FGH can provide flood drainage service in NW-SE direction to overcome the lack of flood drainage capacity in NW-SE direction of Wanqingsha. The new digging of inner-river IJ can coordinate the diversion ratio of runoff and sedimentation between the Xiqiao and the Shawan River to overcome the poor spatial integration of the water network between the Xiqiao and the Shawan River, which can effectively avoid the negative fluvial flooding impact from current narrowing of the Xiqiao River on both banks.

The newly digging inner-river of KL, as the highest density in Nansha, can be used as a main water axis to collect excessive water from adjacent building blocks and then transport the water into Hu estuary.

4.6 Research on the principles and strategies for coastline

4.6.1 General Principles

Coastline is an important spatial element to ensure the safety of flood control, as well as to improve the hydrological and ecological environment in the PRD from the first barrier. According to the document of 'the planning and design of flood control for river channels along the lower reaches of the West River and the North River', the geographical scope of the coastline of the PRD refers to the coastline itself and the land areas 500 meters from coastline.

Spatial planning and design for resilient coastlines focuses on improving the function of coastlines and their surrounding areas and creating coastal buffer belts. The arrangement of the function of coastline should be based on the situation of hydrology, ecology and the requirements of flood control in each coastline segment. Water accommodation spaces and buffer nodes need to be constructed by taking the advantages of spatial elements such as mangroves, tidal flats outside dykes and the public space inside dykes, so as to create a buffering belt and zones that can be used for preventing tidal invasion.

4.6.2 Current situation of the coastline

The coastline of the PRD has experienced thousands of years of slow natural siltation and nearly 50 years of rapid artificial reclamations. Figure 4.33 shows the changes of the coastline of the PRD in the last 50 years. It can be seen that the shape of Gaolan Island, Sanzao Island, Hengqin Island on the west coastline, Qianhai and Shenzhen city Bay on the east coastline changed greatly. The average reclamation rate is 220 m/a, which accounts for about 0.5% of the average width of the Pearl River estuary. Before 1980, the development of the PRD was mainly concentrated in the old urban areas far away from the Pearl River estuary. During this period, most of the coastline was dominated by agricultural reclamation by planting sugarcane, fruit and growing aquaculture. After 1980, especially in the late 1990s, the real estate development and port construction in Nansha, the West Coastline of Shenzhen city and other places led to the destructions of large areas of tidal flats. The topography, ecological and hydrological situation in all estuaries changed greatly, which aggravated the pressure of flood control.

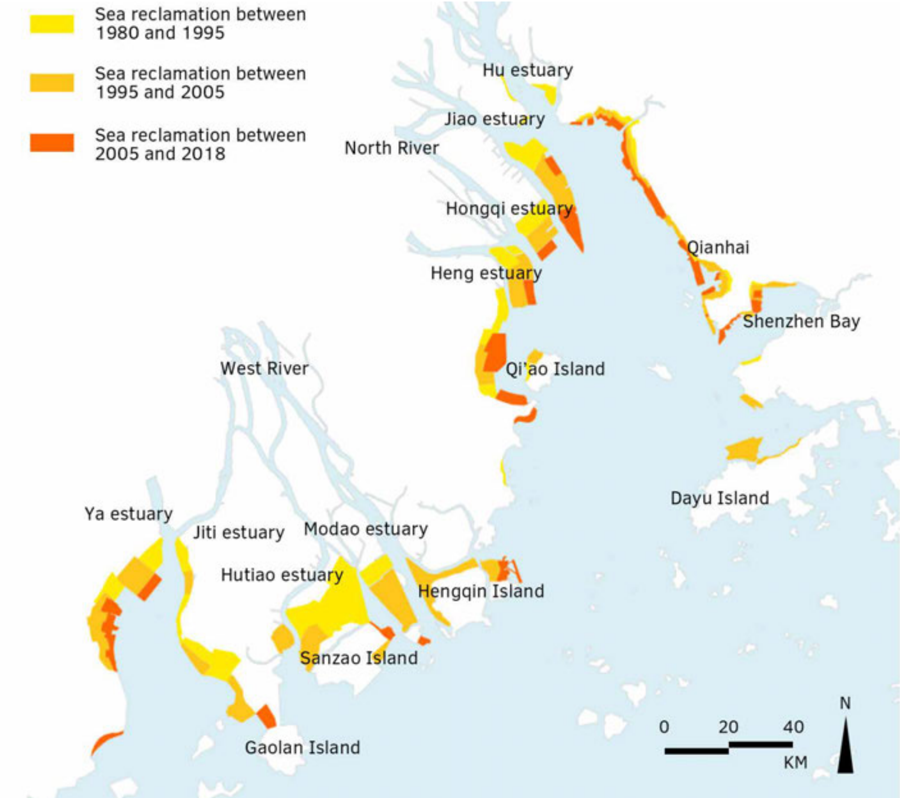


FIG. 4.33 Reclamations of the PRD from1980 to 2018

4.6.3 Coastline development suitability assessment and arrangement of coastline function

Arrangement of coastline function based on the results of coastline development suitability assessment is the key to realize the spatial resilience of PRD's coastline and is of great significance to the future urbanization of the whole PRD. The arrangement of coastline functions should be based on the identification of the current condition, assessment feature and the projection of future development scenario of each coastline segment.

Arrangement of coastline functions is possible to be conducted by the following five main steps.

- **Step 1: Coastline segmentation**
The method of coastline segmentation is based on the understanding of physical geographical conditions. According to the condition of coastline and the surrounding land uses within 500 meters from coastline, the coastline of the PRD can be divided into segments, which are used as the basic units of spatial planning and design for resilient coastline. Compared with the method of coastline segmentation based on administrative boundary, the method of coastline segmentation based on physical geographical condition can better conform to the natural mechanism of the coastline of the PRD and is more conducive to improve flood resilience.

- **Step 2: Identification of current land use of coastline**
Based on remote sensing images of land use and field investigation, after the process of geometric correction and visual interpreting, the usage of current lands within 500 meters from coastline are classified into developed lands and undeveloped lands. The developed lands include the existing residential lands, commercial lands, industrial lands, road squares. The undeveloped lands include forest, wetlands, mangrove forests, cultivated lands, fish ponds and others.

- **Step 3: Coastline development suitability assessment for future**
Guided by the principles of conforming to the natural state of the estuary, coastline development suitability assessment for the future are conducted from four aspects, such as the rate of land subsidence, the inundation depth under 200-year flood, the steady state of surrounding water environment (erosion and sedimentation) and the distribution of spatial natural resources, so as to provide a basis for arranging the function of the coastline for the future.

The steady state of surrounding water environment (erosion and sedimentation), namely whether there is an obvious erosion and sedimentation process in nearby water area around the coastline, can be the main basis for projecting the changes of the shape of the coastline in the future. The steady state of surrounding water environment (erosion and sedimentation) can be measured by the indicator of the average annual retreating or moving forward distances of the coastline. According to the document of ‘Flood Control Planning and Design for the Pearl River Basin’, if the average annual retreating or moving forward distances of the coastline segment is greater than 25 meters, it is considered that the coastline segment is characterized by obvious erosion and deposition process, which further means that the surrounding water environment is unstable for further urbanization. The rate of land subsidence represents the land subsidence speed in each coastline segment.

If the average annual rate of land subsidence is more than 5 mm/a, the condition for further land development is poor. The inundation depth under 200-year flood is the inundation depth of the site affected by both 200-year flood and 0.5 meter sea level rise in 200 years, under the assumption that the existing dyke's height remains unchanged. When the inundation depth is greater than 0.5 meters, the conditions for further urbanization are poor. The distribution of spatial natural resources mainly refers to whether there are mangrove natural protected areas near the coastline which can buffer the tidal invasion and provide high environmental value. When there are important natural conservation lands such as mangroves in the coast the PRD. In the area for development, functions can be arranged such as equipment manufacturing industry, port-neighboring industrial port area, and residential area.

Area for controlled development can be arranged into coastline segments and surrounding 500-meter lands, in which the comprehensive degree of coastline development suitability is moderate or some indicators for coastline development suitability assessment have obvious deficiencies for urban development. When the land resources are exhausted, areas for controlled development can be used as supplements to be constructed in the future. Even for some coastline segments with good conditions for urban development, low-density development should be given priority, and a certain number of space for water accommodation should be left between buildings so as to realize the functional transformation between normal time and flooding disaster time.

— Step 5: Adjustment of coastline function in some key segments

Necessary adjustments should be made to some key coastline segments where the current functions do not match the assessment results of coastline development suitability and the results of arrangement of coastline function. In particular, for urban lands that have been developed in the area for protection, necessary hydro-ecological remediation measures should be taken. For instance, on the outside of dykes the buffer space can be enlarged through sand dunes and tidal flats. On the inside of dykes, measures such as dismantling low value industrial buildings, setting up multi-functional landscape belts with small gardens which can be used as public leisure space in normal time can be taken.

4.6.4 Arrangement of the coastline function in the PRD

In combination with the related data from ‘elevation digital model (DEM) of the PRD’, ‘Planning and design for the flood control and drainage of Pearl River Basin’, ‘Planning and design for the west, the downstream of North River and its delta river channel’, ‘Planning and design for flood control and drainage of Guangzhou city, 2010-2020’ and ‘ Planning and design for flood control and drainage of Shenzhen city, 2010-2020’, the coastline of the PRD can be divided into 310 segments. The longest of the coastline segment is 3.2 kilometers and the shortest of the coastline segment is 1.0 km. The identification of current land uses of each coastline segment are analyzed (Figure 4.34). It can be seen that the coastline around Hu, Jiao, Ya, Ji Estuary and Qianhai, Qiao Island, Hengqin Island and Gaolan Island has been developed to a high degree, and parts of the coastline are saturated for further development. The constructions of tidal flats have damaged the surrounding environment and seriously affected the flood control and drainage in Jiao estuary, Shaodoumen and other areas.

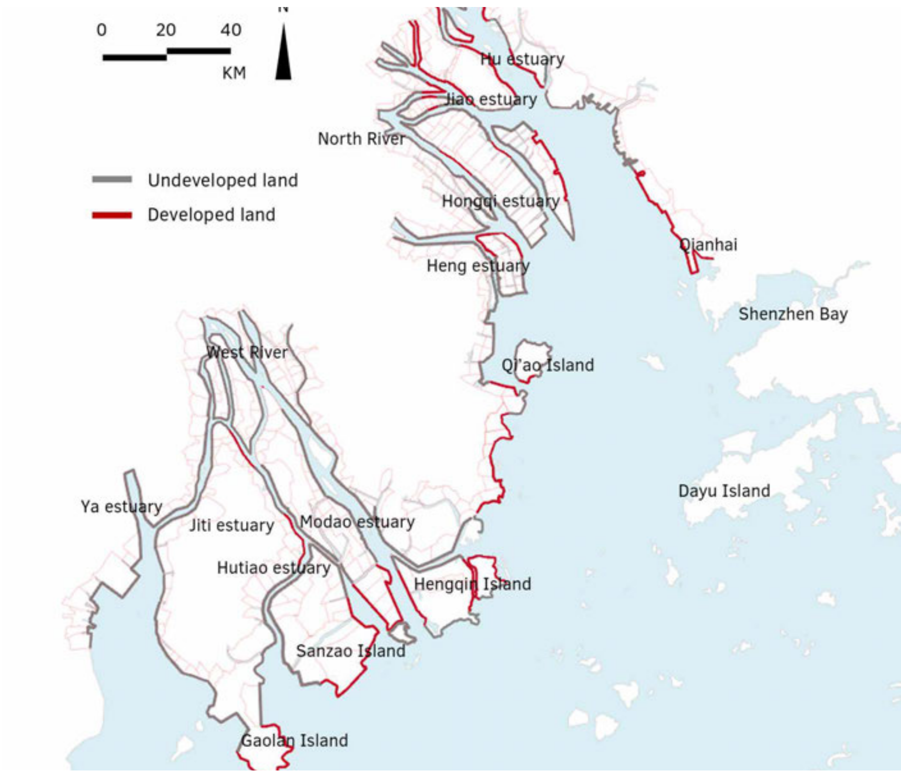
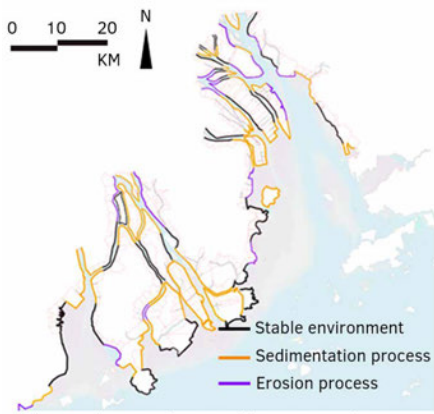
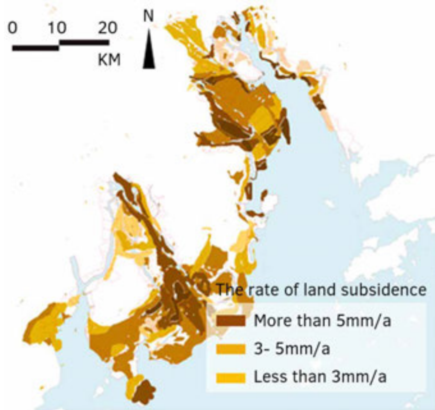


FIG. 4.34 Current land use of coastline in the PRD

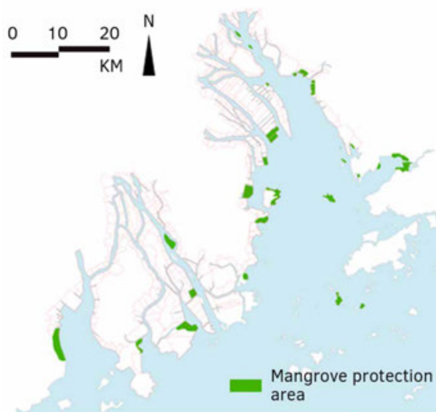
TOC



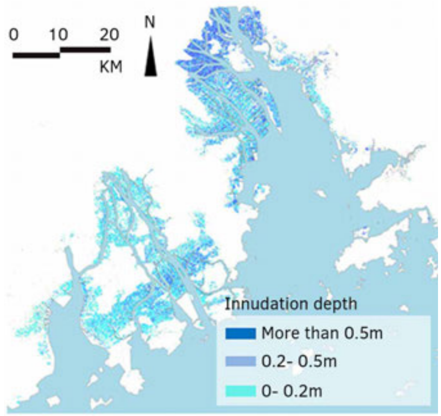
1 The steady state of surrounding water environment



2 The rate of land subsidence



3 The distribution of spatial natural resources



4 The innudation depth under 200-year flood and sea level rise

FIG. 4.35 Coastline development suitability assessments in the PRD

The results of coastline development suitability assessment of the PRD are shown in Figure 4.35. It can be seen from the figure that the steady state of the surrounding water environment (rate of erosion and sedimentation) of the coastline segment near eight estuaries is obviously faster than that of other coastline segments, especially in Hongqi estuary, Hen estuary and Modao estuary. The siltation of the estuaries will lead to the backtracking of the river water, which will affect the future urban development of Pearl Bay in Nansha and Hengqin Island in Zhuhai. The rate of land subsidence in Hongqi estuary, Heng estuary, Modao estuary and their surrounding areas are higher than other areas due to the influence of sea reclamation and groundwater exploitations. In terms of the distribution of special natural resources,

TOC

there are mangrove forest protection areas in Wanqingsha, Qiao Island, Shenzhen Bay, Mipu and Sanzao Island. Under the condition of 200-year floods and sea level rise in 200 years, the flooded area and average depth of inundation of the eastern four estuaries are deeper than that of the western four estuaries.

Based on the results of assessments, the arrangement of coastline function is presented in Figure 4.36. Areas for protection are mainly distributed near estuary areas, the mangrove protection areas, the intersections of river networks, the concave and convex banks of rivers and the central islands of rivers. Areas for controlled development are mainly distributed near the downstream tributaries of the West River, Sanzao Island and Hengqin Island. Areas for development are mainly located near Wanqingsha of Nansha and the waterfront of Zhuhai city. These areas have great development potential and little impact on the surrounding hydro-ecological environment.

By comparing Figure 4.34 and Figure 4.36, some key coastline segments whose current land use and future arranged coastline functions are not matched are selected, based on the results of coastline development suitability assessment. The function and land use of these coastline segment needs to be adjusted. For example, coastline segment AB in Figure 4.36 shows that its current land use is high-density urban areas in Zhuhai city. But the assessment shows that the erosion and sedimentation process in this coastline segment is serious, which leads to the increase of surrounding water levels along the coastline when flooding. It is necessary to add waterfront parks on the outside of dykes, and provide coastal protection buffer areas, wetlands and green parks. On the inside of dykes, places for water accommodations should be built. The current land use of coastline segment CD is industrial development area by sea reclamations, which has a serious impact on the tidal environment of the Modao estuary. A large number of industrial buildings occupied the tidal flats. Measures should be taken in the future to demolish low-valued industrial buildings. At the same time, forestland, garden and open space should be arranged inside the industrial development area. The current land use of coastal segment EF is occupied by Nansha international Port. In the future, attention should be paid to the control of the continuous sea reclamations for the expansion of function of port and real estate. The dredging of riverbed of the port area should be conducted regularly in order to reduce the impact of sedimentation. The current land use of coastline segment IJ is Shekou Industrial zone in Shenzhen city. In the future, the renovation of such industrial area should be strengthened to realize the functional replacement of land use to increase the proportion of natural land use alongside the coastline, and further avoid the irreversible impact of industrial area on the surrounding water environment and ecological environment.

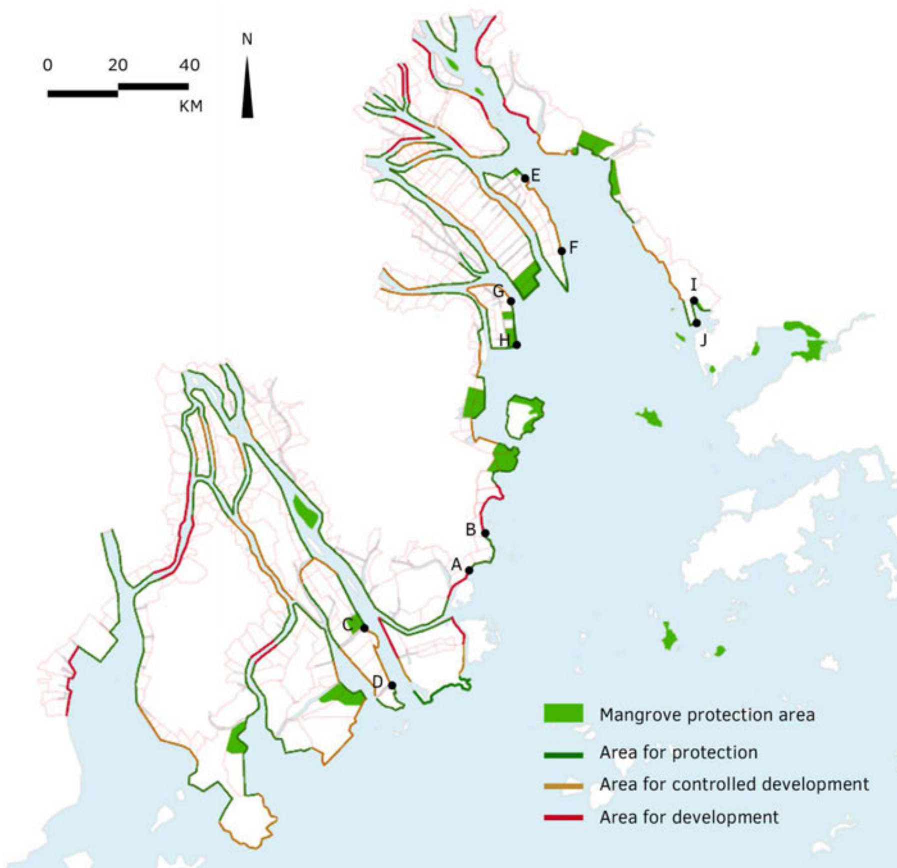
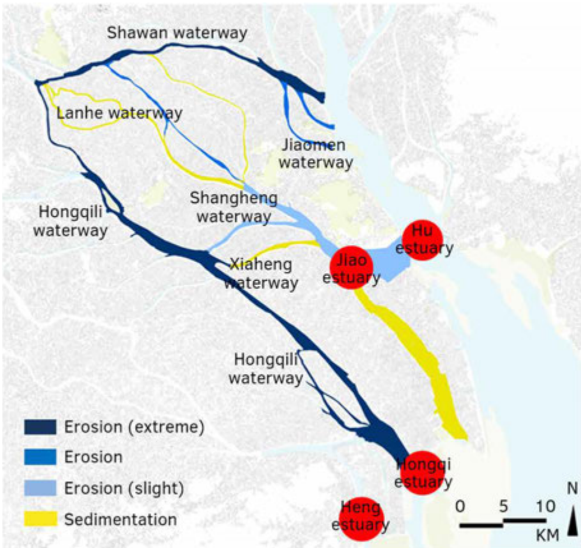


FIG. 4.36 Figure 4.36 Arrangement of coastline function and the adjustment of coastline function in some key segments

4.6.5 Create coastal buffering belt

The creation of a coastal buffering area can reduce the impact of tidal invasion on the site and reduce the impact of excessive sea reclamations on estuaries. The width of the coastal buffering belt should be considered comprehensively according to factors such as hydro-ecological conditions around the coastline, the spatial characteristics of the estuaries, flood control and drainage requirements. Wide coastal buffering belts should be set as much as possible alongside waterfonts that have high rates of sedimentation and erosion. It can make full use of tidal resources outside the dyke, as well as discharge channels and leisure parks inside the dyke to construct the coastline buffer belt for preventing tidal invasion.

When constructing the coastal buffering belt, the dynamic characteristics of the estuaries should be analyzed comprehensively. Suggestions can be put forward for increasing the width of the buffer belt. For example, the coastline of Nansha is formed by both the continuous erosion and sedimentation of waterways and artificial reclamation. The status of erosion and sedimentation of waterways in Nansha is drawn in Figure 4.37, and the characteristics of the coastline in Nansha are predicted in table 4.9. Based on the calculations of hydrodynamic force, 100-200 meters width buffering belts inside of waterways of Hongqi, Shawan and Xiqiao are suggested, which have a fast flow rate and scour significant watercourses. For other waterways, it is recommended to set up 50-100 meters width buffering belts. For Jiaomen waterway, due to its high density of current urban lands along the rivers, it is impossible to set a wide coastal buffer belt. Therefore, the focus of spatial planning and design for resilient coastline should be put into the creation of diversified spaces, and buffering reserved nodes should be set between important buildings.



Name of waterway	Volume change from 1980s-2000s	Situation of erosion and sedimentation
Shawan waterway	-51.44%	Serious erosion
Lanhe waterway	8.04%	Slight sedimentation
Liugang waterway	0.59%	Slight sedimentation
Shiziyang waterway	-15.2%	Erosion
Shangheng waterway	-5.33%	Slight erosion
Xiaheng waterway	0.47%	Slight sedimentation
Hongqili waterway	-23.46%	Serious erosion
Jiaomen waterway	-2.32%	Slight erosion

FIG. 4.37 The status of Erosion and sedimentation of waterways in Nansha area

TOC

TABLE 4.9 Hydrodynamic characteristics of four estuaries of Nansha area

Item	Hu estuary	Jiao estuary	Hongqi estuary	Heng estuary
Volume of tidal influence (billion m^3/a)	228.8	32.5	9.7	13.3
Percentage(%)	80.48	11.43	3.41	4.68
Volume of fluvial influence(billion m^3/a)	60.3	56.5	20.9	36.5
Percentage(%)	34.6	32.4	12.0	21.0
Ratio of fluvial and tidal volume	0.264	1.74	2.16	2.75
Sand transportation amount (thousand ton/a)	6580	12890	5710	9250
Percentage(%)	19.4	38.0	15.3	27.3

4.7 Summary

This chapter uses the whole PRD as a research case, analyzes the spatial evolution and simulates comprehensive flooding and land subsidence risk areas under extreme climate condition. Main challenges are pointed out in the current spatial system of the PRD. Afterwards, possible new planning and design schemes for improving resilient PRD in terms of land use, blue-green networks, and coastline areas are proposed.

Several principles, strategies and measurements for improving resilience are applied.

1 Spatial planning and design for a resilient PRD are closely related to its future land-use situation. Land uses that conform to natural conditions and adapt to hydro-ecological structure can possibly avoid the occurrence of being exposed to natural disasters such as flooding, land subsidence and earthquakes to a large extent. From the perspective of resilience, the principles and strategies for land-use scheme should fully reflect the regional natural base layer. Based on the identification of natural protection, the assessment of agricultural and urban land-use suitability, spatial strategies of forming three-circle coordination and classifying four land-use categories (natural protection area, agricultural area, urban area and coastline area) are formed in new land-use scheme.

2 The regional blue-green networks are the backbone for the organization of various spaces in the PRD. It runs through the relationship between parts and the whole region. The general ideas of organically integrating multiple elements, actively exerting the self-purification ability of the natural ecosystem, controlling the runoff flowing into the agricultural and urban area, and gradually mitigating the risks of the major cities in the PRD are proposed. A new scheme of blue-green networks emphasizes on integrating natural resources, establishing hydro-ecological barrier and improving current water network by applying natural resources and using a minimum cumulative resistance (MCR) model. The MCR model can help select new blue-green corridors that need comprehensive least environmental cost and lowest average land resistance between aimed connecting points when these new blue-green corridors area implemented.

3 Coastline is an important spatial element to ensure the safety of flood control, as well as to improve the hydrological and ecological environment of the PRD. The method of coastline segmentation is based on physical geographical conditions rather than administrative boundary, which is more conducive to improve flood resilience. The coastline of the PRD is divided into 310 segments, which can be used as the basic unit for the arrangement of coastline function. Guided by the principles of conforming to the natural state of the estuary, coastline development suitability assessment for the future are conducted from four aspects, including the rate of land subsidence, the inundation depth under 200-year floods, the steady state of the surrounding water environment (erosion and sedimentation) and the distribution of spatial natural resources, so as to provide a basis for arranging the function of the coastline for future. The functions of the whole coastline of PRD are divided into three categories, including area for development, area for controlled development and area for protection. Corresponding planning and design strategies for resilient coastline are proposed. At the same time, it is needed to actively use the tidal flats outside the dykes and public space inside the dykes to build coastal buffering belt, so as to realize the combination of the functions in both normal time and flooding time.

5 Research on Spatial Planning and Design for Resilient Flood Control and Drainage on Hengli Island

5.1 Introduction

Hengli Island is the most important core area of Nansha District, PRD. With the increasing development of the island, the contradiction between urban development and water environment will be very prominent in the future. Therefore, it is significant to properly consider the 'human-urban-water' relationship and explore an approach for realizing spatial resilience in flood control and drainage.

This chapter makes efforts on spatial planning and design for resilient flood control and drainage. Based on the theories and the methods of spatial resilience and the situations of this specific case, spatial characters of regionality, connectivity, diversity, multifunctionality, redundancy, and modularization will be widely applied and a new spatial scheme for resilient flood control and drainage will be proposed and evaluated. The new scheme aims to establish a possible situation for flood resilience for a long-term development on Hengli Island.

This chapter consists of 10 sections. Section 5.2 presents the case that the Hengli Island will become a high-density, urbanized areas. It is important for this Island to improve its flood resilience level. Section 5.3 presents an overall research framework with general principles and application guidance. Section 5.4 is to comprehensively understand the site and conduct projections for future scenarios. Section 5.5 conducts pre-evaluations for flood resilient spatial organization. Section 5.6 illustrates the main challenges of flood control and drainage under extreme climate change situation. Section 5.7 researches on principles and strategies for organizing resilient flood drainage specifically focused on reconstructing connective water networks and placing diversified water accommodation spots. Multiple strategies like decentralized and modularized water collective units, improvement of water networks, classification of functions for inner-rivers, diversified and multifunctional water storage spots are applied. Section 5.8 researches on principles and strategies for organizing resilient flood prevention, specifically focusing on the dyke system. Appropriate height of dykes, reasonable retreat distance of dykes from shoreline, diversified and multifunctional cross-section dyke shapes are calculated, created and applied. Section 5.9 shows the overall spatial scheme for future resilient flood control system by widely applying the above principles and strategies. Based on the new scheme, water level regulations for different scenarios are proposed. Section 5.10 conducts the evaluation of the effectiveness of the new scheme of resilient flood control and drainage, in terms of the size of potential flooding areas, water storage capacity, spatial integration, peak runoff speed and landscape effects. Section 5.11 establishes a reflection table of the linkage between case applications and resilient spatial characters of regionality, connectivity, diversity, multifunctionality, redundancy and modularization.

5.2 Future Situation of Hengli Island

Hengli Island covers an area of 17.9 square kilometers and the water areas of 0.78 square kilometers. It is the core place in Nansha District. Jiaomen waterway, Shangheng waterway, Xiaheng waterway and large waterways surround the entire Island and create about 21.8 kilometers of shoreline (Figure 5.1). The average daily high tide of the above waterways exceeds the elevation of current land by 2.3 meters. The current land-uses are mainly farmlands and fish-ponds.

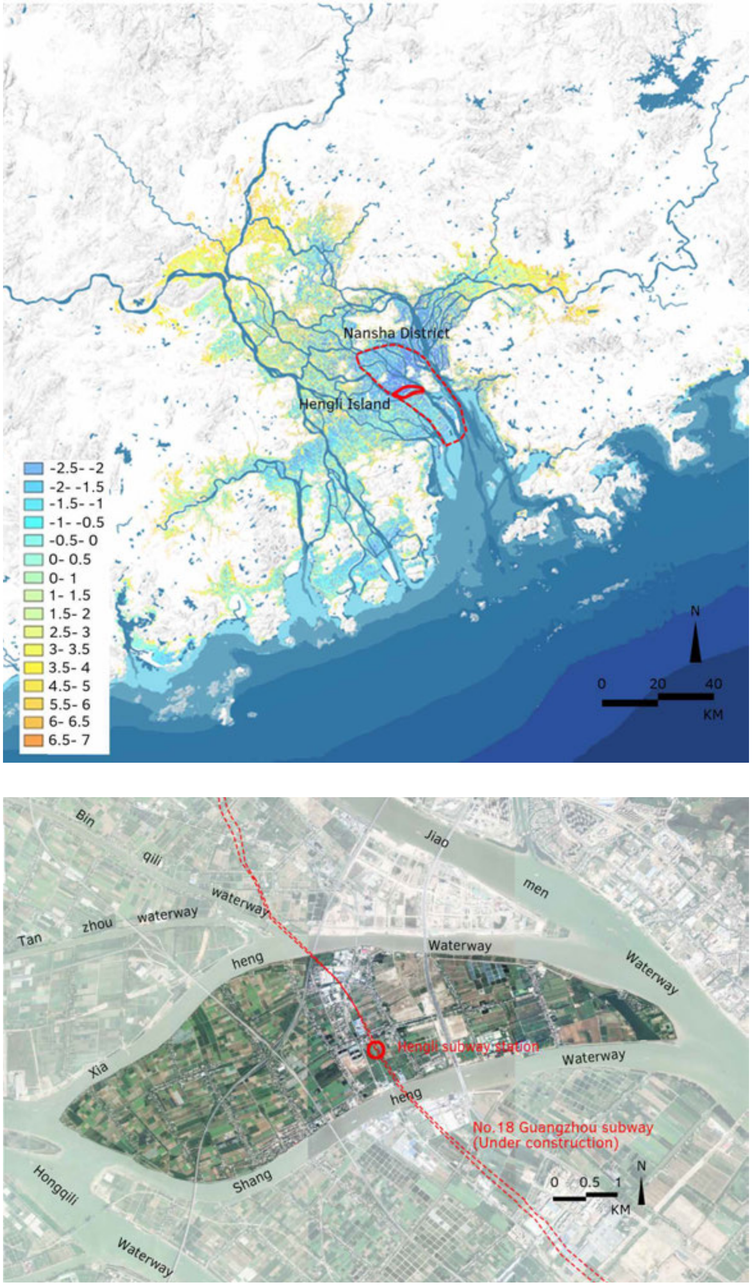


FIG. 5.1 Surrounding environment of Hengli Island. (Source: Author revised based on Google map)

In 2012, Nansha District became the Chinese sixth national new area with the official approval from the State Council. It is stated that the population of Nansha District will increase from 0.72 million in 2018 to 2.25 million in 2030. The Provincial Government has clearly defined the functional positioning of Hengli Island. Hengli Island will be built into an ideal high-level urbanized area with socio-economic, scientific, technological, cultural, hydro-ecological, and leisure center not only in the PRD but also in the worldwide. Figure 5.2 is the bird-eye intentional perspective of the modern core area of Hengli Island in the future.

FIG. 5.2 Bird-eye intentional perspective of the modern core area of Hengli Island (Source: Planning bureau of Guangzhou city, 2013)

5.3 Overall spatial planning and design framework

5.3.1 Planning and design principles

Aiming to deal with the current negative natural environment with water-related issues such as flooding, waterlogging and land subsidence, the theory and methods of spatial resilience are applied into flood control and drainage systems and adheres to the following general principles during the spatial planning and design process.

- Flood control and drainage emphasizes on how we can respond to future uncertain climate disturbances, which challenges low-lying territory. Therefore, spatial planning and design for resilient flood control and drainage places more emphasis on systematic thinking, coordinative thinking, bottom-line thinking, foresight thinking as well as the harmonious coexistence of the urban layer and natural stratum layer.

- It is necessary to deeply understand the situations of land-use, water system, soil and current infrastructures for flood control and drainage. Principles such as natural priority, connective blue-green networks and compact and multifunctional land-use need to be emphasized for spatial development.

- It is important to understand future uncertain disturbances by simulations. By experiencing rational planning and design processes, the robustness and adaptability in new flood control and drainage systems can be improved to provide spatial support. The related strategies and principles need to widely apply resilient spatial characteristics such as regionality, connectivity, diversity, multifunctionality, modularization and redundancy.

5.3.2 Steps of resilient flood control and drainage

The overall technical route for spatial organization of resilient flood control and drainage is shown in Figure 5.3 Related data for this empirical research can be found in Appendix D-1.

TOC

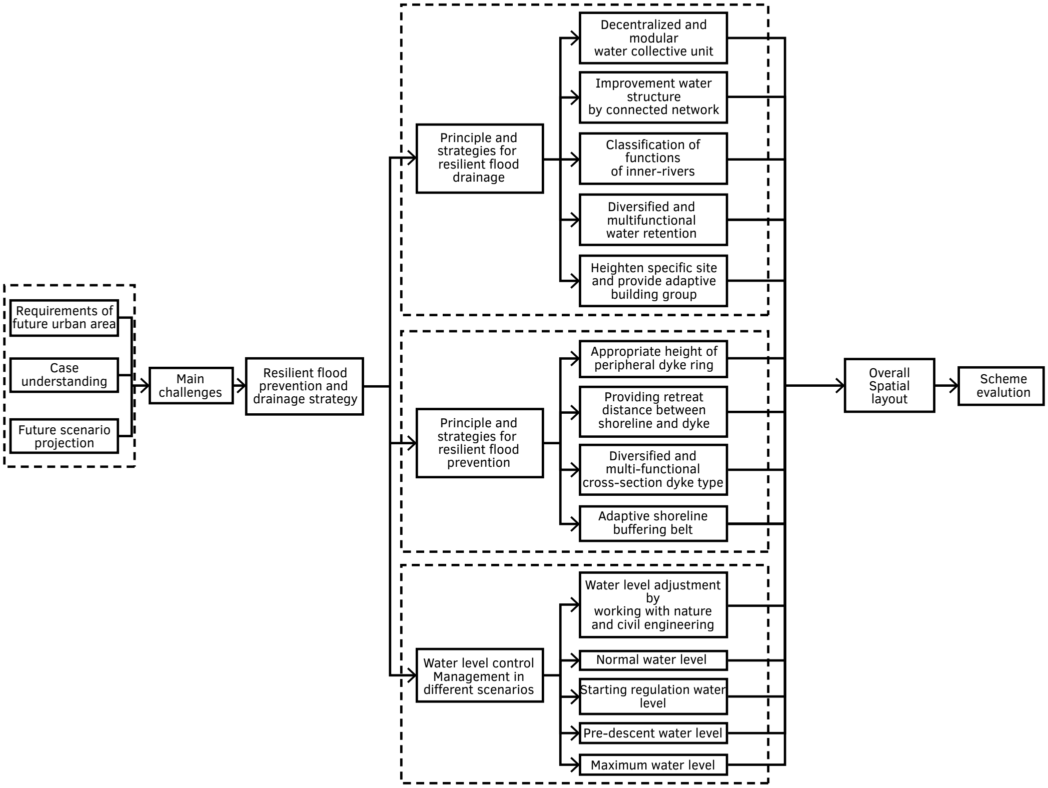


FIG. 5.3 Research technic route

— **Step one** is to comprehensively understand the research case. Based on the principles of regionality, some information such as the elevation, land-use, water system, current flood control and drainage system, historical water-related disasters and future situation of urbanization need to be fully investigated and understood. It is important to analyze the elevation relationships between the water level of outside waterways, inner-rivers, dyke and the site surface. It is important to identify problems in current flood prevention and drainage system.

— **Step two** is to conduct scenario projections under the condition of extreme climate change. The potential impacts caused by extreme climate change on the research site need to be analyzed for rational spatial organization. Therefore, factors that will affect the vulnerability of the water system in the future need to be studied. Specifically, it is important to conduct simulation analyses to evaluate whether the current waterway, inner-rivers and each water collective unit have enough ability to

TOC

store excessive water and whether the current dyke standards have enough ability to prevent water from outside waterways.

- **Step three** is to conduct pre-evaluations for conducting the spatial organization of resilient flood control and drainage. It is necessary to deeply discover the current spatial capacity to respond to future climate change in order to find threats and opportunities in the research case. The items include issues such as: (a) Analysis of water storage of each water collective unit, (b) Spatial distribution of spatial elements which is relative to flood control and drainage and (c) Evaluation of the condition of each shoreline segments.

- **Step four** is to research on strategies for resilient flood drainage. According to site context, strategies are studied such as: (a) Creating decentralized water collective units, (b) Improving the spatial organization of water networks with the assistant elements of low-lying depression, lakes, wetlands, (c) Classifying the functions for inner-rivers based on site characteristics, (d) Establishing diversified and multifunctional water retention spots and (f) Providing adaptive building groups. With the combination of the strategies above, a new water network with sufficient retention spots can be established in order to respond to both pluvial and fluvial influences.

- **Step five** is to research on strategies for flood prevention based on the understanding of redundancy, diversity and multifunctionality. According to the function of dyke system, strategies are studied such as: (a) Calculation of appropriate height of peripheral dyke, (b) Analysis of the distances that dykes can be retreated from shoreline, (c) Analysis for shaping diversified and multifunctional dyke shapes in each shoreline segments and (d) Providing adaptive shoreline buffering belt. With the combination of above strategies, a new dyke system can be proposed in order to respond to extreme sea level rise and tidal invasion.

- **Step six** is to research on strategies for water level control, such as: (a) Adjusting water levels based on working with nature and civil engineering, (b) Reasonably setting sluices and pumps for self-discharge and artificial- extraction and (c) Providing water level regulations for different scenarios.

- **Step seven** is to evaluate the effectiveness of the new resilient flood control and drainage schemes based on indicators of: (a) The size and the spatial distribution of potential flooding and waterlogging areas, (b) The number of gaps between the capacity of water storage and future precipitation, (c) Peak runoff speed in each new water collective unit, (d) Connectivity and the degree of spatial integration of new water networks and (e) Landscape effects of important location.

5.4 Site understanding and future scenario projection

5.4.1 Elevation and land-use

A Elevation

Hengli Island is a low-lying territory formed by long-term accretions of sediments from the North River, the West River and their main tributaries in the upstream of the PRD, and the tidal erosion and deposition of Jiao estuary and Hu estuary in the downstream of the Pearl River Estuary. Figure 5.4 shows the main water system and the elevation of the Pearl Bay. It can be seen that the terrain of the Hengli Island is relatively low in the entire Pearl Bay. The elevation of Hengli Island is shown in Figure 5.5. The entire Hengli Island is at a lower elevation, with an average elevation below 1.0 meters. The maximum elevation difference is 6.8 meters. The highest elevation of the peripheral dyke in the middle and the south part is 3.8 meters. The lowest elevation is -3.0 meters. Figure 5.6 shows the elevation of important sections across —the whole site. Figure 5.7 shows the relative elevation relationship among waterways, inner-rivers and site surface.

Affected by both fluvial and tidal influences, the water level difference between the waterways and inner-rivers are dynamic. In addition to extreme high tides, the changing of the water level of waterways caused by daily tidal fluctuation is also a specific phenomenon. Due to the influence of the daily tide, the water level of waterways can fluctuate with an average of 1.5 -3.0 meters. Therefore, the current elevation relationship between 'waterways- inner rivers- site surface' has two situations. First, when encountering 50-year ~1000-year high tides or daily high tide, the relative elevation relationship can be 'waterway > site surface> inner-rivers'. Second, when encountering 5-year ~20-year high tide or daily low tide, the relative elevation relationship can be 'site surface> inner-river> waterway'.

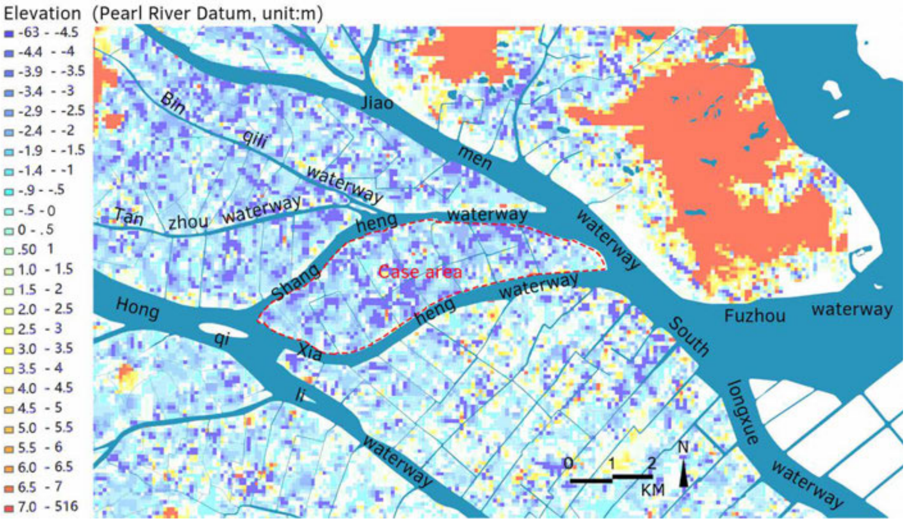


FIG. 5.4 The elevation system and the main water system of Pearl Bay

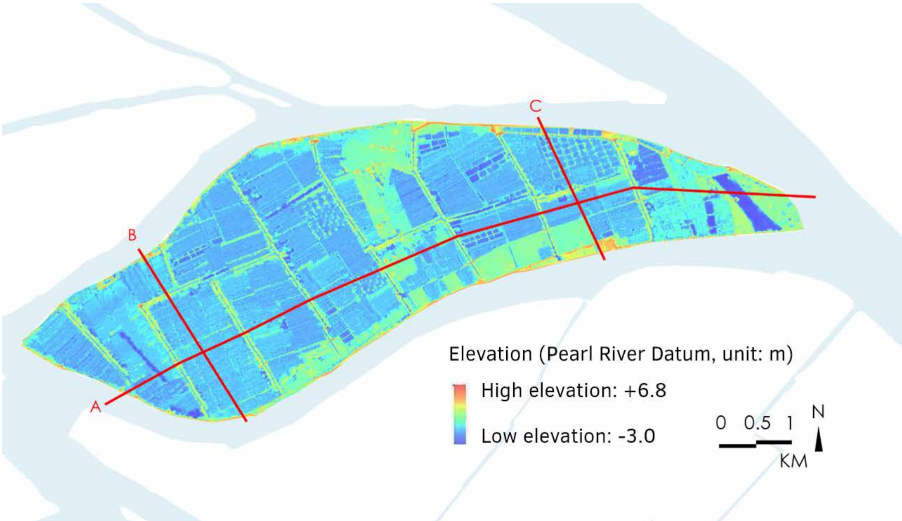


FIG. 5.5 Digital elevation map of Hengli Island

TOC

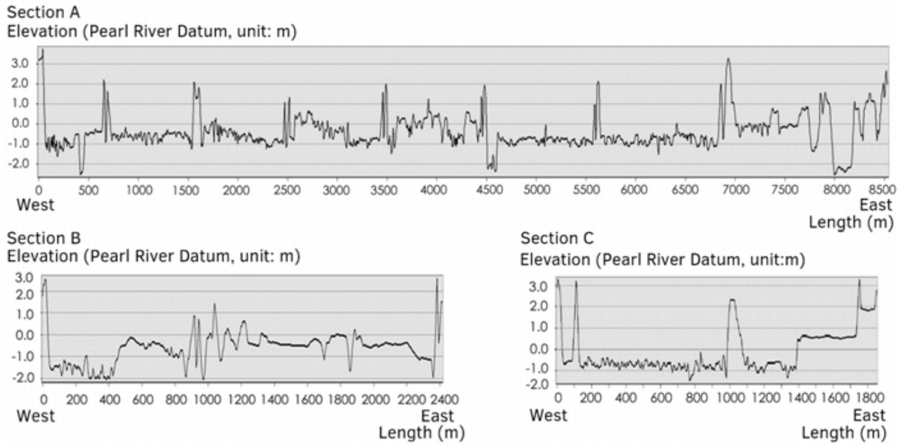


FIG. 5.6 Elevation of important sections across through the whole site

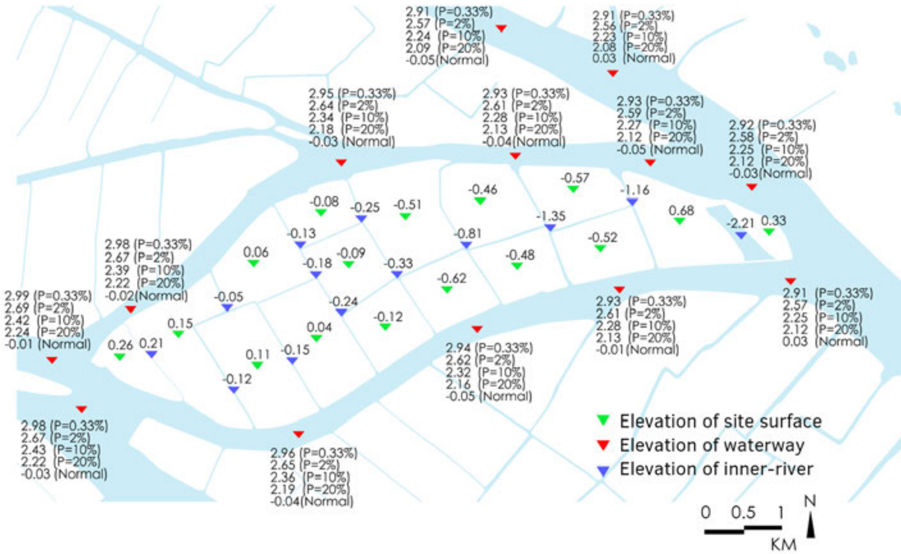


FIG. 5.7 Relative elevation relationships among waterways, inner-rivers and site surface

TOC

B Soil Condition

Soils on the island are mostly characterized by clay tidal muds. The thickness of soft soil layer in some areas can reach up to 40 meters with shallow groundwater level that can occasionally bring the phenomenon of seepage. Under the impact of extreme precipitation, the soil can easily reach to the situation of oversaturation. Figure 5.8 shows the impact of land subsidence. Affected by the impact of waterways, the speed of land subsidence in most low-lying areas of the east and the west islands can reach up to 3 mm /a. Land subsidence will bring challenges to the stable constructions of Hengli Island in the future.

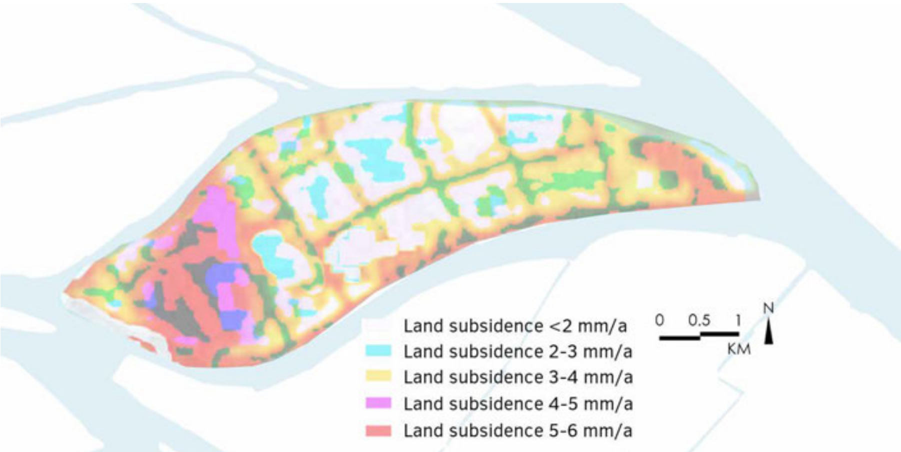


FIG. 5.8 The impact of land subsidence

TOC

C Land-use

The current land-use of Hengli Island is dominated by the rural landscape of semi-natural farmlands and fish ponds. In the future, it will become high-level urban areas. Figure 5.9 is a glimpse of Pearl Bay under construction. The evolution of land-use as well as its influence on the water system can be found in Appendix D-2.

FIG. 5.9 Glimpse of Pearl Bay under construction

5.4.2 Current water system

A Waterway

Figure 5.10 shows the main waterways which include Jiaomen Waterway, Shangheng Waterway, Xiaheng Waterway and Hongqili Waterway around Hengli Island. Waterways are important navigation channels that connect PRD's hinterlands and estuaries. The average width of Jiaomen Waterway is about 800 meters. The average width of Shangheng Waterway and Xiaheng Waterway is 300 meters. The length of Jiaomen Waterway is 16 kilometers and its exit gate is in Jiao estuary with two deep underwater grooves outside the estuary. One groove extends from the northwest to the southeast along the east of Wanqingsha in the south and forms South Longxue Waterway. Currently, Hongqi estuary is seriously blocked with low capacity of water discharge and navigation.

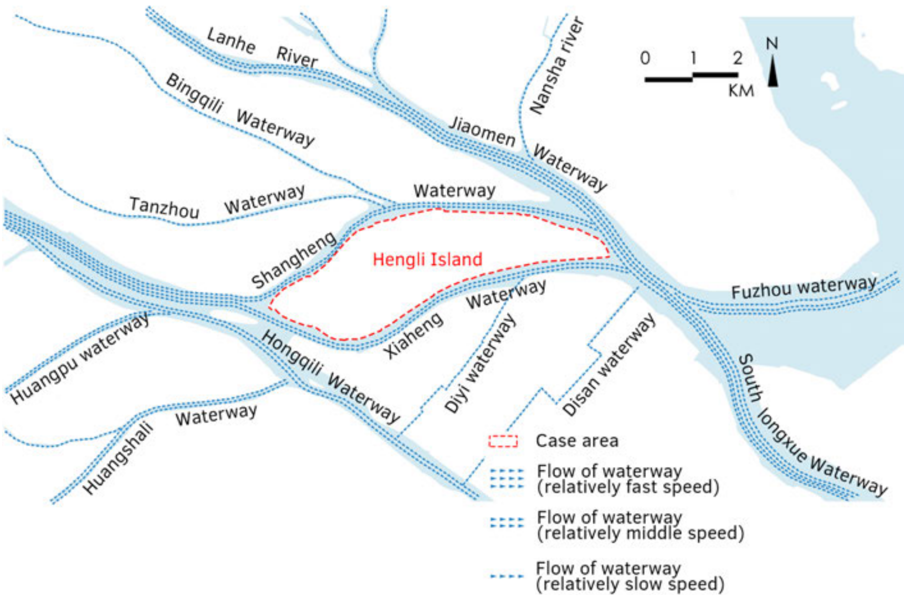


FIG. 5.10 Main waterways around Hengli Island

TOC

B Inner-rivers

Because of long-time 'mulberry- fishpond' agricultural production modes in the PRD, many inner-rivers and massive low-lying depressions exist. Figure 5.11 shows the inner-rivers with the direction of water flow. The total area of these inner-rivers is 0.78 square kilometers. The average elevation of the nearby dykes is 2.3 meters. Affected by the spatial distribution of elevation differences, the overall east-west water flow is bounded by Yisha inner-river. Water of inner-rivers in the west side flows to east, and water of inner-rivers in the east side flows to west. In the north-south direction, the water of overall inner-rivers flows from north to south. Currently, insufficient number of depth and width of inner-rivers leads to limited volume of water storage. Some parts of inner-river surface are artificially narrowed which causes bad water circulation.

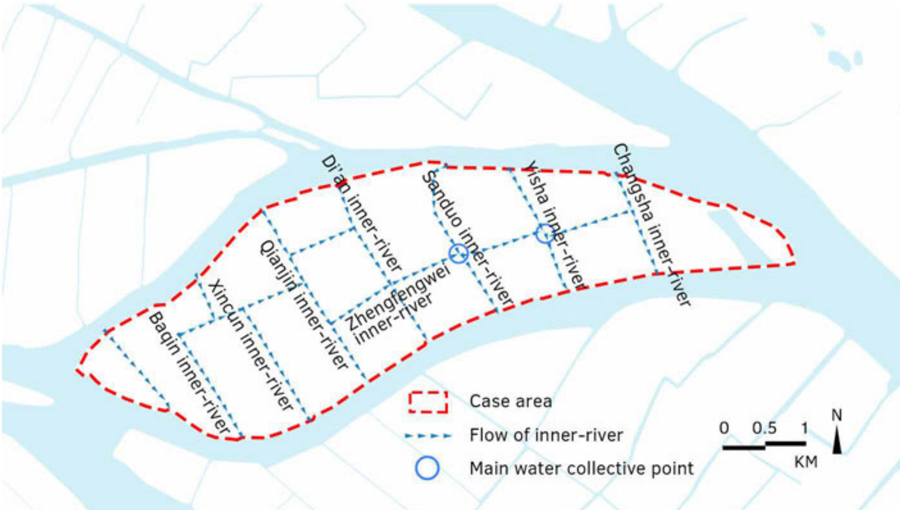


FIG. 5.11 Main inside inner-rivers

C Erosion (Sedimentation) analysis

Figure 5.12 shows the erosion (sedimentation) of waterways. Detailed data for supporting erosion (sedimentation) analysis can be found in Appendix D-3. For a long time, the erosion (sedimentation) effects have been changing the outline of the shoreline and affecting the construction condition of peripheral dykes. It can be found that Jiaomen Waterway was cut by an average of 2.7 meters, and the intersection of Jiaomen Waterway, Shangheng Waterway and Xiaheng Waterway (# 15, # 8) was deeply cut. Due to the construction of Jingzhu Expressway Bridge, section #9 of Shangheng Waterway had a larger cutting degree. Section #6 of Xiaheng Waterway had a large silting degree. It can be predicted that in the future Jiaomen Waterway and Shangheng Waterway will continue to be cut by increasing passing water and faster flow velocity. Affected by the bifurcation of the sedimentation of Hongqili waterway and Xiaheng Waterway, the Xiaheng Waterway may continue to be silted or to be cut by passing water. Continuous sway of waterways can have adverse effects on peripheral dykes which will not be conducive for flood resilience.

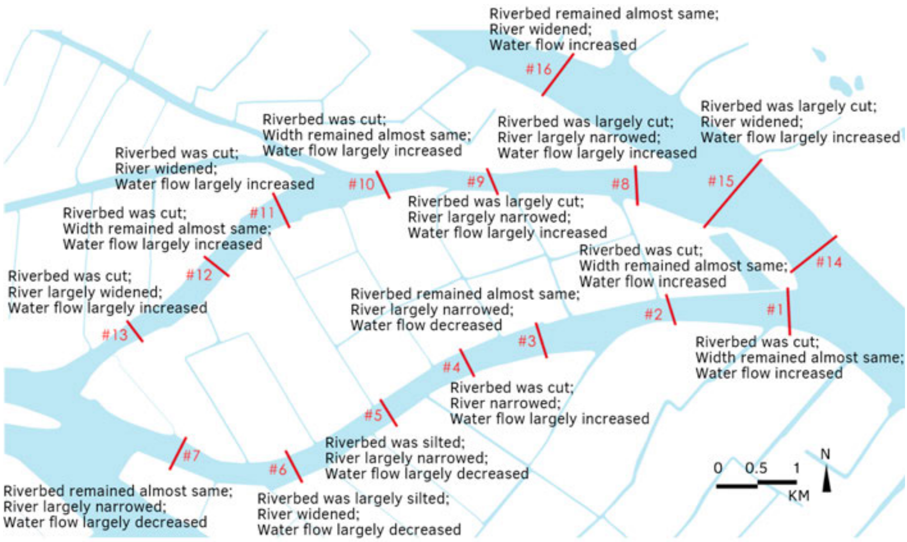


FIG. 5.12 The condition of sedimentation (erosion) of waterways

D The simulation of natural surface runoff

Potential natural surface runoffs will generate when the future precipitation exceeds soil's infiltration capacity. Natural surface runoffs will merge into the surrounding branches and eventually merge into a bigger water corridor. The 'source-confluence-flow' process of natural surface runoff is based on the terrain elevation, inner-rivers and waterways. A simulation is conducted for exploring main potential natural surface runoffs. Hundreds of natural surface runoffs and 48 potential important water points are discovered as shown in Figure 5.13. Natural surface runoffs can play important roles for shaping new water corridors and promoting smooth water circulation.

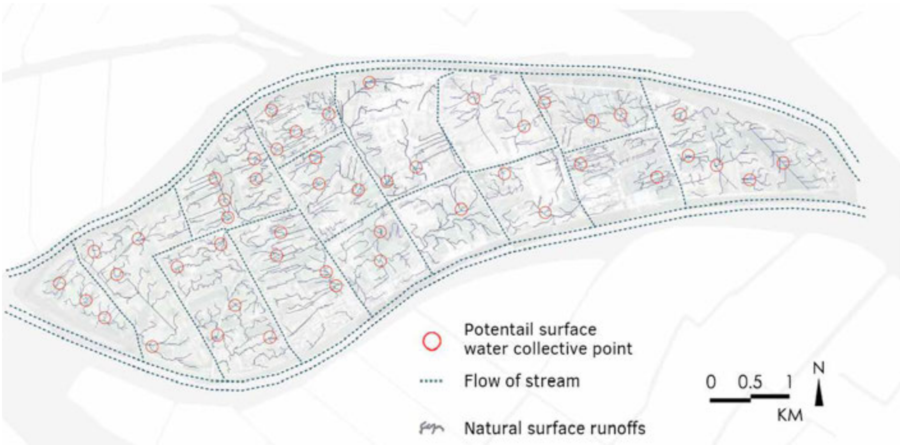


FIG. 5.13 Simulation of natural surface runoffs

TOC

5.4.3 Current Flood control and drainage system

A The situation of current water collective unit

Water collective unit is a place within certain natural boundaries for water storage, drainage and regulation. Figure 5.14 shows the current distribution of water collective units. According to the terrain conditions and inner-rivers, 15 water collective units can be divided. Detailed information for basic parameters and characteristics of each water collective unit can be found in Appendix D-4.

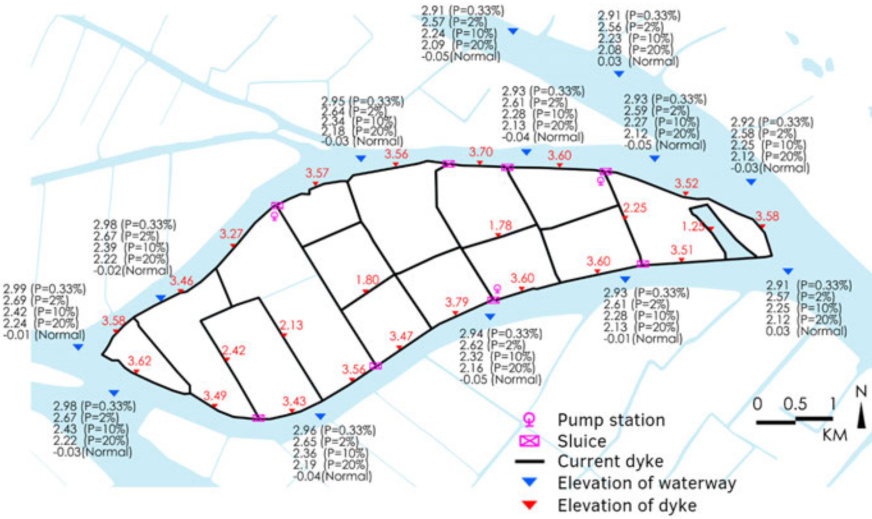
FIG. 5.14 The current distribution of water collective units

B The Current Status of Flood Control Infrastructure

The current flood control infrastructure consists of dykes, sluices and pumping stations. Figure 5.15 shows current flood control infrastructure and its corresponding technical parameters. At present, most of the peripheral dykes have heights between 3.2 ~3.8 meters and the widths between 5.0 ~ 7.0 meters. Most of dykes are made of sandy clay with turf slope protection on both sides. Parts of the dyke have a lower elevation with a thin dyke body that leads to a low ability to prevent floods and tides. At present, the inconsistent heights of dykes can cause a short-board effect and lead to a huge challenge. Figure 5.16 shows that under two situations, the relationship among the changing water level of outside waterways, inner-rivers and dykes' height are different.

1 Inner-river

2 Dyke

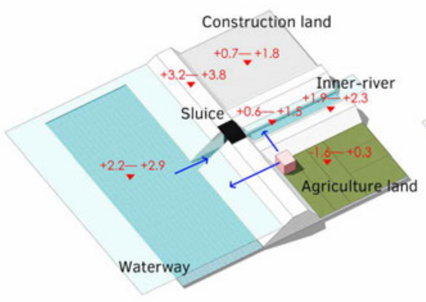


3 Current flood infrastructure

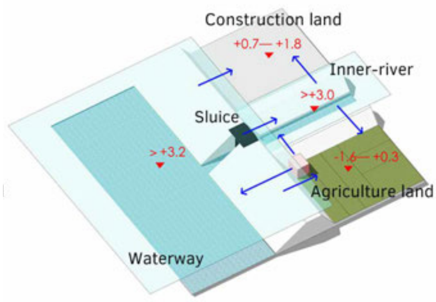
FIG. 5.15 Current flood control infrastructure and its corresponding technical parameters

Situation 1 is under the scenario of high tides that have 200 years recurrence period (P=0.5%). The water level of waterways is almost equal to the lowest point of the current peripheral dyke. When factors such as wave run-up and wind banked-up are overlapped with the height of high tide, the distances of 50 ~ 100 meters of lands near peripheral dykes will be invaded by water. Because the water level of waterways is higher than that of inner-rivers, all sluices are closed. The drainage task inside the dyke can only be realized by pumping stations that reduce the excessive water level of inner-rivers.

Situation 2 is under the overlapping scenario of both extreme high tides whose recurrence period is longer than 200 years (P=0.5%) and sea level rise. Because the water level of waterways is higher than the lowest point of current peripheral dyke, the high tide of the outside waterway will directly pass the dyke and cause large areas of lands to be flooded.



1 Situation 1: 200-year high tide



2 Situation 2: Sea level rise + 200-year high tide + Land subsidence

FIG. 5.16 Relationship between the changing water level of waterways, inner-rivers and dyke's height under two situations

C Current Status of Drainage Infrastructure

When heavy precipitation occurs, soils are often oversaturated because of the characters of the clay tidal muds. Infiltration of water through the soil becomes difficult. It can only flow into low-lying areas through natural surface runoffs and finally flow into adjacent inner-rivers. Due to the limited water storage capacity, waterlogging may occur when water level rise higher than the dykes on both sides of inner-rivers. On the one hand, sluices that connect waterways with inner-rivers should be closed. On the other hand, pumping stations should extract excessive water from the site into outside waterways. Sufficient capacity of water storage, sluices and pumping stations can exert a positive impact on flood resilience.

Currently, sluices and pumping stations are of outdated facilities, aging components and low construction standards. Water cannot be transported from inner-rivers into waterways on time. The standards of current sluices are not efficient enough to meet the requirements of waterlogged soil drainage during extreme climate condition.

5.4.4 Scenarios projection under extreme climate change

A Review of Historical Highest Flood in 2018

In 2018, typhoon ‘Shanzhu’ crossed. The precipitation in 24 hours was 250.1 mm, and the cross-section water velocity reached 12 m/s. The water level of waterway caused by typhoon ‘Shanzhu’ was equal to the lowest point of dyke and exceeded the elevation of the site by 1.96 ~ 2.16 meters. Typhoon ‘Shanzhu’ caused the highest tide in history. The flooded areas accounted for 31.6% of the total size of the island with more than 2 meters of water depth. A simulation is conducted for ‘representing’ this impact on the site based on the situation of the current dyke. Figure 5.17 represents the outcomes.

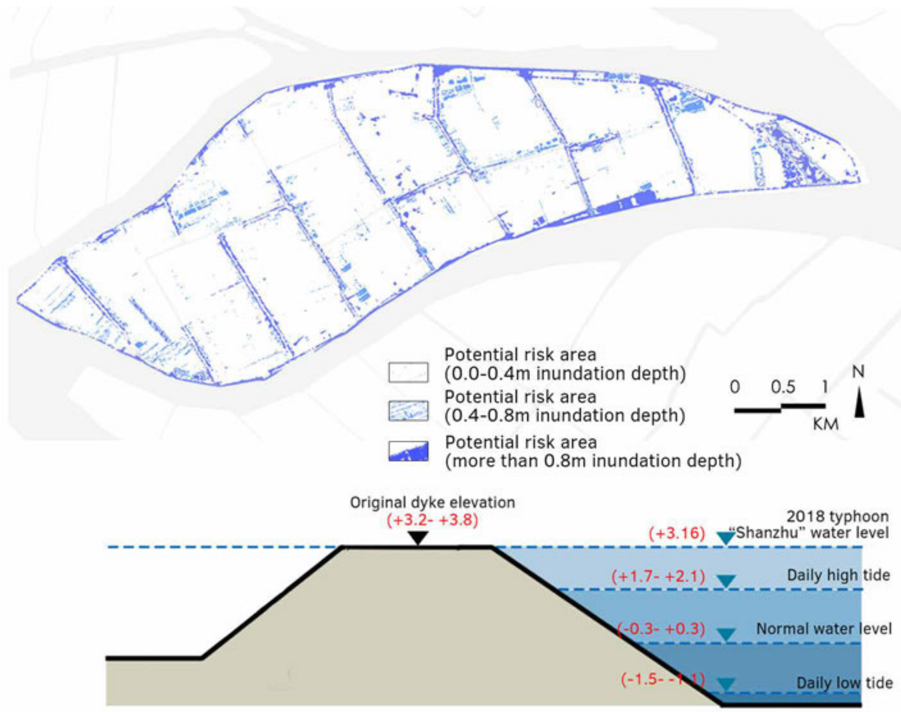


FIG. 5.17 The simulation of flooded areas under current flood control and drainage system when Typhoon ‘Shanzhu’ occurs

It can be seen from figure 5.17 that if the current dyke and flood control and drainage system will not be changed, a large area will be flooded in the Island. If the heights of wave run-up and wind banked-up tides are overlapped, 33.7% of the size of the Island will be flooded. The simulation result is consistent with the actual situation of the real flood disaster that occured in 2018.

B Projection of sea level rise and high tide

The site is a ‘bowl-shaped plain’ surrounded by multiple waterways. The water levels of waterways are not only affected by the fluvial influence from the West River, the North River and their corresponding branches and tributaries on the upstream of the PRD, but also by the tidal influence of Hu estuary and Jiao estuary on the downstream.

When the flood comes from both upstream and the estuaries, the water level of outside waterway often gets higher than the elevation of the site. Because the riverbeds of Jiaomen Waterway and Shangheng Waterway were seriously cut, it has led to increasing passing water volumes and 0.3 meter water level rise in the past 60 years. It can be predicted that when fluvial flood and tidal surge overlap, the water level will exceed the height of the dyke. Figure 5.18 shows the predicted water level of different high tide scenarios with different cumulative frequencies. Appendix D-5 shows the water level of outside waterways from 1950s to 2010s in details.

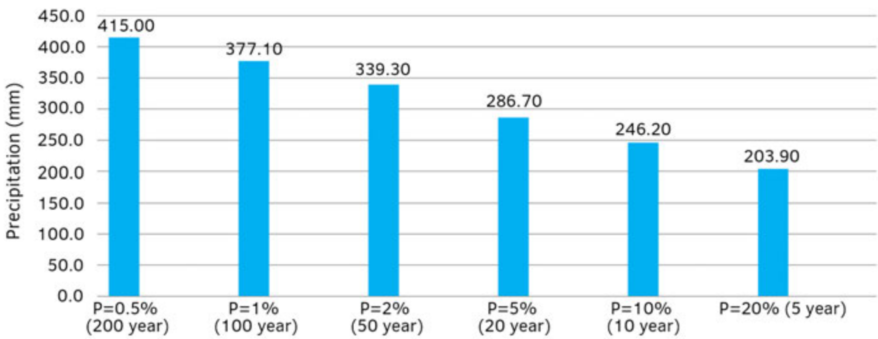


FIG. 5.18 The projection of max daily precipitation under different climate scenarios

Sea level rise near PRD is higher than 100 millimeters during the period between 1980 and 2011. It is estimated that the sea level of Pearl River Estuary will rise to 0.25 meters in 2100 under moderate climate change and to 0.50 meters in 2100 under extreme climate change. Figure 5.19 simulates the flooding areas on the site under the overlapping influences caused by both sea level rise and 200-year (P = 0.5%) high tide.

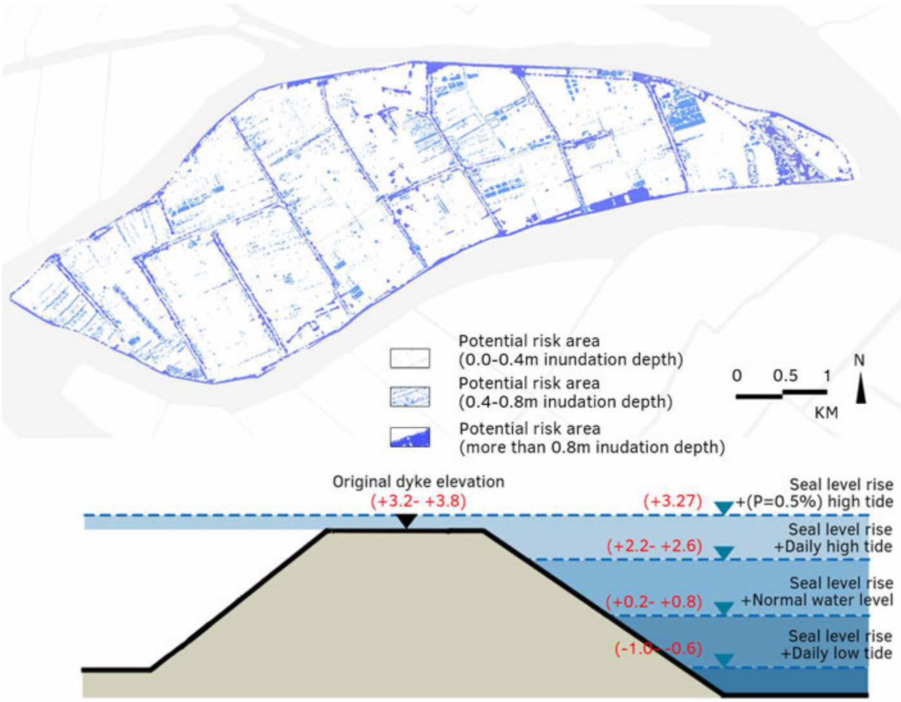


FIG. 5.19 The simulation of flooded areas under current flood control and drainage system when overlapping influences caused by both sea level rise and 200-year high tide

5.5 Pre-evaluation for flood control and drainage

5.5.1 Storage of water collective unit

Uncertain extraordinary rainstorms can be a serious disturbance for future urbanization of Hengli Island. It is necessary to analyze the gaps between current water storage and future requirement. From 1981 to 2017, the years when maximum daily precipitation exceeded 210 mm were respectively; 1983, 1989, 1999 and 2010.

According to 'contour map of heavy precipitation parameters for planning and design', 50-year heavy precipitation in 24 hours is estimated to be 339.3 mm. 100-year heavy precipitation in 24 hours is estimated to be 377.1 mm. 200-year heavy precipitation in 24 hours is estimated to be 415.0 mm. Meanwhile, urbanization will further affect the underlying surfaces of the land and influence the process of infiltration. Figure 5.20 shows the number of gaps between current water storage capacity and future requirements in each water collective unit under the scenarios of 50% and 80% urbanization respectively. Detailed calculation methods can be found in Appendix D-6.

The analysis of water storage capacity of each water collective unit can guide spatial planning and design for resilient flood control and drainage. The capacity of the water storage of the current water system is insufficient such that the excessive water cannot effectively flow into its adjacent outside waterways. Due to the current spatial distribution of inner-rivers, the size of each water collective unit is too large. In order to respond to this situation, current water collective units should be divided into some smaller pieces to reduce the distances from waterlogging points to adjacent water bodies. By increasing the volume of original inner-rivers, the capacity of water storage can be largely increased in the whole Hengli Island. Through decentralized and modular water collective units, the peak runoff speed in each water collective unit can be controlled.

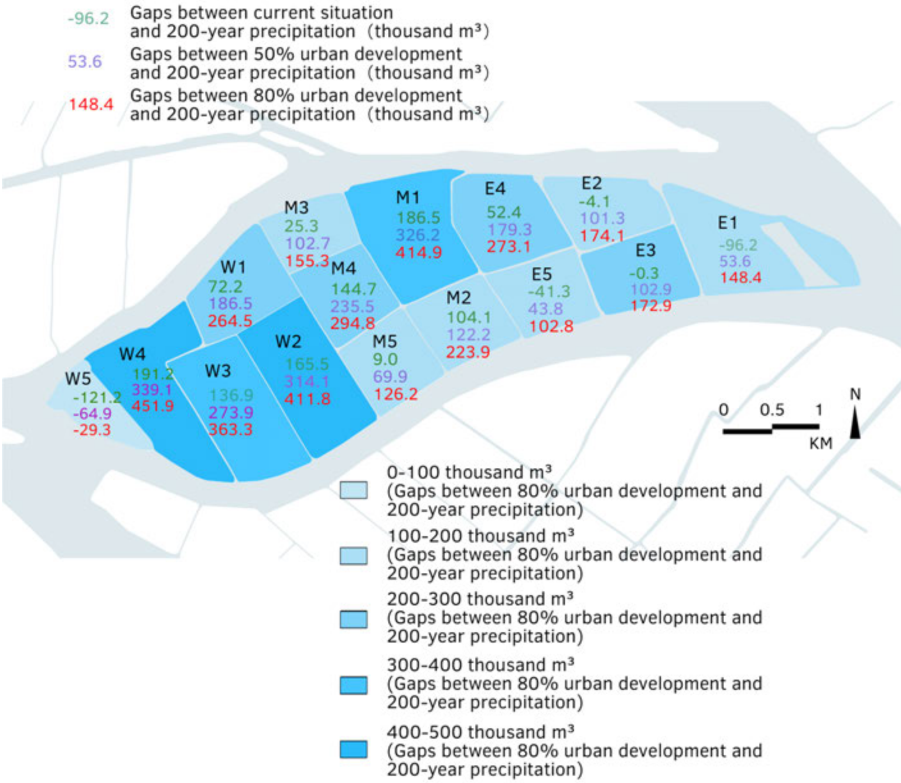


FIG. 5.20 The number of gaps between future precipitation and capacity of water storage in each water collective unit
(Note: The number of gap = future precipitation- the capacity of water storage).

5.5.2 Relative Elements of flood control and drainage

The potential elements to be organized in spatial planning and design for resilient flood control and drainage are shown in Figure 5.21. The rational utilizations of these elements can be the basis for improving flood resilience. Lands with higher elevation can provide good foundations for important blocks/ emergency routes. Lands with lower elevation can be used as potential depressions to store excessive water. Tidal flats on riverbeds outside dykes can contribute to resilient flood control, waterlogging reduction and peak discharge regulation. Beautiful landscape resource can be utilized to provide good spatial quality for leisure and tourism. The dyke with corresponding shapes should be distributed based on the understanding of the terrain conditions of different shoreline segments.

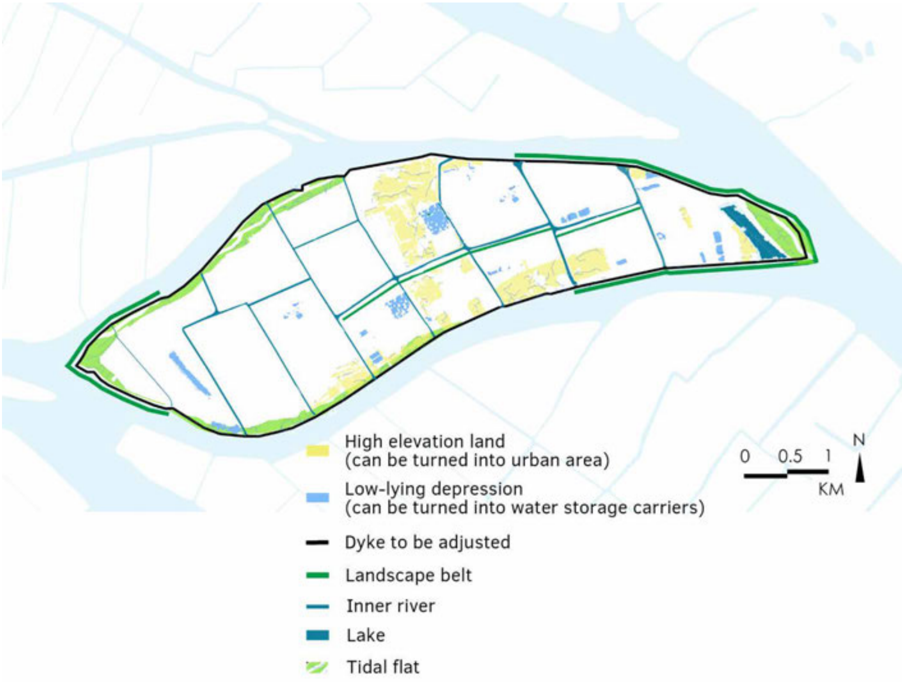


FIG. 5.21 Potential elements to be organized for flood control and drainage

5.5.3 Shoreline features

For organizing appropriate spatial elements, it is necessary to understand terrain conditions of each shoreline conditions and assess land-use suitability. Figure 5.22 shows the evaluations of the condition of each shoreline segments. Factors such as the flood control requirements, land subsidence situation, sedimentation, slope, landscape, and reserved land can function as guides for redundant, diversified and multifunctional waterfront landscape and dyke construction. Detailed assessment indicators for shoreline condition can be found in Appendix D-7. Figure 5.23 shows the probability-of-occurrence of urban area, which overlaps indicators such as slope, elevation, surface water, underground water, traffic elements.

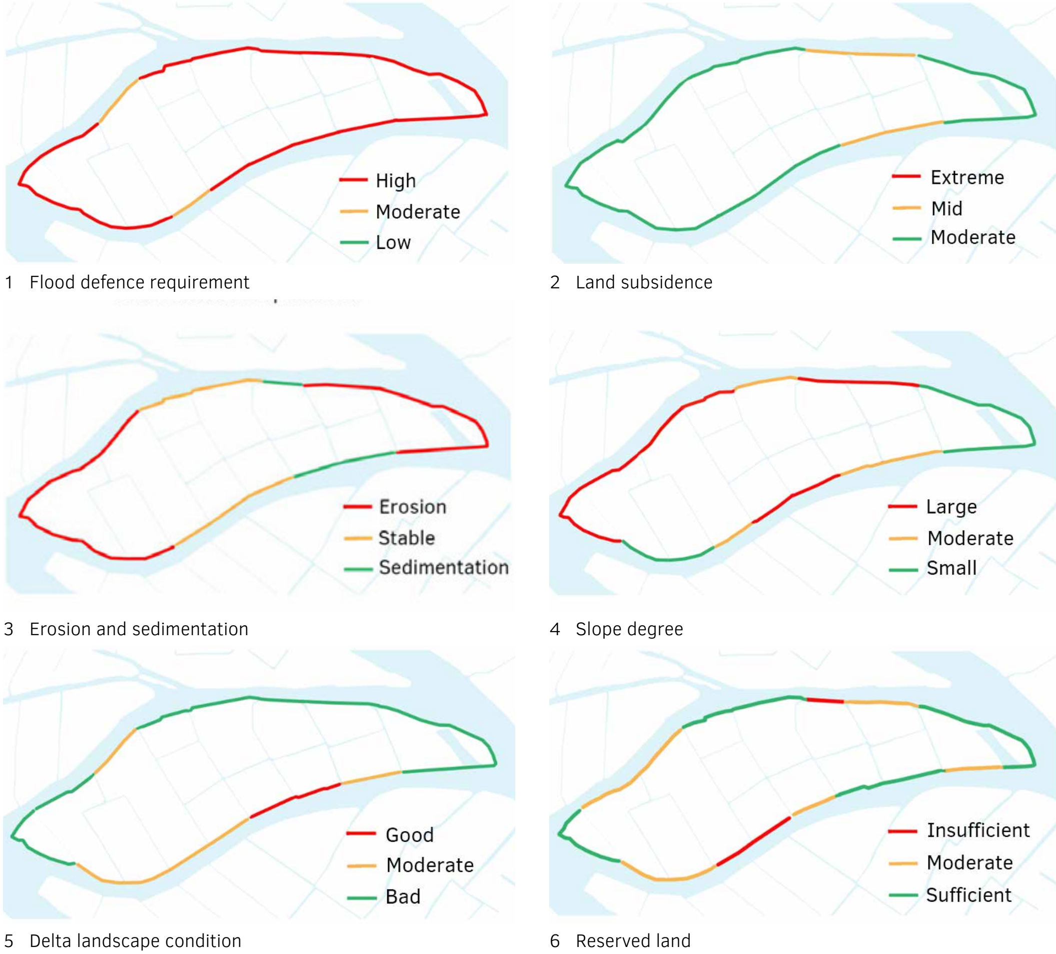


FIG. 5.22 The feature evaluation of shoreline

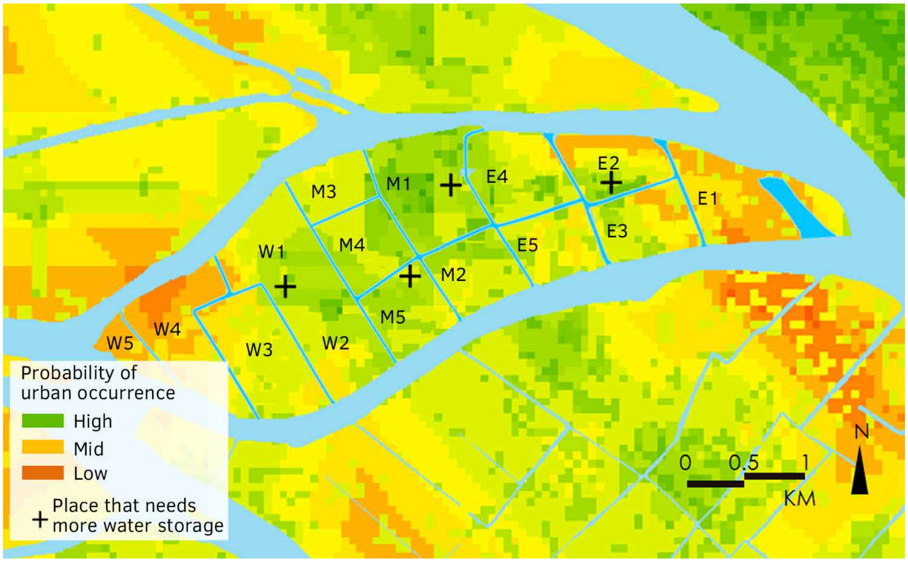


FIG. 5.23 Probability-of occurrence of urban area

5.6 Main challenges of flood control and drainage under extreme climate change condition

According to previous simulations and evaluations, it can be found that there are gaps between current situation of flood control and drainage and future requirement under extreme climate change conditions.

— There are large gaps between dyke's height and water level under extreme climate conditions. At present, inconsistent peripheral dykes' height can only defend 50-year flood. The water level brought by 2018 typhoon 'Shanzhu' has already reached to the lowest point of dykes. If multiple factors such as sea level rise, 200-year high tide, land subsidence, wave run-up and wind banked-up tides are considered, the existing dyke needs to be heightened based on preliminary calculation.

- There are large gaps between current water storage and future precipitation. The size of current water collective unit is too large which creates long distances between potential waterlogging points and adjacent waterways. With further urbanization, it is certain that the gap will increase greatly because the underlying surfaces will be hardened with decreased amount of natural surface and the lowered capacity of soil infiltration.

- The standards of sluices and pumping stations are not efficient enough. Besides potential spatial elements to be considered for organization, sluices and pumping stations are important facilities that can connect waterways and inner-rivers. Currently, sluices' and pumping stations' standards are only consistent with the requirements of agricultural lands, which cannot contribute to future situation of a socio-economic headquarters center.

- It implies that water collective units of West 2, West 3, Mid 1 and East 4 of figure 5.23 require larger water storage carriers to support future urban lands.

5.7 Principles and strategies for resilient flood drainage

5.7.1 Application guidance of resilient spatial characteristics in flood drainage

Faced with future extreme climate change and site conditions, spatial planning and design for resilient flood drainage has great practical significance. The main spatial characteristics of resilience presented by planning and design such as regionality, network, diversity, multifunctionality, redundancy and modularization should be widely applied to improve the robustness and adaptability of current flood drainage systems. Figure 5.24 is the technical route for resilient flood drainage.

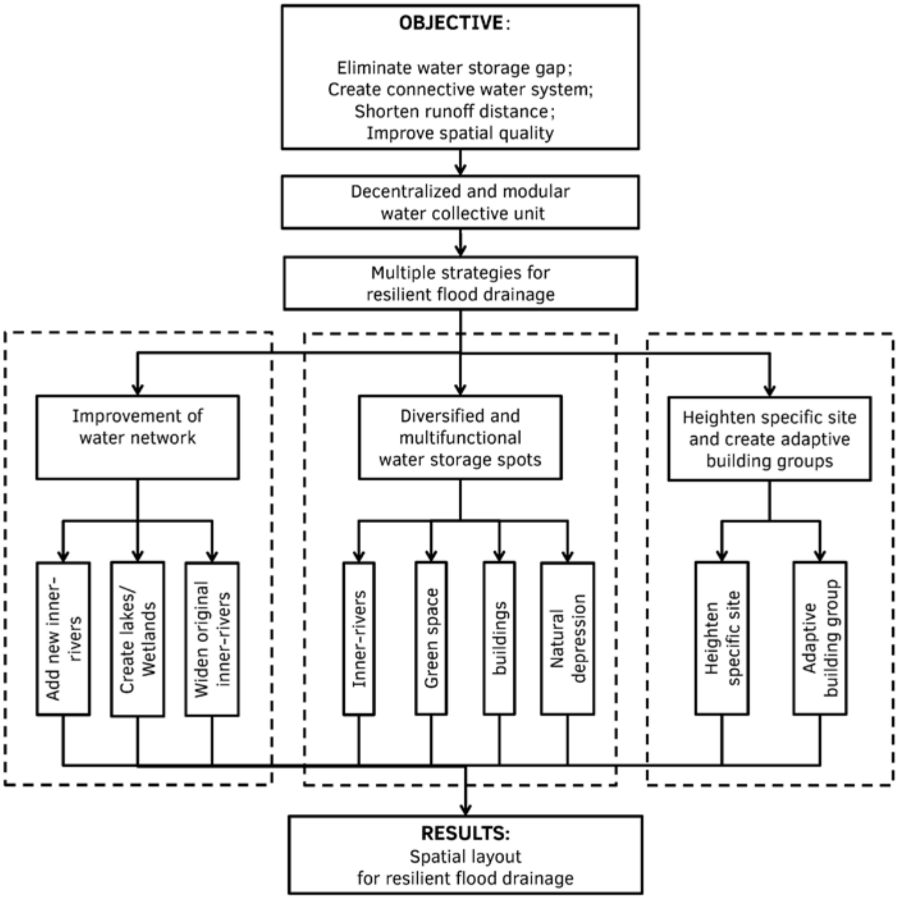


FIG. 5.24 Technical route for resilient flood drainage

- The application of rationality refers to comprehensively considering the factors such as elevation, water level, dyke heights and considering the assessment results of land-use suitability, water flow and water circulation.

- The application of connectivity refers to improving current water networks which consist of inner-rivers, regulation lakes, wetlands and low-lying depressions. It is necessary to increase network density and network connectivity to increase water storage. On the one hand, by transforming the existing inner-rivers, lakes, wetlands and underground water bodies, the original water networks can be increased to expand the water storage. On the other hand, through the reconstruction of water networks, the necessary inner-rivers and other water retention bodies for accommodation can be added, and some closed water surfaces can be set up as storage areas near residential areas and industrial parks. New networked water systems can provide function for strengthening the spatial connectivity that transports excessive water from each catchment unit to adjacent water bodies and outside waterways.

- The application of modularization refers to dividing existing water collective units from a centralized model to a decentralized model in order to disperse flood risk. According to water storage gaps, the centralized water collective units need to be changed to decentralized and modular water collective units. According to new distributed water collective units, the distance from each potential waterlogging point to adjacent water bodies can be reduced, for improving smoother water circulation.

- The application of redundancy refers to buffer spaces along the shoreline and the creation of tidal plats to reduce the impact of Shengheng waterway and Xiaheng waterway. Before the extreme precipitation occurs, the water level of inner-rivers can be lowered below the normal water level in order to further increase the water storage capacity.

- The application of multifunctionality refers to specific classification of inner-rivers based on the surrounding site's characters. It is important to combine flood safety with irrigation, landscape-viewing, navigation and social communication.

- The application of diversity refers to diversified water level adjustment with regulation, self-drainage and artificial extraction. Regulation is the storage of excessive water with inner-rivers, low-lying depression, lakes, wetlands to prevent flooding and waterlogging. Self-drainage refers to letting excessive water be automatically self-discharged to waterways by using the principles of elevation difference. Artificial-extraction is to extract excessive water from inner-rivers with low water level to waterways with high water level. The water from inner-rivers can be extracted by using pumps to reduce the water level and prevent potential waterlogging. Through the combination of regulation, self-drainage, and artificial-extraction, the principle of diversity can be applied into space.

5.7.2 Decentralized and modular water collective unit

The objectives of arranging new water collective units for realizing resilient flood drainage is to eliminate the water storage gaps and shorten the distances between potential waterlogging points and adjacent water bodies. The spatial outcome is based on territorial understanding of topography, flow, land-use function, and potential applied spatial elements for public space and water accommodation. The purpose for setting new modular water collective units is to change original water collective units from fragmented pattern to networked pattern. By using ArcGIS hydrological toolbox, after several rounds of simulations and manual revisions, new decentralized and modular water collective units are finally proposed, which consist of 48 new water collective units shown as in figure 5.25.

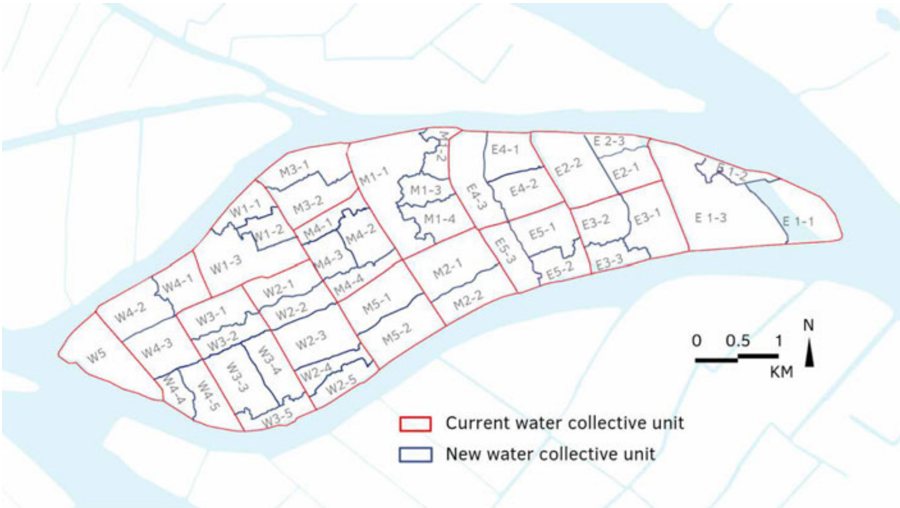


FIG. 5.25 Division of new water collective units (units)

5.7.3 Improvement of water network

Improvement of the water network aims to reconstruct water systems based on new decentralized and modular water collective units and potential spatial elements such as natural surface runoffs, new branches, lakes and nourished wetlands. The capacity of water storage can be increased by opening up new connective inner-rivers and ditches. Excessive water can flow to adjacent inner-rivers in time through both rainwater pipelines and natural surface runoffs with less than an 800- meter distance, which can prevent the accumulation of water on the way. According to the characteristics of original terrain conditions, large water bodies such as natural and artificial lakes, nourished wetlands, and buffering areas on both sides of inner-rivers are suggested to increase the total capacity of water storage.

Figure 5.26 presents the scheme of improved water networks with new connected inner-rivers and opened up water accommodations such as nourished wetlands and lakes. The new water system can greatly improve the capacity of water storage by increasing density and connectivity. When digging new inner-rivers, it is important to maintain water branch corridors and capillary corridors at all levels as much as possible. According to the distribution of new water collective units, existing inner-rivers and low-lying depressions can be used as links to connect new branches and ditches to form a new multi-level water networks and reduce the distances for water transportation.

It can be seen from the figure 5.26 that the entire water system has formed a highly connected network to increase water storage. The scheme strengthens the connectivity of rivers by digging new water channels to make the whole system more robust. The capacity of original inner-rivers like STUVWX shown in figure 5.26 is greatly increased by widening its width and deepening its depth. New inner-rivers such as IRS, XY shown in figure 5.26 are also dug. IRSTUVWXY becomes a new axis of inner-river shown in figure 5.26. It can not only provide the sufficient water storage for the nearly 10 decentralized water collective units, but also forms a golden tourist route. New east-west central waterways can be used as main spatial axis of water networks and play a role in integrating functions of flood control, landscape-viewing and tourism.

Three artificial lakes with a total water surface area of 1.35 square kilometers are set near the main inner-rivers to further enhance the capacity of water storage based on the terrain condition and future land-use function. Lakes are connected with main waterways. In addition, two new wetlands in the low-lying areas have been added in advance as a reserve for future extreme precipitation. At ordinary times, new wetlands can be used to improve the spatial quality of the whole area. When extreme precipitation occurs, new wetlands can supply additional water shortage capacity. Assisted by the dynamic water level, the tidal flats of outside shoreline segments such as EFGHIJKLMN, YA shown in figure 5.26 are used to build natural parks to buffer the serious impact of waterways under extreme climate condition. All redundant space such as artificial lakes, nourished wetland and tidal flats and other spaces together enhance the degree of adaptability to future extreme precipitation. They not only supplement the limited water storage capacity of old water networks but also greatly improve the spatial quality of future public space for citizens.

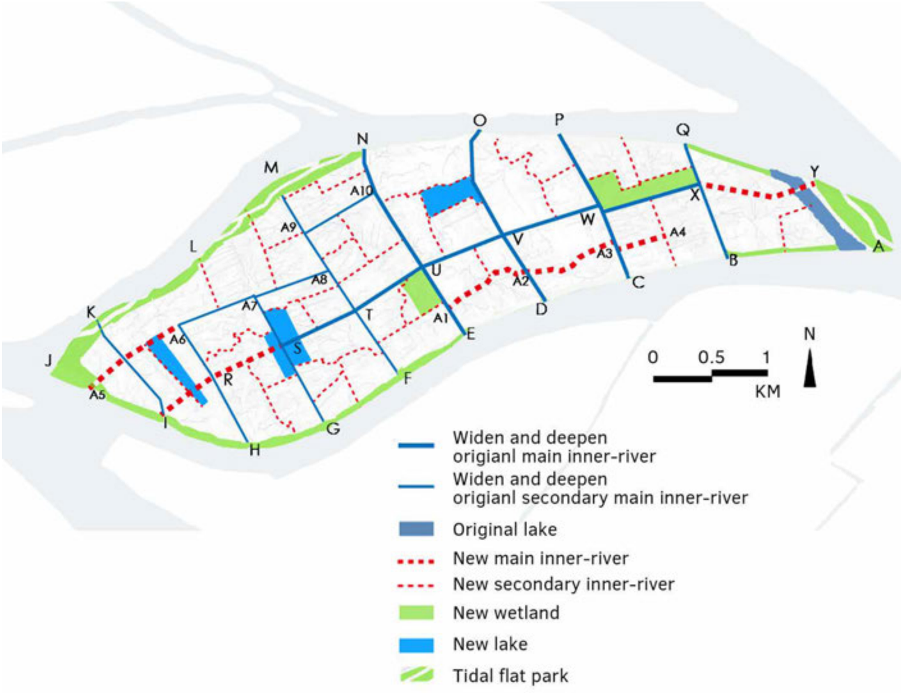


FIG. 5.26 Improved water networks with new connected inner-rivers and water accommodation

5.7.4 Classification of functions for inner-rivers based on site characteristics

Inner-rivers are dominated elements for composing systems and can function as backbone structures for future urbanized areas. Therefore, besides the main function of water storage, these inner-rivers should also become multifunctional. According to the different surrounding environment, future positioning and the assessment results of land-use suitability of each block and the classification of functions for inner-rivers based on site characteristics is necessary.

— Class-A is a type of inner-rivers which are the main corridors for flood control and drainage with both strong water storage capacity and sufficient landscape resources. According to the results of pre-evaluation of spatial organization in previous section, inner –rivers such as IRSTUVWXY, NUE, OVD, QXB shown in figure 5.26 are defined as Class-A waterways. For any Class-A waterway, it is necessary to integrate multiple functions of flood control and drainage, landscape, leisure, tourism and navigation.

TOC

Plant-grown stone masonry revetment and plant-grown concrete block revetment can be selected. Natural slopes can also be used in shoreline sections with slower water flow speed.

- Class-B is a kind of inner-rivers which are mainly for transportation. In this case, inner-rivers such as MTF, A1A2A3A4, A5A6A7A8 and A9A10 shown in figure 5.26 are defined as Class-B, which is advisable to adopt hydro-ecological revetment forms with certain strength materials, such as mesh pad vegetation composite revetment, frame-cover soil composite revetment, plant-prototype block stone frame revetment, and stone cage ecological retaining walls. Pure natural soil slopes are not suggested for use in high –level urban areas.

- Class-C is a type of inner-rivers which are mainly for drainage and irrigative carriers. Class-C is mostly in the form of independent loops with small radiuses. In this case, all the rest new inner-rivers except class-A and class-B shown in figure 5.26 are defined as Class-C. It is advisable to adopt natural material revetment forms such as aquatic plant revetment, timber revetment, stone-revetment, rock fill revetment and gabion water reclaimed composite revetment. Slope dyke surface can be planted with local vegetation grass and trees. Non-planted hard dykes and full-section lining should be avoided.

In addition to above measurements, buffering areas are suggested to be arranged according to the above classified functions. They are usually used as landscape-viewing leisure places for citizens and as water retention areas when extreme precipitation occurs. The width of buffering areas on both sides of the Class-A should not be less than 40 meters, width of buffering areas on both sides of Class-B not less than 30 meters and width of buffering areas on both sides of Class-C not less than 20 meters. Permanent construction is strictly prohibited inside the buffering area.

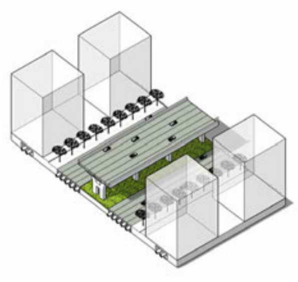
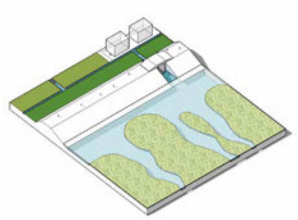
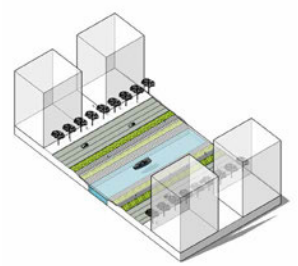
5.7.5 Diversified and multifunctional water storage spots

The capacity of water storage can be increased by expanding the volume of inner-rivers. However, it is still necessary to take diversified and multifunctional measures for creating water storage spots. The actions of storage, dredging and utilization of excessive water can be realized with the assistance of potential spatial carriers such as public space, parks, fish-ponds and floodable areas.

Table 5.1 represents some diversified and multifunctional measurements for water storage and utilization in important elements.

TOC

TABLE 5.1 Diversified and multifunctional water storage spots

Items	Measurement
 Water storage and utilization from road element	– Water- permeable materials should be used for road covering such as porous grass-bricks, gravel pavements, and permeable concrete. Water-permeable pavement materials should also be used on pedestrian, community roads, squares, parking lots. – Coordinate the elevation relationship between the road and the surrounding green space to create smooth rainwater flow. The elevation of the water-permeable pavement needs to be higher than its surrounding space. – The outlet of water overflow should be set at the junction of roads, or between roads and surrounding space. – The road surface can be used as water pathways so that the runoff rainwater which is generated on the impermeable pavement surface flows into the green space in the middle of the road and infiltrates. After the green space is saturated with water, water can flow to the outlet of water overflow.
 Water storage and utilization from natural depressions and floodable areas	– Apply potential natural depressions for water storage due to its original low-lying characters
 Water storage and utilization from inner-rivers	– Inner-rivers should be widened and deepened in order to increase capacity. Use climate forecast to pre-descend water level of the inner-river before huge precipitation occurs – Coordinate the elevation relationship between inner-river and the surrounding green space to create smooth rainwater flow. – The slope of inner-river needs to be reduced in order to slow down the speed of peak discharge

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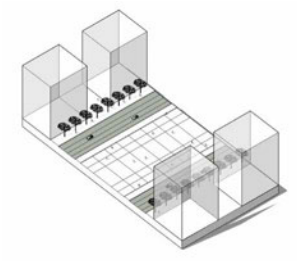
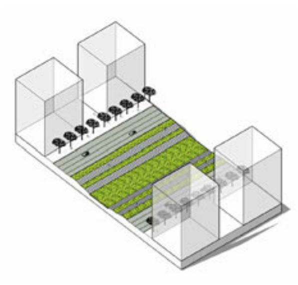
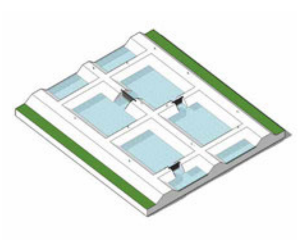
TOC

TABLE 5.1 Diversified and multifunctional water storage spots

Items	Measurement
 Water storage and utilization from square	– Apply water- permeable materials and drain surrounding green space. – Consider terrain height difference in setting out square – Rainwater guide troughs and ponds should be constructed in the surrounding square – During normal days, public space can be used for recreation and entertainment. During moderate precipitation, the water in the square can flow into the pond though troughs and forms natural water feature. During extreme precipitation, the square can be used as a water storage place
 Water storage and utilization from green space	– Green space should be developed in order to store and infiltrate water. Adding water storage layers and permeable layers between the plants and the soil can slow down the peak runoff speed. – Set up ecological treatments for green space and guide purified infiltrated water into the rainwater reuse system. – Recycle water resources for greening, spraying and irrigating plants in green space.
 Water storage and utilization from fishponds	– Coordinate the height difference between the fish-pond and the surrounding shoreline to ensure that the water level of the fish pond is always lower than the surrounding site. – Utilize the terrain height difference and the potential natural surface runoffs to maintain the water connection between the fish-ponds. – Put sand into the bed of fish-ponds, and use the adsorption function of the surrounding vegetation, to nourish and maintain the fish - ponds during the rainstorm.

5.7.6 Adaptive building Groups

The thesis proposes by applying the above-mentioned measures such as improved water network, classification of inner-rivers, adding diversified and multifunctional water storage, the degree of spatial resilience for flood control and drainage can be greatly improved. For special land-use such as emergency routes, evacuation plots and important blocks, the standards for flood control and drainage can be further improved in order to meet the requirement of redundancy by ground filling to increase the elevation of land.

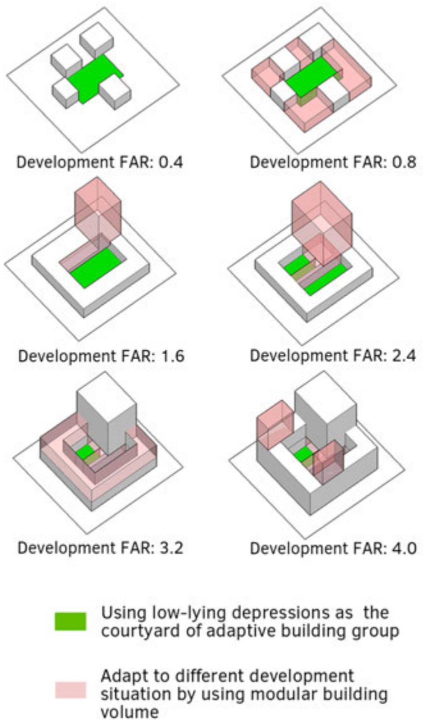


FIG. 5.27 Adaptive building groups by using low-lying depressions as middle courtyard and modular building volume

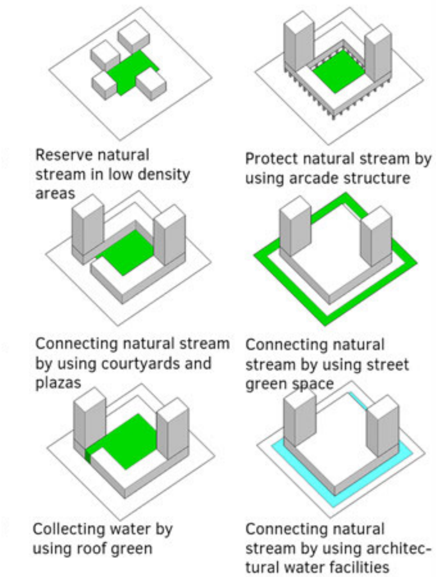


FIG. 5.28 Maintain important site water circulations by using multiple construction methods

In addition, it is advocated that modular building blocks can adapt to the characteristics of low-lying land. It is shown in Figure 5.27 that in each micro water collective units, it is important to reserve a certain area of low-lying land as water storage points and public space. The modular building blocks can be built around it.

The spatial layout of the building group conforms to the original natural runoff texture in the site. The building groups can be developed with appropriate density to provide buffering space for further development.

As seen in Figure 5.28, if there are no natural low-lying lands, the reserved space can be combined with the building plaza, street green space, arcade space, roof greening, and water around building to connect water runoffs between important nodes to maintain the integrity of the site blue-green corridor. Buildings need to respect the surface and underground water system by adjusting to overhead buildings or arcade.

5.8 Principles and strategies for resilient flood control

5.8.1 Application guidance of resilient spatial characteristics in flood control

The flood control should fully highlight the regional natural characteristics. The influence of tides can be reduced by increasing the height of the dyke, and the buffering distance between buildings and shoreline. Based on prevention strategies, multiple protective measures can be adopted to reduce the probability of tidal influence. According to the functional characteristics and terrain conditions of different shorelines, a diversified and modular approach can be taken to shape a new dyke system. It is necessary to consider coastal resources and organically integrate the flooding defense function, landscape-viewing function and urban service function, to improve harmonious relationship among human, urban and water relationship. Figure 5.29 is the technical route for resilient flood prevention.

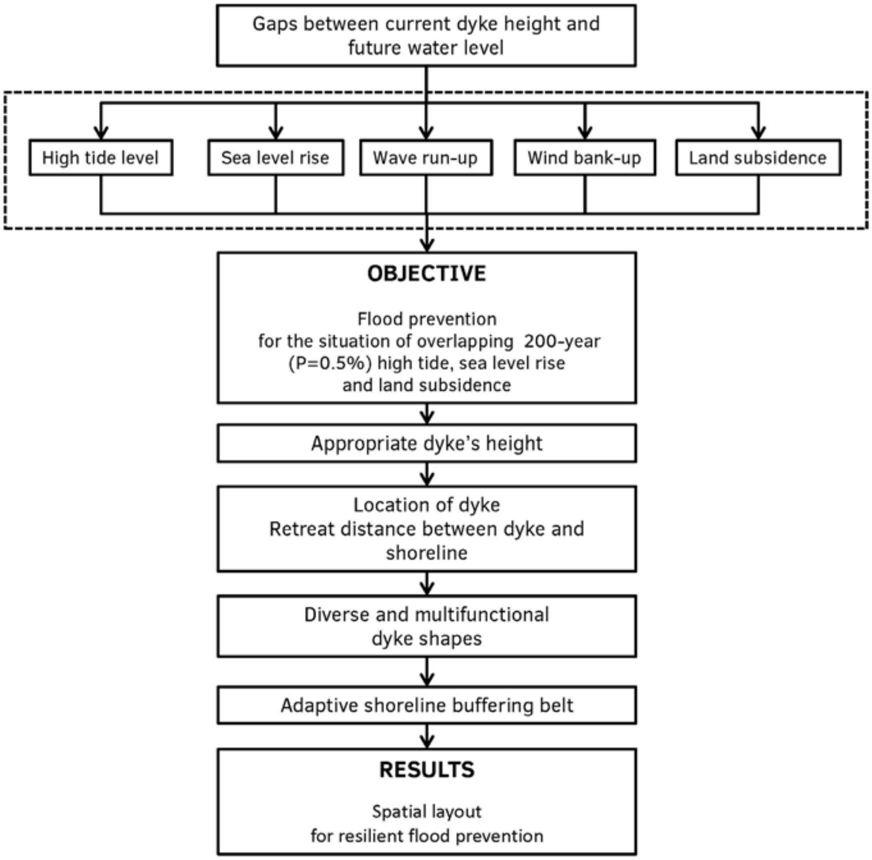


FIG. 5.29 Technic route for resilient flood prevention

- The application of redundancy refers to measures such as providing appropriate height of dykes, creating reasonable buffering areas and setting adaptive shoreline buffering belts. The influence of tides can be reduced in order to ensure the spatial safety and landscape-viewing under extreme climate change conditions.

- The application of regionality and diversity refers to comprehensively understanding spatial characteristics of each shoreline segment and applying different cross-section dyke shapes based on the difference of functional characteristics and terrain conditions in each shoreline segment.

— The application of multifunctionality refers to adaptive shoreline buffering belts that can connect different cross-section dyke shapes and can be used as a landscape belt on a normal day and function as floodable space under extreme climate condition.

5.8.2 Appropriate height of dyke

The dyke is the first barrier to prevent tidal influence under the situation of extreme climate change. The core parameter of dyke is its height. Therefore, the key mission of the resilient flood control for dyke is that the height of dyke must attain a certain level to resist potential negative impacts caused by tidal influence and rising sea level.

For the height of future dykes, several factors have to be taken into consideration such as the height of extreme high tide, sea level rise, wave run-up tide, wind banked-up tide, land subsidence and height for safety redundancy. Meanwhile, it should be allowed that small amount of water by wave can partially overflow dykes if water can be later absorbed by sufficient well-prepared buffering areas on the site and can avoid flooding. Based on the above factors, the appropriate height of dyke to prevent 200-year tidal influence can be determined as shown in Figure 5.30. The height of dykes can be adapted to more extreme climate change with certain safety redundancy. Appendix D-8 shows the detailed calculation process for the appropriate height of dykes in detail.

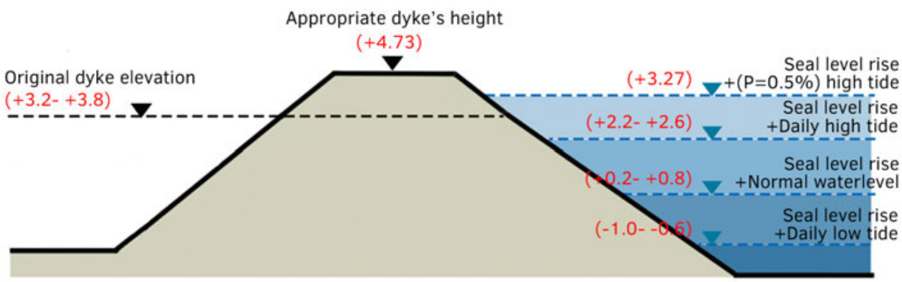
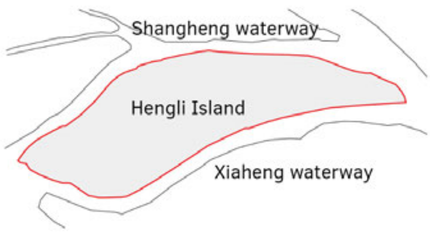


FIG. 5.30 Appropriate height of dyke

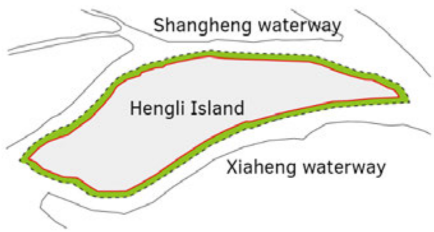
5.8.3 Appropriate distance between dyke and shoreline

After providing appropriate height of dykes, then the question that remains is, where can dykes be established to increase spatial resilience? There are two proposals to be chosen, as shown in figure 5.31. Proposal 1 is that the dyke is constructed directly next to the shoreline. Proposal 2 is that the dyke is retreated some distances from the shoreline. Because the appropriate height of a new dyke is higher than the elevation of the site surface, proposal 1 may hinder landscape-viewing. Proposal 2 can reduce the negative effects of proposal 1. The space provided by shoreline retreating can be used as buffering areas. When extreme flooding occurs, the approach of shoreline retreating can be benefit to the expansion of flooding redundancy and increasing width of outside waterways, which is helpful in reducing the water level of outside waterway. In addition, well-prepared buffering areas can be built into multifunctional leisure parks, as well as serve to absorb occasionally overflowing waves.

However, proposal 2 sacrifices a certain size of valuable construction lands. Figure 5.32 shows relationship between the retreated distances and decreased water level of waterways. Appendix D-9 shows the method of calculations in details. After calculations and simulations, a 70-meter distance is selected on both the front and the back part of the Hengli Island.



1 Proposal 1: No retreat distance between dyke and shoreline



2 Proposal 2: leaving some retreat distance between dyke and shoreline

FIG. 5.31 Two proposals

TOC

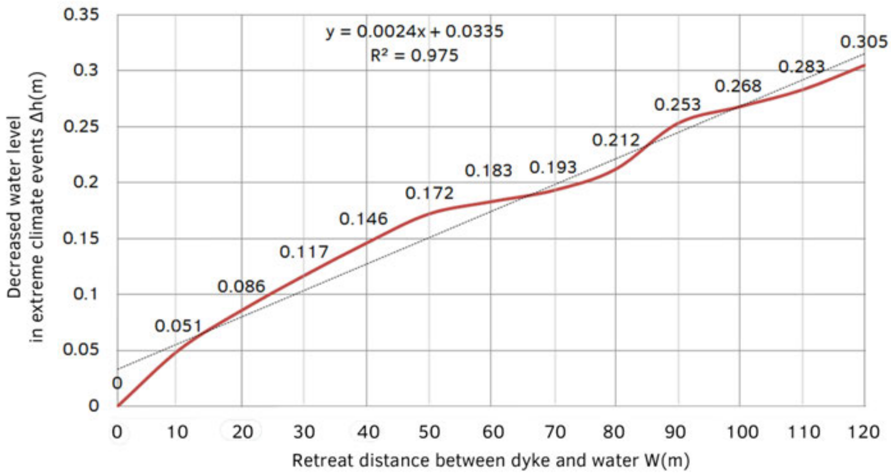


FIG. 5.32 The relationship between the retreat distance from dyke to shoreline and decreased water level of waterways under extreme climate change condition.

5.8.4 Diversified and multifunctional cross-section dyke shape

According to the regional characteristics and future development position of Hengli Island, the form of each dyke section should be based on the conditions and the functional orientation of the adjacent block where the shoreline is located. It should adopt diversified technologies to improve multi functions of the dyke that integrates flood prevention functions and landscape sightseeing. The dyke should be considered for future reinforcement, development and utilization so as to leave appropriate redundant space for the future. Appendix D-10 provides possible cross-section dyke types and their advantages and disadvantages as well as applicable condition.

Figure 5.33 is the planning and design scheme of dyke systems. Through strengthening, elevating, demolishing and rebuilding the original dykes, new dykes can reach the standard height of above 4.73 meters required by '200-year sea level rise +(P-0.5% high tide)'. The dyke shape for each suitable shoreline section is of multi functions to form a consistent closed loop around the island. Besides the core function of flood prevention, this new dyke system combines coastal parks, floodable areas, and tourism space and leisure centers with dyke infrastructure. A new dyke system not only has strong robustness capacity against external tide, but also becomes a charming coastal landscape belt and cultural belt.

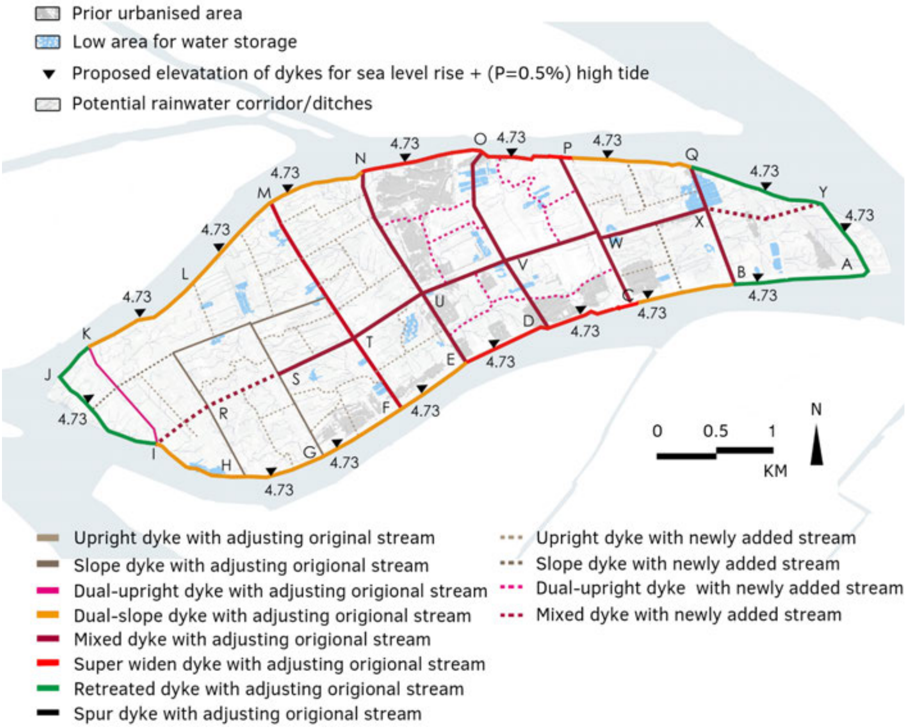


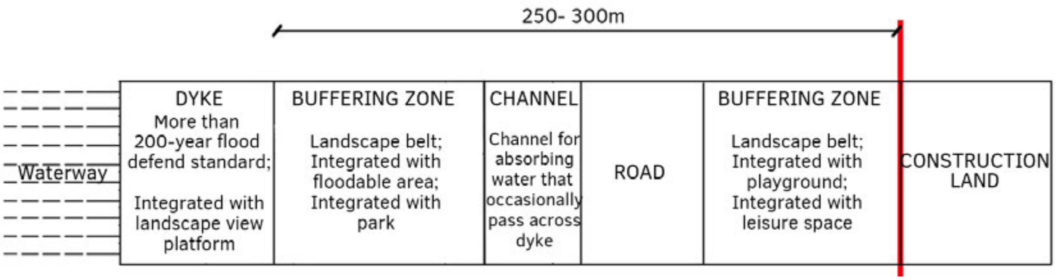
FIG. 5.33 Diversified and multifunctional cross-section dyke

It can be seen that the shoreline segments such as QYAB and KJI of the island frontier adopt the dyke shape with 70- meter retreated distances. The impacts of extreme tide, wind and wave can not only be defended by dyke barriers, but also tidal parks can be provided in areas between old and new dykes. The application of super wide dykes for shoreline segments EDC and NOP are located in the most prosperous central areas and hydrological junctions. A Dual-slope dyke shape is applied for shoreline sections IHGFE, KLMN, which are of relative low requirements for landscape-viewing and relatively low budget in construction costs. Due to the good conditions of a wide and deep water surface, unchanged water level and slow speed of sedimentation and erosion, shoreline APONMG can function as the future central axis of the island. For the same reason, several north-south shoreline segments such as NUE and OVD will also be suggested to apply mixed-shape dykes due to high requirements of landscape-viewing and low reserved space. For the other inner-rivers with small amount of reserved lands, dyke shapes of upright or dual-upright are suggested.

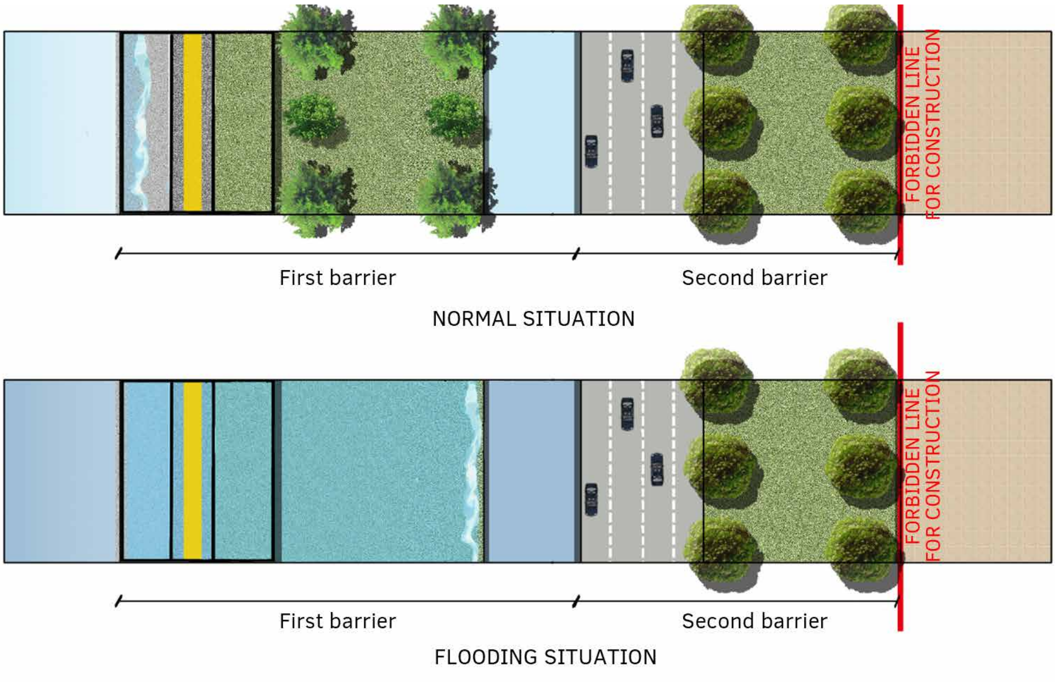
TOC

5.8.5 Adaptive shoreline buffering belt

An adaptive shoreline buffering belt is required for further adaptability in order to connect different cross-section dyke shapes in each shoreline segment. On the premise of closed dykes that meets the standard of 200-year high tide and sea level rise in 200 years, a redundant buffer belt is proposed with the width of 250 ~ 300 meters from dyke to buildings in order to prevent the occasional occurrences of overflow waves in extreme situation. A channel inside the buffering belt is also proposed for connecting inner-rivers and absorbing overflow waves. The buffering belt can integrate the functions of leisure, entertainment and sports and be built into a beautiful scene surrounded by roads, green spaces, and river channels. The buffering belt can also be used as an important part of water storage areas during flooding days. Figure 5.34 shows the buffering belt between dykes and buildings with a proposed construction forbidden line.



1 The functional division of buffering belt



2 The situation of buffering belt under normal and flooding situation

FIG. 5.34 Adaptive shoreline buffering belt

5.9 Overall spatial scheme for resilient flood control and drainage system

5.9.1 Multi-Layer flood resilience framework

The above sections have elaborated on principles and strategies for resilient flood control. Conclusively, resilient flood control and drainage by spatial organization is based on the three-layer framework shown in Figure 5.35, which widely adopts resilient spatial characters of rationality, diversity, modularization, redundancy, connectivity and multifunctionality.

The first layer refers to the dyke system. The purpose of this layer is to prevent flooding by raising the appropriate height of the dyke and retreating a certain distance between dyke and shoreline so that the dyke can reach the standard of flood control that occurs once every 200 years or more (P-0.5%), to reduce the possibility of floods and reduce the impact of extreme high water level on the site. Measurements are taken in the specific program as follow: (1) Calculate the dyke height that can withstand 200 –years flood with a certain margin to form the closed dyke circle, in order to prevent floods beyond the dyke. (2) Analyze the natural conditions of different shorelines and future urban functional requirements. (3) Determine the form of the dyke by comprehensively considering the functional requirements of flood prevention, cost and landscape benefits of dyke construction. (4) Combine the function of flood prevention with landscape–viewing of shoreline and adopt diversified dyke forms. (5) Set buffer areas on both sides of the dyke.

The second layer is the drainage layer inside the dyke. The purpose of this layer is to prevent waterlogging in the site in the event of extreme precipitation. Measurements are taken in the specific program as follow. (1) Scientifically calculate the gap value between amount of precipitation under extreme climate change and the existing water storage capacity. (2) Increase the width, depth and length of the existing inner-river, and increase the water storage of inner-river. (3) Modularization of water collection area and decentralized drainage. (4) Based on the water storage gap value and the division of regional water collection area, new inner-rivers can be developed to shorten the distance of flood discharge. (5) Improve the water network. The connectivity and density of the water system network should be improved through various measures such as inland surges, lakes, buffer areas, flood

TOC

detention areas, and increasing the drainage capacity of sluice and pumping station systems. (6) Appropriately raise the elevation of foundation for special spaces and set up emergency evacuation channels and special critical functional facilities. (7) Strengthen the water storage, infiltration and diversion for large-scale public development projects, squares, parks and public green spaces, and land for roads.

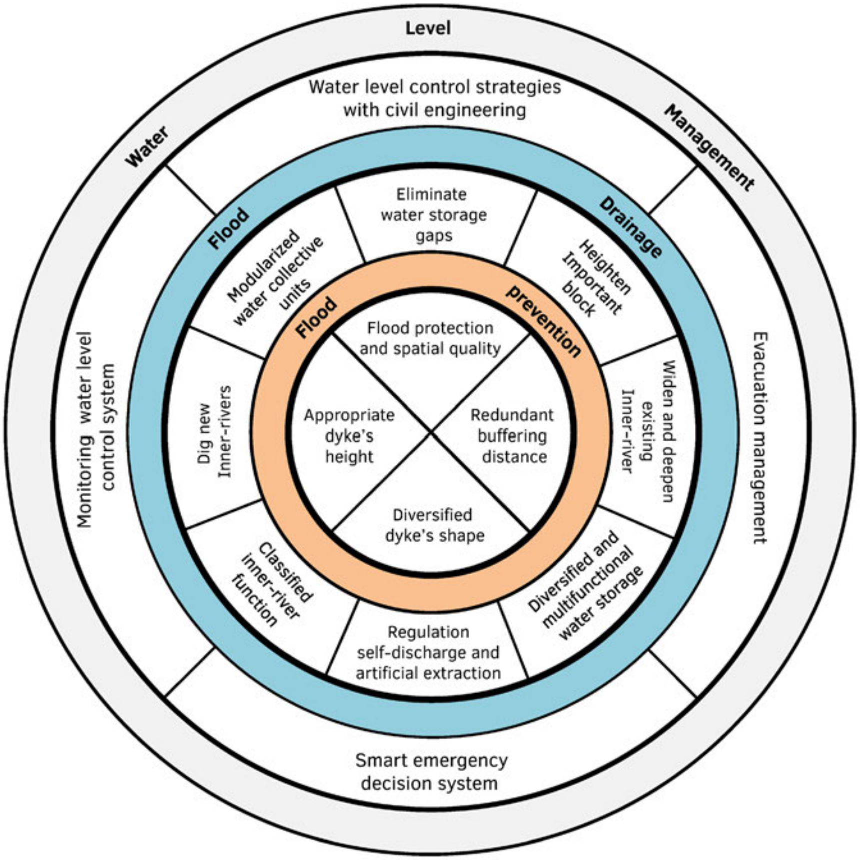


FIG. 5.35 The overall framework of the multi-layer resilient flood control and drainage

The third layer is to strengthen water level regulation and management. On the basis of flood control and drainage measures of the first and second layer, the purpose of this layer is to formulate water level control schemes so as to ensure that flood control and drainage can be improved under various scenarios. Measurements are taken in the specific program as follows: (1) Establish decision systems composed of damp-proof drainage hydrology telemetry systems, computer network systems, and network communication systems and decision support systems. Smart computer systems, communication systems and decision support systems can be applied for formulating emergency evacuation plans when over-standard flood occurs. (2) Establish sluice and pumping station automatic control system, to generate an emergency command and decision system. (3) Formulate emergency evacuation route for flood control and drainage beyond the standard. (4) Determine the water level management and corresponding elevation parameters of the site under different scenarios.

5.9.2 Spatial layout for resilient flood control and drainage

Figure 5.36 shows the new scheme of the spatial layout for resilient flood control and drainage systems by applying principles and strategies proposed in previous sections. Figure 5.37 shows new land uses based on spatial layout for resilient flood control and drainage, land-use suitability assessment and probability-of-occurrence of urban areas. Figure 5.48 represents new elevation relationships. Table 5.2 represents the parameters of classified inner-rivers in the new scheme.

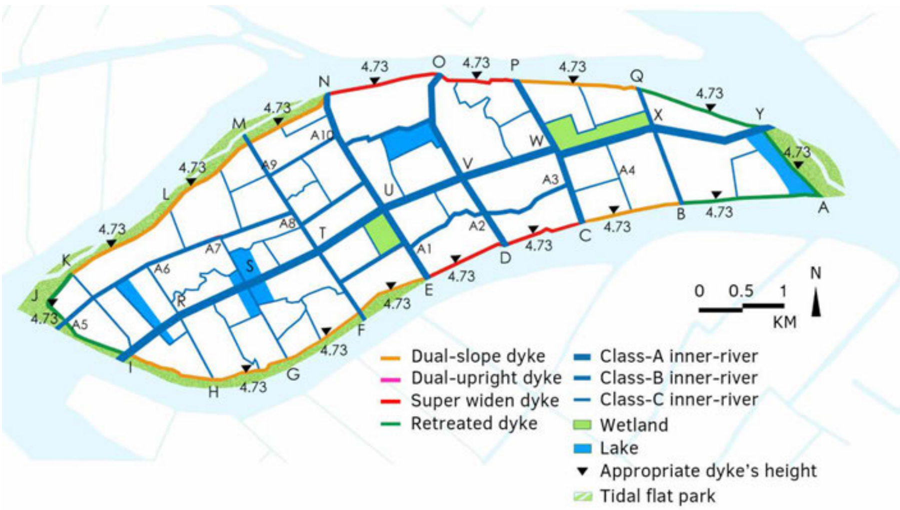


FIG. 5.36 Spatial layout for flood control and drainage

FIG. 5.37 New land uses based on spatial layout for resilient flood control and drainage and land-use suitability assessment and probability-of-occurrence of urban areas

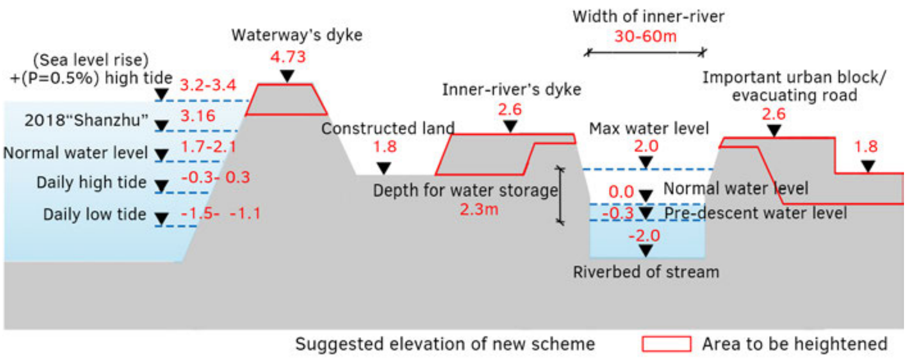


FIG. 5.38 New elevation relationships

TABLE 5.2 Parameters of classified inner-rivers in new scheme

Classification	Class—A	Class—B	Class—C
Function	Flood prevention, drainage, landscape-viewing and navigation	Flood prevention, drainage, landscape-viewing	Flood prevention and drainage
Width (m)	40-60	30-40	20-30
Dyke shape(m)	Mixed dyke shape	Dual-upright dyke shape, dual-slope dyke shape	Upright dyke shape, slope dyke shape
Height of dyke(m)	2.60	2.60	2.50
Width of buffering areas on both side	> 40	> 30	> 20
Average elevation of riverbed(m)	-2.0	-2.0	-1.5
Normal water level(m)	-0.3~+0.3	-0.3~+0.3	-0.3~+0.3
Pre-descent water level(m)	-0.30	-0.30	-0.30

The proposed scheme shows that the height of the new dyke system can be 4.73 meters so that the dyke system can reach the standard for preventing 200-year high tide with sea level rise in 200 years. The new dyke system, which integrates both flood prevention and landscape-viewing, combines coastal parks, floodable areas, tourism and leisure places, with different cross-section dyke shapes in each shoreline segment. Dykes in frontier shoreline segments such as QYAB and KIJ are proposed to have a 70- meter retreat distance. Appropriate dyke' height and retreat distances provide possibilities where not only floods can be conductively defended, but also nourished tidal flats outside dyke can be retained. For shoreline segments such as CDE and PON that are located in the most prosperous central areas, the application of super widened dykes can not only integrate dykes with their adjacent commercial center and subway station, but also play a positive role in buffering excess water. For shoreline segments such as KLMN and IHGFE that have relatively low requirements for landscape-viewing and a low budget for construction cost, dual-slope dyke shapes are applied.

For further improving the adaptation ability of flood control and drainage, a buffering belt of 250~300-meter forbidden construction area is set between dykes and buildings. The buffering belt can integrate the functions of leisure, entertainment and sports into a golden coastline surrounded by roads, green spaces, rivers, and forest belts. The buffering belt can also serve as a water retention area for overflowing water.

The new scheme also shows classified functions of inner-rivers. The inner-rivers can be classified into three classes based on their nature condition and the requirement for future urbanization. New scheme shows the methods of land-use based on the comprehensive pre-evaluation results of probability-of-occurrence of urban areas that respect the natural terrain conditions and processes (Figure 5.23). Ground with high elevation can be used for construction while ground with low elevation can be reserved for water accommodations. For instance, spatial blocks such as NOVU, UVED, VWCD shown in figure 5.37 are arranged as high-density development blocks because of their high socio-economic value, high elevation, convenient traffic and stable soil-water conditions. Other blocks can be planned as medium and low-density areas. The methods for constructing adaptive building groups are adopted which can be suitable for changing intensity while retaining main flood control and drainage space.

5.9.3 Water level adjustment by the processes of self-discharge and artificial-extraction

Based on the new spatial layout, in addition to increasing the necessary water storage capacity, regulating water levels of the new water system is required by working with nature. Spatial transformation of excessive water from the site to inner-rivers then to waterways can be realized by water regulation, self-drainage and artificial-extraction.

Under extreme situations, the water level of inner-rivers can be adjusted by two methods that includes self-discharge and artificial-extraction, based on the relative water level relationship. When the water level of the inner-river is higher than that of outside waterways, the sluices are opened. The excessive water in inner-rivers can be automatically self-discharged by using the elevation difference in a natural way. Artificial-extraction is to extract excessive water from a low water level of inner-rivers to a high water level of outside waterways. The water from inner-rivers can be extracted by using pumps to lower the water level of inner-rivers and prevent potential water-related issues.

Under the principles of working with nature, new sluices can be set at the junctions of inner-rivers and outside waterways, as well as at the junctions of two important inner-rivers. The capacity of self-discharge is related to water level difference and the width of sluice. The width of sluice should take several factors into account such as shipping and tidal blocking. When the water level of the outside waterway is higher than that of inner-rivers, sluices should be all closed. The pumping stations will be set at the main junctions of inner-river and outside waterways. The capacity of artificial-extraction is mainly related to the power of installed pumps. The larger the installed power is, the greater the capacity of artificial-extraction. Pumps should be arranged centrally to facilitate management and reduce construction space.

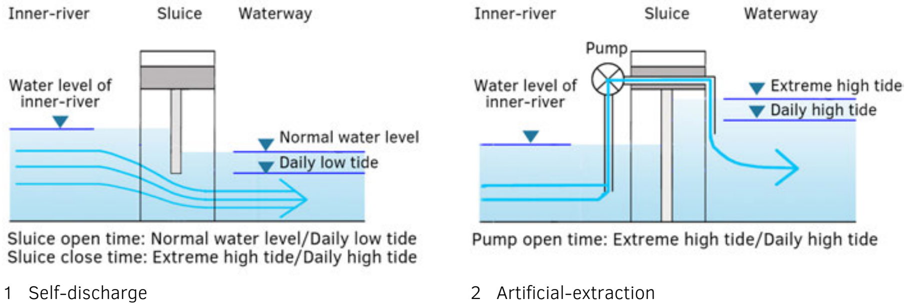


FIG. 5.39 Water level adjustments by the processes of self-discharge and artificial-extraction

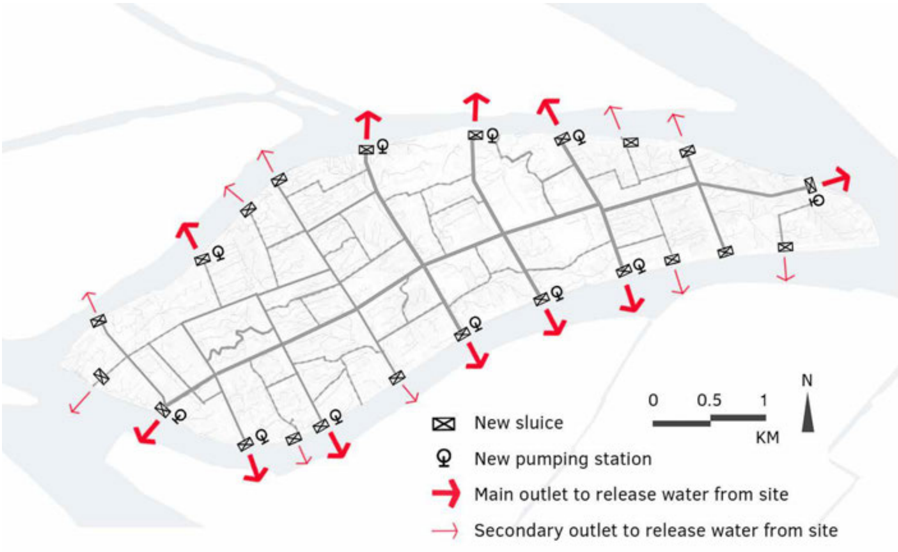


FIG. 5.40 Proposal for new sluices and pumping stations

Figure 5.40 is the proposal of sluices and pumping stations for improving resilient flood control and drainage based on new water collective units and improved water networks. When extreme climate condition occurs, it is required to make full use of the process of self-discharge by the principles of working with nature, than to make artificial extraction in order to improve the robustness and adaptability of the whole Island.

5.9.4 Water level regulations

Besides principles and strategies from spatial organization, it is important to establish emergency water management systems such as automatic control system of sluice and pumping station and the alarm systems of upstream and downstream. The water levels of inner-rivers and waterways needs to be obtained and can be used for decision-making.

Whether the water level of inner-rivers is normal or not, directly affects drainage, navigation and landscape functions. Therefore, the water level of inner-rivers must be controlled in a reasonable range. Controlling the upper limit of the water level of inner-rivers can effectively prevent the occurrence of water-related issues in extreme climate. To control the lower limit of the water level of inner-rivers can guarantee navigation functions and landscape functions. Water level management is an important part of resilient flood control and drainage. Based on the new scheme and spatial layout of resilient flood control and drainage, water level regulations under normal conditions and emergent conditions are researched together with civil engineers. Detailed principles and strategies for water level regulations in different scenarios can be found in Appendix D-11.

5.10 Evaluation of the effectiveness of resilient flood control and drainage

Based on improving core capabilities of resilient flood control and design, the following indicators are selected to evaluate the effectiveness of resilient flood control and drainage.

1. **The size and the spatial distribution of potential flooding and waterlogging areas**
The size and the spatial distribution of potential flooding and waterlogging areas can be used to intuitively show the overall responsive effects to the water-related issues under the scenario of extreme climate change and fast urbanization.

2. **The number of gaps between the capacity of water storage and future precipitation**
The outcomes of the evaluations of the number of gaps between the capacity of water storage and future precipitation can illustrate whether the site has sufficient water storage capacity in each new water collective unit to face extreme climate change and fast urbanization.

3 **Peak runoff speed in each water collective unit**
According to the principle of water circulation, the size of impervious underlying surfaces will increase sharply with continuing rapid urbanization in future, which will significantly change the environment of the water system. The blockage of the water system caused by impervious underlying surfaces and the reduced number of natural surface runoffs will further impair the natural 'source-confluence-runoff' process, which can lead to an increasing speed of peak runoff in each water collective unit. Reducing peak runoff speed and delaying the occurrence time of peak runoff are goals for resilient flood control and drainage.

4 **Density, connectivity and the degree of spatial integration of the water system**
For resilient flood control and drainage, the higher the density, the better the connectivity of water system is. The higher the degree of integration of key hydrological points of water system is, the stronger the regulation ability of the new proposed water system to respond to the situation of extreme precipitation.

5 **Landscape effect**
It is necessary to strengthen the construction of spatial quality and environmental form. It is necessary to reflect the concept of natural-oriented, and establish a diversified and multifunctional space.

Table 5.3 shows the outcomes of comparative evaluation of resilient flood control effects before and after plan and design by the above related indicators.

TABLE 5.3 Comparative evaluation of resilient flood before and after plan and design

Indicator for resilient flood control	Before	After
The elevation of the top of peripheral dyke (Pearl River Datum, m)	+3.2-+3.8	4.73
Water level that can be reduced during extreme climate condition(m)	0	0.193
Minimum distance between potential waterlogging point and adjacent waterways (m)	1200	800
Number of inner-rivers	12	35
Water storage capacity of inner-rivers (thousand m^3)	1186.0	3349.2
Volume of lakes, Wetlands (thousand m^3)	256.8	1268.3
Volume of other water bodies (thousand m^3)	3909.3	5054.2
Density of water system(km/km^2)	1.21	3.65
Number of water collective units	15	48

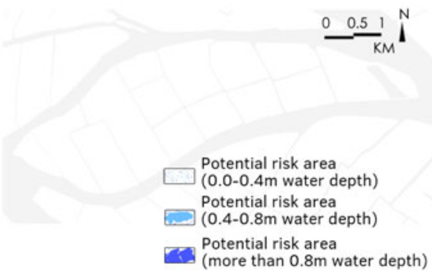
TOC

5.10.1 Potential flooding and waterlogging areas

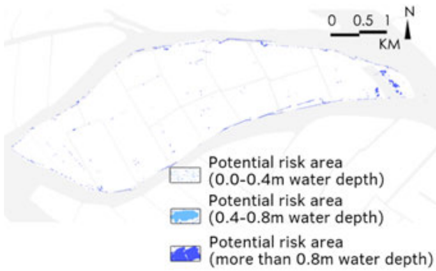
In order to test the effectiveness of the new scheme, Table 5.4 simulates the spatial distribution of potential flooding and waterlogging areas under different scenarios. The simulation results are shown in Figure 5.41.

TABLE 5.4 The simulations of potential flooding and waterlogging areas under different extreme climate situation

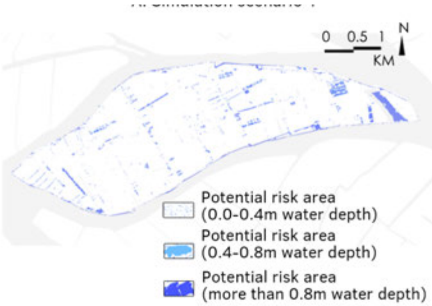
Simulation scenario number	Proposed elevation of dyke (m)	Water level under different extreme climate situation	Spatial distribution of potential flooding and waterlogging areas
1	4.73	200-year high tide +sea level rise 0.5m	Figure 5.41 A
2	4.73	Water level in simulation scenario number 1 +0.3m	Figure 5.41 B
3	4.73	Water level in simulation scenario number 1 +0.6m	Figure 5.41 C
4	4.73	Water level in simulation scenario number 1 +0.9m	Figure 5.41 D



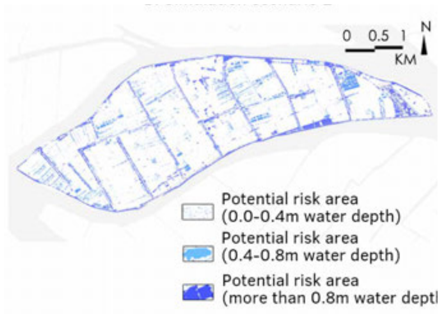
1 A: simulation scenario 1



2 B: simulation scenario 2



3 C: simulation scenario 3



4 D: simulation scenario 4

FIG. 5.41 The simulation of the spatial distribution of potential flooding and flooding areas under different scenarios of water level, dyke's height is 4.73 m

Figure 5.41 A shows that the water-related issues caused by flooding and waterlogging can be prevented when applying the proposed dyke height of 4.73 m. Figure 5.41 B shows that flooding and waterlogging areas begin to occur around the dyke when the water level of outside waterways is increased by another 0.3m. These areas can function as buffering areas that occasionally has overflowed water. Figure 5.41 C~ Figure 5.41 D show that the size of flooding and waterlogging areas can be increased significantly not only around the dyke but also on both sides of inner-rivers when the water level of outside waterway increases for another 0.6m~ 0.9 m.

The simulation results indicate that the site only begins to be affected by water-related issues when the water level of outside waterways exceeds another 0.3 m. Therefore, it is reasonable to propose the height of peripheral dyke to be 4.73 m. The simulation results prove the effectiveness of the proposed height of the peripheral dyke.

5.10.2 Water storage capacity

A Assessment of the water storage capacity before plan and design

The capacity of water storage can directly indicate the capacity of flood control and drainage to respond to the extreme climate change. Theoretically, if the capacity of water storage is less than the amount of extreme precipitation, flooding and waterlogging will inevitably occur. The situation of flooding and waterlogging becomes serious when the number of gaps increases. Figure 5.42, Figure 5.43, and Figure 5.44 respectively shows the number of gaps between the capacity of water storage and future precipitation under three different scenarios.

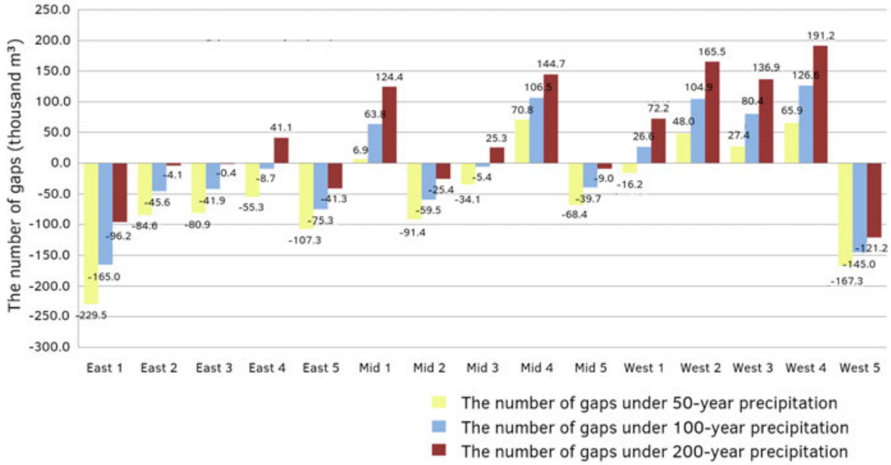


FIG. 5.42 The number of gaps between the capacity of water storage and future precipitation under current situation (unit: thousand m³)

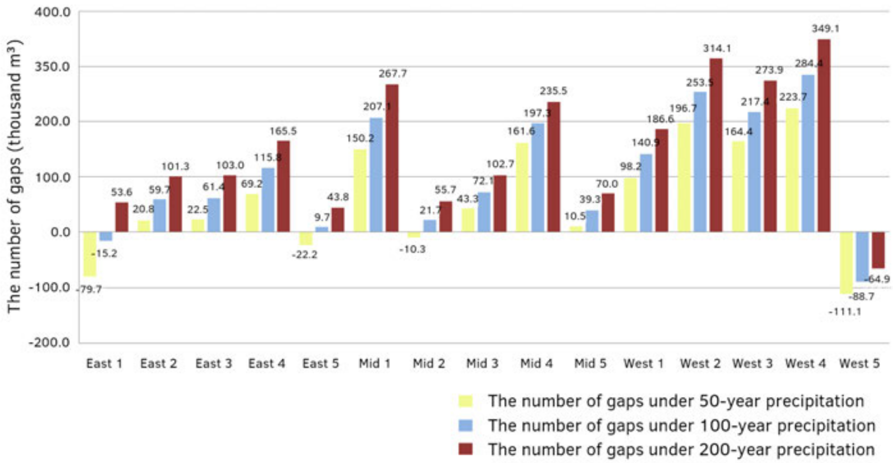


FIG. 5.43 The number of gaps between the capacity of water storage and future precipitation under 50% urban development (unit: thousand m³)

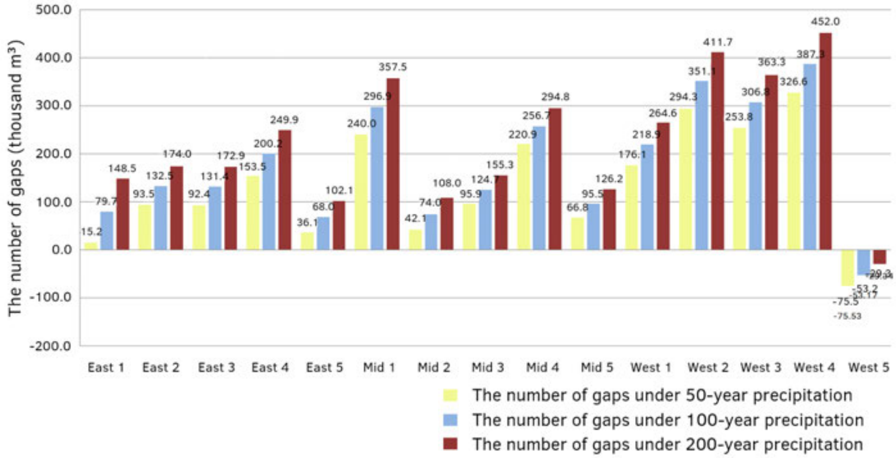


FIG. 5.44 The number of gaps between the capacity of water storage and future precipitation under 80% urban development (unit: thousand m³)

From Figure 5.42 to Figure 5.44, it can be seen that water collective units such as East 4, Middle 1, Middle 3, Middle 4, West 1, West 2, West 3, West 4 have a certain number of gaps, especially in West 2 and West 4 where the gaps can be as large as 191.3 thousand cubic meters, when overlapping current situation with 200-year precipitation. This gap can become more prominent with the increasing urbanization rate. Under the condition of 50% urbanization, the capacity of water storage in all water collective units will become insufficient. Furthermore, under the condition of 80% urbanization, the capacity of water storage in all water collective units will become more insufficient. Due to the serious shortage of the capacity of water storage in all water collective units, waterlogging can occur during extreme precipitation.

B Assessment of water storage capacity without the consideration of pre-descent water level

It can be assumed that the capacity of water storage of the site will be largely increased. Figure 5.45 shows the surplus between the capacity of water storage and future precipitation without the consideration of pre-descent water level in east, mid and west water collective units. The surplus is equal to the capacity of water storage minus the amount of future precipitation.

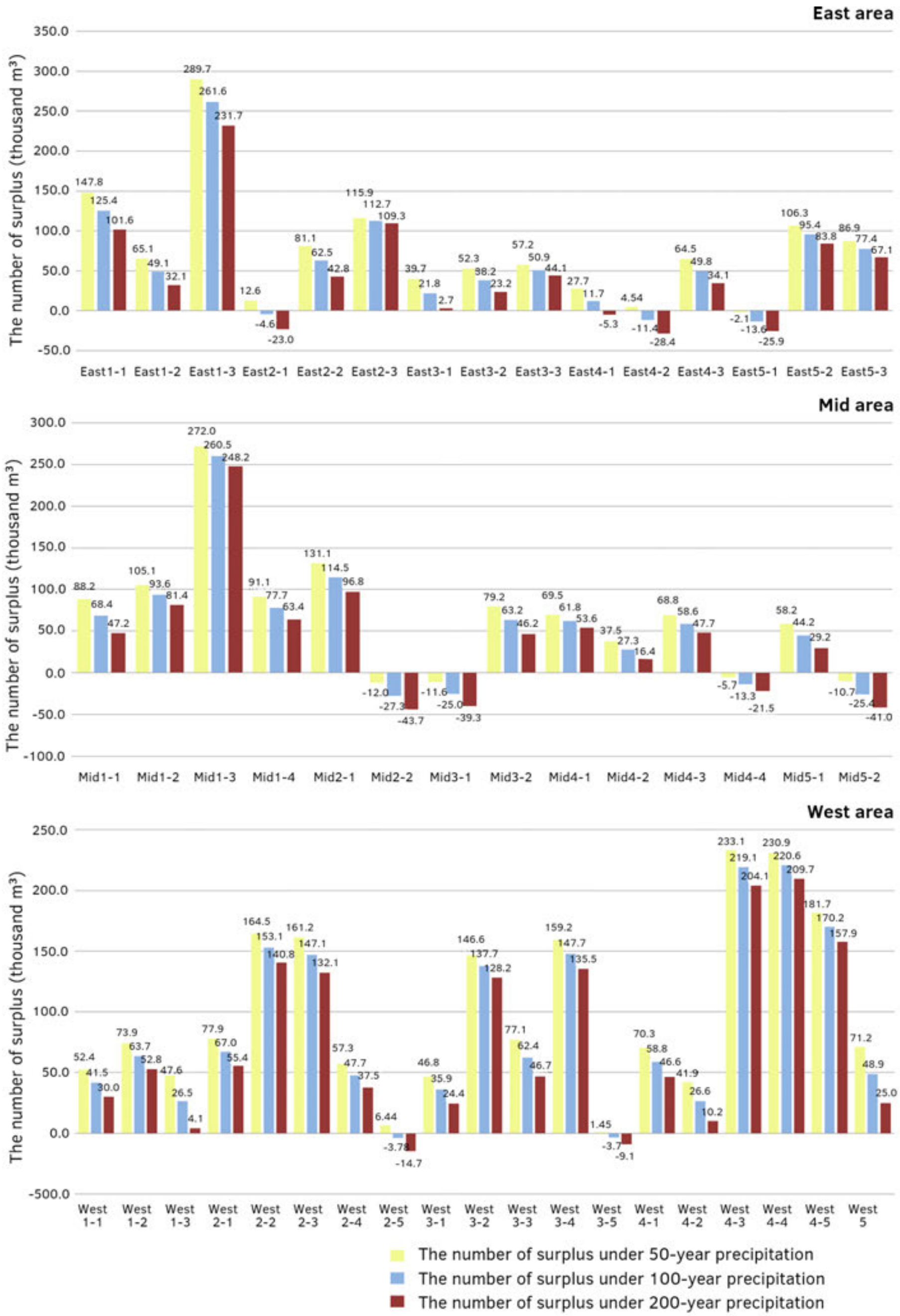


FIG. 5.45 The number of surplus between the capacity of water storage and future precipitation without the consideration of pre-descent water level (presented in number, unit: thousand m³). (Note: The number of surplus= the capacity of water storage – future precipitation).

It can be seen from Figure 5.45 that the capacities of water storage are larger than the amounts of future precipitation in most of the new water collective units, under all precipitation scenarios. However, there are also some water collective units such as East 2-1, East 4-2, East 5-1, East 3-1, Mid 2-2, Mid 4-4, Mid 5- 2. West 2-5, West 2-5, which still have insufficient capacities of water storage but the values are not large. Most of water collective units with insufficient capacities of water storage are located along the east-west main inner-river or along the outside waterway. Figure 5.46 shows this result in space.

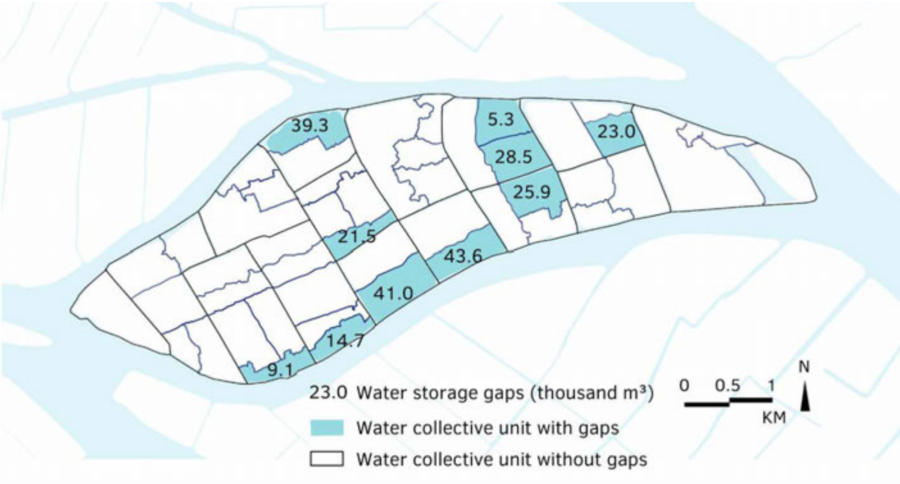


FIG. 5.46 The number of gaps between the capacity of water storage and future precipitation without the consideration of pre-descent water level (presented in space, unit: thousand m³).

C Assessment of water storage capacity with the consideration of pre-descent water level after planning and design

It is important to reduce the water level of inner-rivers to pre-descent water level in advance by self-discharging or artificial-extraction before the occurrence of extreme precipitation in order to make more space for water storage of inner-rivers. Figure 5.47 shows the number of surplus between the capacity of water storage and future precipitation with the consideration of the pre-descent water level of -0.3 meters. It can be seen from Figure 5.47 that all water collective units have surplus capacities of water storage to respond to future extreme precipitation. It shows that the scheme has stronger adaptability to future extreme precipitation. Figure 5.48 shows corresponding result in space.

TOC

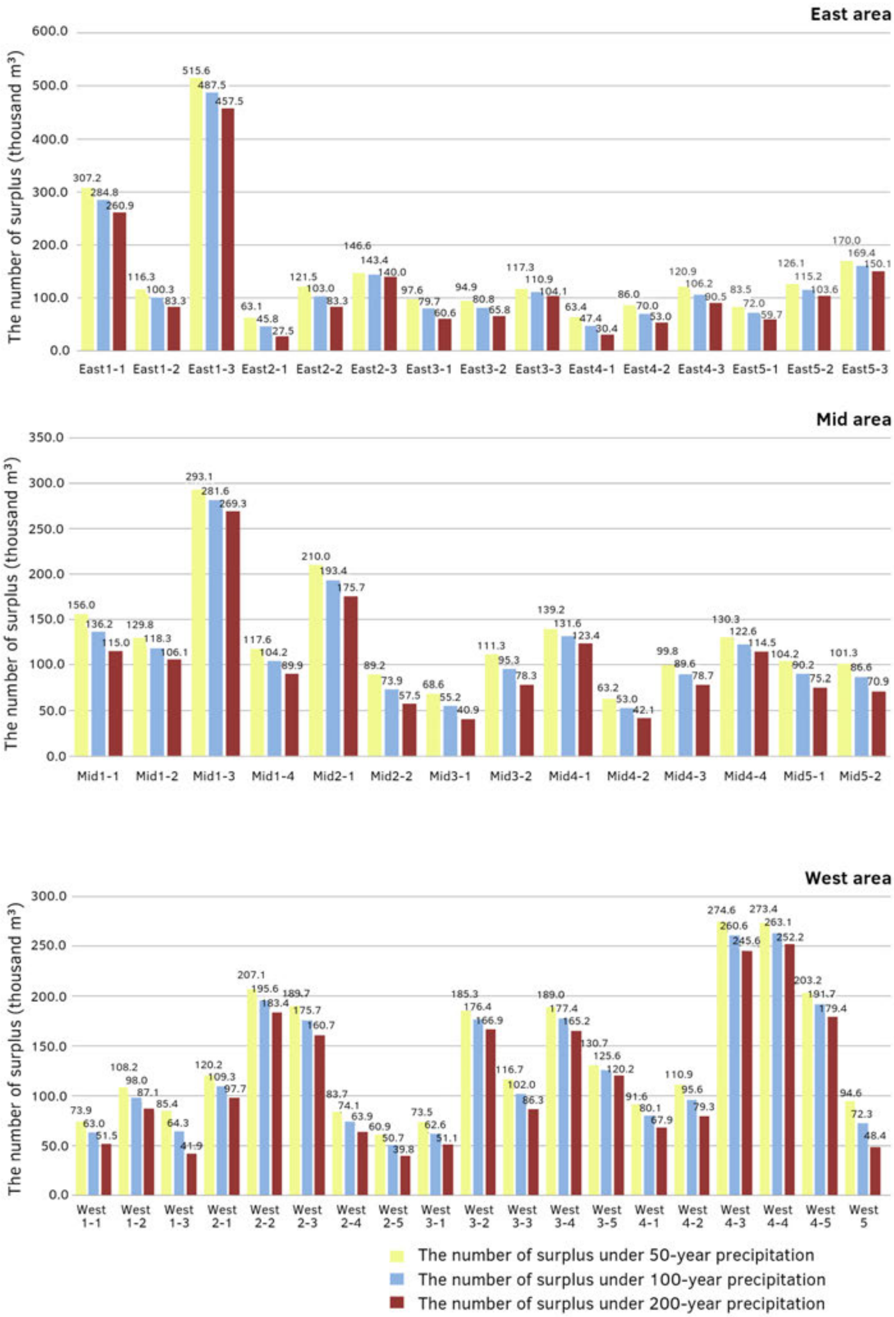


FIG. 5.47 The number of surplus between the capacity of water storage and future precipitation with the consideration of pre-descent water level of -0.3 meters in advance (presented in number, unit: thousand m³). (Note: The number of surplus= the capacity of water storage – future precipitation).

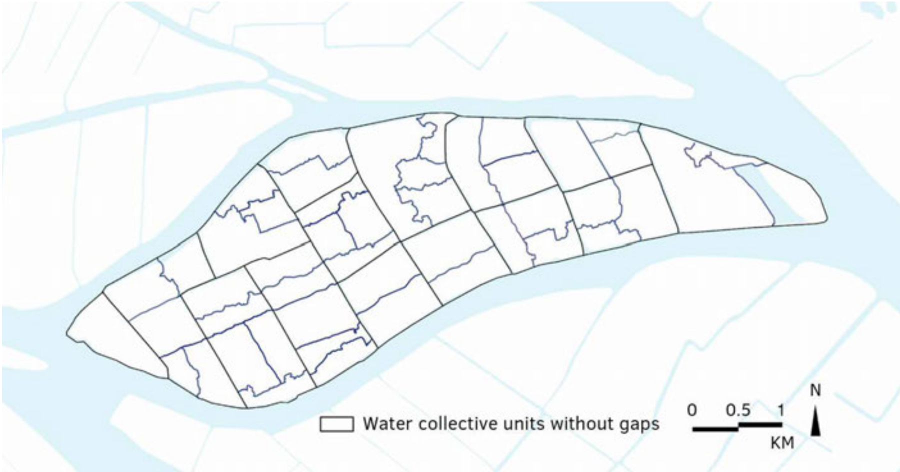


FIG. 5.48 The number of gaps between the capacity of water storage and future precipitation with the consideration of pre-descent water level of -0.3 meters in advance (presented in space, unit: thousand m³).

5.10.3 Spatial integration

Spatial integration reflects the proximity of connection between one point and others in a system. The greater degree of spatial integration can make for higher convenience and stronger accessibility. By using ArcGIS hydrological toolbox and spatial syntax analysis software, the degree of spatial integration of each key hydrological point in both old and new water systems can be explored in Figure 5.49. Detailed data can be found in Appendix D-12. It can be seen from Figure 5.49 and Appendix D-12 that there is an increasing degree of spatial integration of each key hydrological point inside the site (# 1~ # 19) of the water system after planning and design. It is helpful to increase the degree of spatial integration of hydrological key points in the regional water network around the site (# 20 ~ # 28) and to promote smooth regional hydrological circulation.

TOC

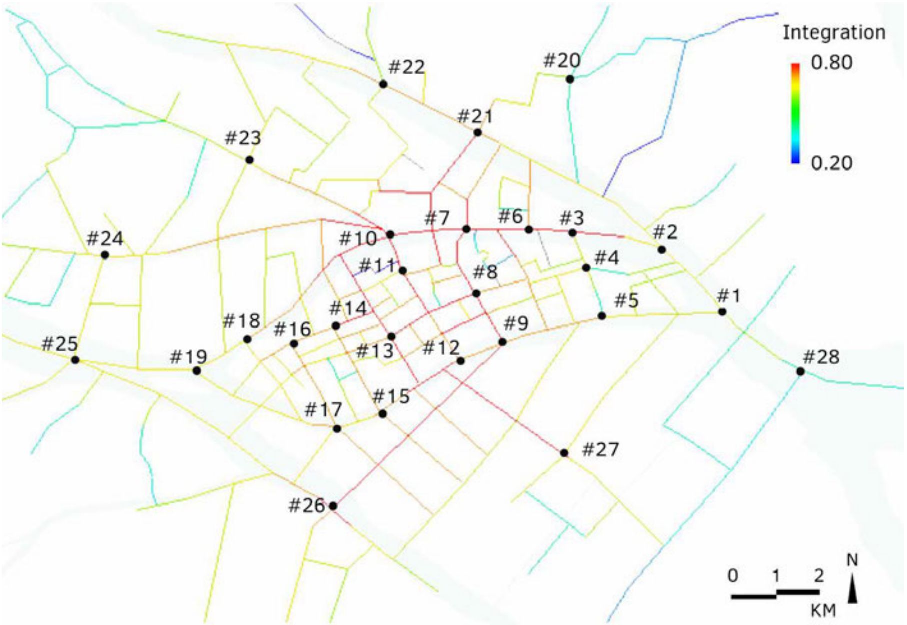


FIG. 5.49 The degree of spatial integration of key hydrological points in scheme

5.10.4 Peak runoff speed

Appendix D-13 shows the peak runoff speed of each water collective unit. It can be seen from the table that the peak runoff speed of each water collective unit decreases after planning and design. It means that the performance of flood drainage is improved.

The comparison results of the above-mentioned aspects show the effectiveness of the proposal for resilient flood control and drainage under the background of sea level rise, extreme high tide, extreme precipitation and fast urbanization.

5.10.5 Landscape effects

The proposal for resilient flood control and drainage in the delta not only creates a more secure water environment, but also creates a more pleasant space. It is important to combine the construction of flood control and drainage engineering with the construction of future delta landscapes by making full use of the natural advantages of the coastal landscape resources of the PRD.

The proposal focuses on the harmonious relationship among ‘human-water-urban’ and aims to increase the spatial qualities from multiple scenes such as buffering areas of shoreline of outside waterways, east-west main inner-rivers, north-south inner-rivers, important floodable areas, and cultural space of inner-river. On the whole, a more vivid ‘productive, living, hydro-ecological’ friendly future delta urban space can be generated.

Figure 5.50 shows the comparisons of landscape effect of the shorelines’ atmosphere of outside waterways. It can be seen from the figure that shoreline areas will be changed from a single farmland and fish-pond landscape to a large-scale of green, three-dimensional, multifunctional landscapes, which are full of green parks and water storage areas.

Figure 5.51 - Figure 5.52 show the landscape effects of inner-rivers. It can be seen that the east-west inner-river becomes the main axis of the landscape of the whole site with multiple functions of shipping, fishing, communicating, etc., which becomes a more distinctive, vibrant and delta-characterized space.

1 Landscape of outside waterway before planning and design

2 Landscape of outside waterway after planning and design

FIG. 5.50 The comparison of landscape effect of outside waterway

1 Landscape of east-west central inner-river before planning and design

2 Landscape of east-west central inner-river after planning and design

FIG. 5.51 The comparison of landscape effect of east-west central inner-river

1 Landscape of north-south inner-rivers before planning and design

2 Landscape of north-south inner-rivers after planning and design

FIG. 5.52 The comparison of landscape effect of north-south inner-rivers

5.11 Summary

This chapter is based on the theory and method of resilience for improving the flooding and waterlogging environment on Hengli Island. The overall resilient flood control and drainage scheme are proposed by widely applying resilient spatial characteristics such as rationality, network, diversity, multifunctionality, redundancy and modularization. Simulations and evaluations show the feasibility and effectiveness of this new proposal. The reflection on linkage between resilient spatial characteristics and application in food control and drainage is shown in Table 5.5.

TABLE 5.5 Reflection on linkage between resilient spatial characteristics and application in food control and drainage

Spatial Characteristics	Applications in resilient flood control and drainage
Regionality	– Analysis of natural base layer and exploration of main challenges – Original low-lying land can be used for natural areas and high elevation land can be used for construction – Suggestions for land-use to be protected or developed based on the evaluation of land-use suitability – The choice of different cross-section dyke types based on the evaluation of the condition of each shoreline segment.
Redundancy (Main approach to improve the capacity of adaptability)	– Multi-layer redundant collaboration is set with the combination of modular water collective units, redundant dyke systems and dynamic water level control. – Provide safety margins when calculating appropriate dyke height. Choose the dyke shape that can be easily increased in the future – Expand floodable space for water accommodation between dyke and shoreline with the assistance of the spatial elements like sand dunes, detention land, mangrove space and tidal flats. – Provide buffering areas inside dykes and reserve low valued lands for floodable areas which are forbidden to be constructed on. Buffering areas can become redundant areas for flood control and drainage when necessary. – Natural or artificial lakes and nourished parks can be placed by using original low-lying space. These spaces can not only provide public space for citizens in normal days, but also provide large volume for water storage and retention to address the situation of extreme climate conditions. – Heighten ground elevation of specific places which have higher flood control standard by ground-filling. – In areas with high elevation and a dense population, several emergent safety evacuation sites should be arranged to ensure spatial safety. – Provide floodable space for water accommodation with low-valued land.

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TABLE 5.5 Reflection on linkage between resilient spatial characteristics and application in food control and drainage

Spatial Characteristics	Applications in resilient flood control and drainage
Modularization	– The method of flood control and drainage shifted from a centralized model to decentralized model with modular configuration. Based on simulation, more modular water collective units are arranged. With the principle of modularization, the scheme improves the functions of respectively collecting excessive water in different areas, draining water in different modules, shortening the distance of potential flooding and waterlogging points to adjacent water bodies and smoothing the water circulation. – According to the different functional positioning of each modular water collective unit and surrounding environment, the function of inner rivers is classified.
Connectivity	– According to the division of new water collective units, inner-rivers, waterways, branches and ditches should be connected to form a multi-level water storage network. The reconstructed water networks can greatly improve water storage capacity and network density – Create good spatial conditions for flood control and drainage, stagnation and runoff regulation by using networked water system composed of tidal flats, inside surface water and potential natural surface runoff. – Smooth water circulation with networked water system. Excessive water can be collected by natural surface runoff and rainwater pipes that can discharge to adjacent waterways. Through the process of self-drainage and artificial-extraction, the excessive water can be released to outside rivers. – According to the terrain elevation, water flow and land-use function, green-blue patterns like lakes, wetlands and parks are connected.
Diversity	– Current water networks are improved by diversified methods such as increasing density of water, opening up potential water bodies and increasing the capability of water storage of existing water channels. – Dynamic water level control is provided by diversified methods such as regulation, self-drainage by working with nature, artificial extraction, – The capacity of water storage is increased by diversified methods such as increasing the volume of current water system, increasing the density of water networks and setting pre-descent water levels before climate condition occurs. – Water is storage by diversifying retention spots which can regulate, dredge, infiltrate and utilize excessive water. – The shape of dykes is diversified.
Muilti-functionality	– The Dyke system not only plays a role in flood control and drainage, but also in shoreline landscape functions. In addition to the anti-flood effect during extreme climate condition, it is usually used as a transportation space and sightseeing facility. – Adaptive shoreline buffering areas, lakes, wetlands and tidal flat parks can not only function as places for flood control, but can also provide landscape sites to improve the environment and become a tourist and cultural education area. – The proposed water system integrates flood prevention and drainage, navigation and urban service.

6 Conclusion and Discussion

6.1 Conclusion

This doctoral dissertation consists of four parts. The first part is the introduction, which explains the main spatial problems of the PRD, and clarifies the significance of the research and key research questions. The second part is a theoretical study that consists of the second and the third chapter, which focuses on the theory and the method of spatial planning and design for resilience. The third part is the empirical research of spatial planning and design for resilient PRD, which is composed of the fourth and the fifth chapter. The fourth part summarizes and reflects the key research questions proposed in the first part, and discusses the works that needs further in-depth research.

This doctoral dissertation mainly provides the following contributions.

1. Main spatial existing problems of the PRD and the necessity of spatial planning and design for a resilient PRD are explained. Subsequently, the literatures about the delta are studied. The analyses of spatial planning and design practices in deltas of America, the Netherlands and the PRD are conducted.

2. The theory of spatial planning and design for resilience is researched systematically. Core capabilities of spatial planning and design for resilience, fundamental thinking characteristics of spatial planning and design for resilience, the main spatial characteristics for resilience that can be present through planning and design, and the internal thinking logic of spatial planning and design for resilience are proposed by explaining the reasons why these attributes can help improve spatial resilience.

3 The implementation method of spatial planning and design for resilience is proposed. The process of spatial planning and design for resilience and the key points of each phase in the whole process are described from the aspects of target determination, system interpretation, system projection, spatial planning and design, evaluation and feedback.

4 The principles and strategies of spatial planning and design for a resilient PRD are proposed. By analyzing the current spatial status, spatial evolution and the risk areas of flooding and land subsidence under the scenarios of future climate change, the spatial existing problems in the current spatial system are summarized. Then, the strategies of spatial planning and design for a resilient PRD in the macro scale are proposed from the three aspects of land-use, blue-green networks and coastline.

5 The principles and strategies of spatial planning and design for resilient flood control and drainage on Hengli Island are put forward. Resilient flood control and drainage in the micro scale such as Hengli Island needs to widely apply spatial characteristics presented by spatial planning and design for resilience such as regionality, diversity, multifunctionality, connectivity, redundancy, and modularization. Then, the principles and strategies of spatial planning and design for resilient flood control and drainage on Hengli Island are put forward respectively. Finally, the framework for evaluating the effectiveness of resilient flood control and drainage systems is established.

6.2 Reflection to research questions

This doctoral dissertation is closely organized around the main research question:

'What are the theories and methods of spatial planning and design for resilience? How is it possible to apply the theory and method of spatial planning and design for resilience to the PRD?'

Chapter 1 focuses on answering Q1. Literature review of the PRD (Appendix A) and spatial planning and design of deltas in the world are conducted (Appendix B). This chapter elaborates the background and the significance of research on resilience from contradictions between a fragile natural base layer, fast urbanization and future climate change that can cause flooding and land subsidence in the PRD. It is demonstrated that the method of traditional planning and design should be transformed into a new method of spatial planning and design for resilience in the PRD.

Q1: What is the scientific basis for transforming the method of traditional planning and design into a new method of spatial planning and design for resilience in the PRD?

After more than 40 years of rapid development of industrialization and urbanization, the PRD region has made remarkable socio-economic achievements. However, the natural base layer of the PRD is becoming more fragile at present. Natural disasters such as flooding and land subsidence caused by climate change in the PRD are more frequent, uncertain and destructive than those in other regions. Faced with the superposition of factors such as the external disturbances -- natural disasters caused by extreme climate change, and internal interactions -- the contradiction between natural conditions and rapid urbanization in both space and time, the traditional planning and design that pursues mainly economic development cannot be further sustainable when presented with the situation of a fragile natural base layer and unexpected impacts posed by the changing climate. It is necessary to transform traditional planning and design into a new method of spatial planning and design for resilience in the PRD, and coordinate scenically the relationship between urban development, natural protection and continuous climate change in the PRD.

SQ1-1: What are the main existing problems in the PRD?

There are several problems in the PRD.

1 The role of the natural base layer has been neglected. The shortcomings of the low-lying location can be exposed increasingly when the natural base layer is fragile. Some key blue-green spaces are often encroached by urban spaces. Key natural lands are changed into other land-use types with the lack of protective activity. Land carrying capacity is decreased.

2 The water environment has been changed and the sizes of tidal flats in the estuaries are decreased. The large-scale reclamation activities have led to the continuous decrease of the length of the coastline, which directly weakens the ability of flooding resistance of the rivers and estuaries.

3 The method of extensive land-use is unsustainable. Rapid urbanization makes the demands for construction lands to increase dramatically. Public space and valuable natural space are squeezed, and resources for suitable lands for construction are exhausted.

4 The problems of flood control and drainage under an extreme climate scenario is more challengeable. In the past two decades, the phenomena of strong storm surges, huge precipitation and unexpected tidal invasion in the PRD increased. Since 2006, there have been more than 10 strong storm surges in the PRD, which caused serious disasters to the region. Engineering -based flood control and drainage systems under extreme climate scenario are challengeable (Section 1.1, Appendix A).

SQ1-2: What role can spatial planning and design for resilience play in addressing the above problems in the PRD?

PRD is a complex socio-ecosystem. The contradiction between rapid urbanization and the fragile natural base layer is the internal cause of the vulnerability of the PRD. The uncertain disturbance of climate change is an external factor that aggravates the vulnerability of the PRD. Facing the pressures of the future development of PRD, the traditional planning and design that mainly pursues economic benefits is challengeable. In the future, the ability of the PRD to address uncertain changes can be improved by land-use with sufficient land carrying capacity, connective blue-green networks, multifunctional and buffering coastline, and resilient flood control and drainage systems. It is necessary to set up the bottom- line thinking and fully pay attention to the integrity of the natural processes, as well as multi-factor and multi-scale coordination. Spatial planning and design for resilience can reduce the impact of extreme climate change on the PRD and maintain the core functions and structures (Section 1.1.4).

Chapter 2 focuses on answering Q2. The theory of spatial planning and design for resilience is systematically studied as a base for the following research.

Q2: How is it possible to improve the resilience of a spatial system?

Aimed at addressing the dynamic system mechanism and uncertain disturbances like flooding and land subsidence caused by extreme climate change, the dissertation researches the inherent logic and spatial characteristics for resilience from a spatial planning and design perspective, in order to provide a theoretical basis to improve the resilience of a spatial system.

SQ2-1: What does the resilience mean in this doctoral dissertation? What are the core capabilities under the theory of spatial planning and design for resilience?

Resilience requires that a system has capacities to respect its own evolution mechanism, maintain its core functions when disturbed and adapt to unexpected disturbances. The concept of resilience emphasizes not only the maintenance of the original capacities of a spatial system when being disturbed, but also the adaptability to disturbances. The capacities of recovery and maintenance are mainly reflected in the robust capacity of a system (Section 2.4.1). The adaptability is reflected in the foresight thinking in the spatial planning and design for resilience in response to unexpected changes. The purpose is to have the ability to cope with the disturbances and adapt to the change of environment (Section 2.4.2).

SQ2-2: How is it possible to improve the core capabilities of robustness and adaptability in spatial planning and design?

Robustness describes the stability of a system. It is the tolerant degree of a system to the changes of structure and parameters within a certain range. It is the key to establish healthy operation for long-term development. Robustness is helpful to ensure that a spatial system can maintain its most fundamental function and structure when disturbed. Identification of future major disturbances is an important basis for improving the robustness of a spatial system. Therefore, it is necessary for spatial planning and design for resilience to be more targeted and have foresight, and be good at identifying the most likely and worthy of prevention measures against various possible disturbances (Section 2.4.1).

Adaptability refers to the ability of a spatial system to adapt to the change of environment and the planning and design object itself. Adaptability is reflected not only in the capacity to adapt to the change of site, especially the natural base layer, but also in adapting to unexpected climate change. The key to improving the adaptability is to enhance network connectivity in order to realize moderate advancement and extensibility, and to improve redundancy and multifunctionality characters of a spatial system. Based on prevention, the spatial system adapts to the changes of the future environment by adopting various adaptive forms such as interface flexibility, coordination and initiative. By properly adjusting the function and structure of the original space, the changed -space can adapt to the new environment with little cost. In short, adaptability emphasizes on an advanced network and redundancy to create conditions for future changes (Section 2.4.2).

SQ2-3: What are the fundamental thinking characteristics of spatial planning and design for resilience?

The thinking characteristics of spatial planning and design for resilience mainly consist of four aspects, namely, systematic, coordinative, bottom- line and foresight thinking.

Systematic thinking is one of the essential attributes of spatial planning and design for resilience. Spatial Planning and design for resilience should proceed from the overall situation instead of dealing with problems in isolation and statically from a local perspective. It is meaningless to study a complex system from any isolated parts. Multi-elements and multi-scale coordination should be carried out to achieve the goal of an integrated system. It should coordinate all elements of the spatial system, and make the functions and forms of all elements of the spatial system subject to the overall goal of the whole system. Spatial planning and design for resilience should adopt targeted classified and stratified planning and design methods under the guidance of overall objectives. Systematic thinking also means that when addressing external disturbances, spatial planning and design for resilience should take the initiative to adapt to it, rather than avoid it (Section 2.5.2).

Coordinative thinking is also one of the fundamental attributes of spatial planning and design for resilience. Facing a multilevel and complex nonlinear system, spatial planning and design for resilience requires coordination among different scales. Spatial planning and design for resilience should promote a system to be orderly in space, time and function through coordination. The purpose of coordination is to realize harmony between human and nature. Multi-disciplinary collaboration should be emphasized. Coordination is not only a means, but also an objective of spatial planning and design for resilience of a complex system (Section 2.5.3).

Spatial resilience can be realized by bottom-line thinking. The bottom line is a threshold that a system can maintain the core function and core structure when the spatial system is subjected to disturbances. For a resilient system, the bottom line cannot be destroyed. In a spatial system, the identification of bottom line should be based on the assessments of land carrying capacity, natural resources and land-use suitability. Bottom-line thinking means that priority should be given to the fundamental natural base layer that can provide basic elements and valuable functions for long-term development (Section 2.5.4).

Foresight thinking is also one of the thinking attributes of spatial planning and design for resilience. Addressing future disturbances is an important characteristic for resilience. Spatial planning and design for resilience requires paying attention to the future trend of a spatial system. Starting from the current development, background and objective conditions, spatial planning and design for resilience should actively explore the main trends that will happen in the future. The main scenario should be constructed, and conditions should be created to provide possibilities for various developments. Spatial planning and design for resilience should not only consider problems from history, but also from unexpected future (Section 2.5.5).

SQ2-4: What are the main spatial characteristics that can be presented by spatial planning and design for resilience?

Regionality, connectivity, diversity, redundancy, multifunctionality and modularization are six main spatial characteristics that can be presented by spatial planning and design for resilience.

Regionality is the first characteristic to be presented in spatial planning and design for resilience. Spatial planning and design for resilience requires fully respecting the characteristics of the research case, especially the natural base layer. It is an important goal to create a distinctive regional spatial form that adapts to the local environment. Land-use distribution needs to be based on the principle of regionality. The scheme which combines nature-based solutions with corresponding technology is advocated to adapt to the natural base layer. According to local conditions, valuable spatial resources can be applied (Section 2.6.1).

Connectivity is the essence of a networked organizational structure of interconnection among system elements. In order to realize that a spatial system can better absorb the influence when it is disturbed, the system is required to have multiple points, connectivity, and interaction, so that the systems can interact with each other through matter, information and energy. Multi-scale connectivity and multi-dimensional connectivity are emphasized in spatial resilience. Blue-green corridors are important spatial carriers of cross-scale connectivity networks. The 'node and path' of the blue-green networks should be improved to connect the important fragmented blue-green patches to stimulate the network functions of a system. Focusing on improving blue-green networks, the construction of natural corridors should be strengthened (Section 2.6.2).

Diversity is the basis for providing multifunctional spatial services. Diversity increases the efficiency of spatial resources' utilization. Diversity can breed new opportunities and bring more possibilities to address problems. The realization of spatial diversity needs scientific structure arrangement. To realize diversity, spatial planning and design for resilience should broaden thinking and put forward diversified solutions. The application of integration technology and compact and mixed use of land should be advocated to create a multifunctional space (Section 2.6.3).

Multifunctional utilization of land is an important representation of diversity with the situation of limited land resources. The realization of each function of space requires a corresponding amount of land supply as the basis and corresponding spatial support. Multifunctional land-use becomes an inevitable requirement of spatial planning and design for resilience. By regulating the type, mode and intensity of land-use, a variety of functions can be organically combined and rationally arranged to improve land-use efficiency. Multifunctional utilization of spatial elements emphasizes the use of the same space in both normal and disaster situation.
For example, in addition to realizing the functional requirements of engineering, infrastructure such as dykes can be effectively combined with the natural environment to transform the grey infrastructure into a multifunctional landscape. The multifunctional use of dykes can also provide space in different time periods through spatial shacking or time shifting. Different services make the applications of hard dykes more diverse, which not only improve the spatial safety, but also improve the quality of space (Section 2.6.4).

Redundancy refers not only to the replicability of the core elements and functions of a system, but also to the prepared-conditions in which space or facilities are created in advance through spatial planning and design to address new changes that may occur in the future. Redundancy is an important measure to improve the adaptability of a spatial system. Redundancy emphasizes that the spatial system should be able to adapt to the new changes through the appropriate transformation or expansion of original space or the appropriate change of spatial function. Redundancy makes existing spaces flexible and extensible. When a system is in a normal state, the redundancy allows the system a certain margin of particles. When a system is subjected to large disturbances, redundancy becomes necessary to maintain the spatial safe. If necessary, redundant facilities can be used in a multifunctional manner (Section 2.6.5).

Modularization is an important spatial organization measure for resilience. Modularization is to reduce risk by moving the spatial layout from a centralized model to decentralized model in order to disperse the negative influences caused by disturbances. A system can be divided into several modules under the guidance of integrity, and each module has certain independence and completes specific functions. Modules should be strengthened according to the systematic requirements so that each module has the function of autonomy, stability, and self-detection of fault. Spatial planning and design for resilience advocates for setting modules that can be expanded according to future requirement flexibility. The collaboration between modules should be strengthened to improve self-organization ability (Section 2.6.6).

SQ2-5: What is the internal thinking logic of spatial planning and design for resilience?

The theory of spatial planning and design for resilience emphasizes more on the comprehensive grasp of natural base layer and the scenario of extreme climate change, so that the future spatial development can be based on the healthy natural base layer, sufficient land carrying capacity, and the harmonious relationship between human and nature. The theory of spatial planning and design for resilience emphasizes on systematic, coordinative, bottom-line and foresight thinking. It extensively applies some spatial features such as regionality, connectivity, diversity, multifunctionality, redundancy and modularization in order to closely focus on improving the core capabilities of robustness and adaptability. The keys to realizing spatial resilience are as follows.

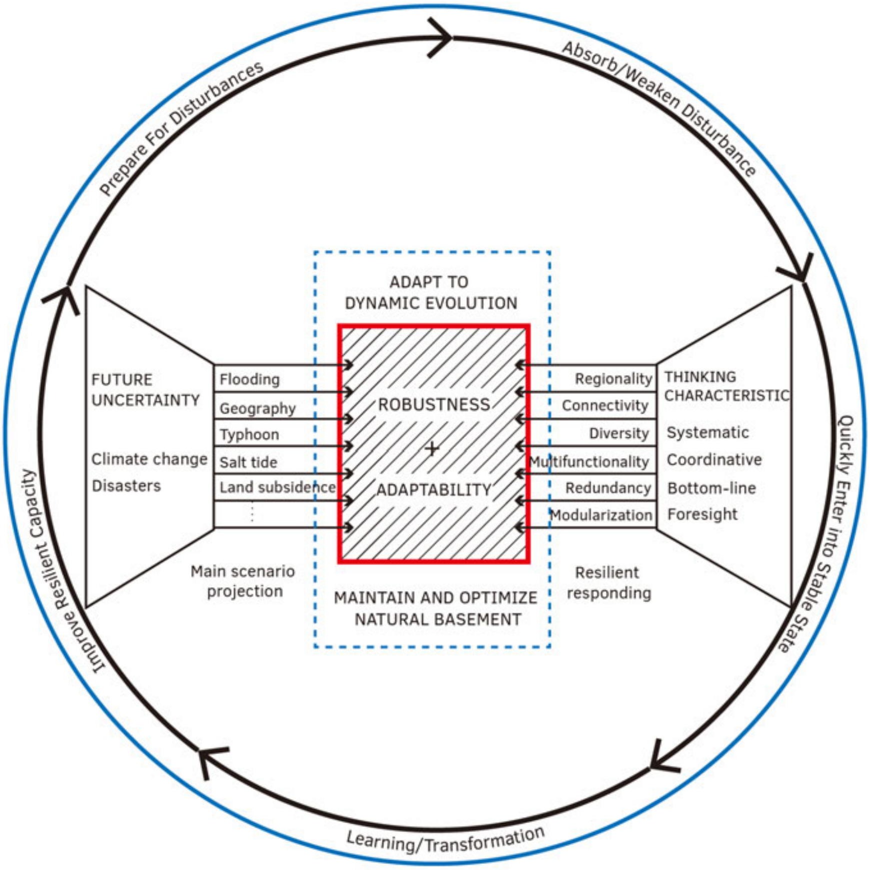

FIG. 6.1 Internal thinking logic of the approach of spatial planning and design for resilience

1 Identification of spatial status and projection of external disturbances. By conducting the assessment of the natural base layer, land carrying capacity, natural resources, land-use suitability and vulnerable areas, the most likely disturbance in the future will be identified from the uncertain multiple future risks, and the main disturbance needs to be taken as the object of resilience and main scenario for spatial planning and design.

2 Improving spatial robustness and adaptability is the essential requirement of spatial resilience. Spatial planning and design for resilience should be good at learning from the experiences of other countries in addressing external disturbances, and take these lessons as an important source of wisdom for planning and design.

TOC

In order to improve the robustness and adaptability of a spatial system, spatial characteristics presented by planning and design for resilience, such as regionality, connectivity, diversity, multifunctionality, redundancy and modularization needs to be widely applied.

3 Self-learning based on evaluation feedback. Due to the limitations of objective conditions and cognitive level, whether the predetermined resilience can be achieved or not can only be tested after experiencing disturbances. Spatial planning and design for resilience should learn from disturbance experiences and absorb reflections into the improvement of planning and design process. The key logic model of spatial planning and design for resilience is shown in figure 6.1.

SQ2-6: What are the innovations of the approach of spatial planning and design for resilience?

The research contents in previous literatures mostly include the indicator system for evaluating the vulnerability of the current spatial system, or projecting different scenarios' situations influenced by climate change, but little on how is it possible to improve the resilience of a spatial system from a planning and design perspective. Some related concepts, such as 'sponge city', 'low impact city', 'sustainable city' also emphasize on keeping the natural attribute of the site and stress on the existing sustainable use of natural resources and socio-economic resources, although the breakthrough points are not focused on addressing unexpected climate change and creating spatial resilience in the future. The theory of resilience from spatial planning and design perspective has not been systematically studied (Section 2.3).

The theory of spatial planning and design for resilience studied in this doctoral dissertation has important significance and practical value. First of all, it answers some important theoretical questions such as the core capabilities, thinking attribute, spatial characteristics and internal logic of spatial planning and design for resilience. It points out that natural base layer and artificial system have a synergistic evolutionary relationship, and the law hidden under the appearance can be found through the study of historical evolution. Planners and designers need to face up to the inevitability of the disturbances brought by climate change, and adopt progressive and innovative mechanisms to address the inevitability of such disturbances, so as to make new schemes that have long-term adaptability. Spatial planning and design for resilience emphasizes multi-scale collaboration. It is not only necessary to consider the impact of schemes on the current environment, but also to project the long-term dynamic changes to ensure the long-term effectiveness of a space.

Chapter 3 builds a bridge between theoretical knowledge and case application to answer Q3 .The principles, organizations, technical route and working process of spatial planning and design for resilience are described in details.

Q3: How is it possible to implement the theory of spatial planning and design for resilience into practice?

To apply the theory of spatial planning and design for resilience to empirical research, it is also necessary to clarify the implementation principles of spatial planning and design for resilience, organization, working process and key points of each phase (Section 3.1).

SQ3-1: How can we organize the work of spatial planning and design for resilience?

Spatial planning and design for resilience emphasizes that the assessment of spatial evolution, water system, ecosystem, land-use suitability and potential flooding and land subsidence risk areas should be systematically analyzed as pre-evaluation results (Section 3.2).

The process of spatial planning and design for resilience has many phases, such as investigation, analysis, arrangement, planning and design, comparison and selection and implementation. A multi-disciplinary database and expert consultation system should be established. A cross-scale collaboration platform should also be established. According to the duration of a scheme, the construction phase can be divided into short term, medium term and long term. It is important to focus on the connection of short-term, medium and long-term actions (Section 3.3).

SQ3-2: What is the process of spatial planning and design for resilience?

The process of spatial planning and design for resilience is shown in Figure 3.2. The evolution of space through the two dimensions of time and space is analyzed to find a bridge between history and the future. Potential flooding and land subsidence risk areas should be assessed. The main development scenarios should be identified and the corresponding strategies should be implemented.

Planning and design is the most important part of the whole process. Based on the characteristics of a spatial system, the planning and design for resilience should take land-use as the core of the whole process. The land-use strategies depend on the

TOC

evaluation results of natural resources, natural protection and land-use suitability. The infrastructure should be strengthened in areas with high vulnerability of flooding and land subsidence and low land carrying capacity. The proposed- scheme should strengthen network connectivity of blue-green networks. The functional distribution of coastline needs to respect its surrounding urban and water environment. It is of great importance to build a resilient flood control and drainage system on the basis of fully understanding the mechanism of delta estuaries (Section 3.3).

SQ3-3: What can be the key points of spatial planning and design for resilience at different scales?

Macro-scale planning and design should focus on critical issues such as integrity of large spatial patterns, land-use, cross-regional blue-green networks and coastline. Giving priority to the natural process and focusing on important hydro-ecological corridors are important. As an intermediary connecting macroscopic and microscopic scales, the spatial planning and design at the meso scale should implement the results of the macro's scheme. The diversity, multifunctionality and redundancy of each type of node space should be strengthened in the micro scale's planning and design. The natural processes should be respected, and the adaptability of node space to climate change should be strengthened. Spatial characteristics presented by spatial planning and design for resilience should be applied to organize the spatial configuration to better adapt to the environment. The spatial layout should be moderately advanced in network and redundant elements to provide diversified options for addressing future disturbances (Section 3.4, 3.5).

Chapter 4 focuses on answering Q4. The principles and strategies of spatial planning and design for resilience in the PRD at the macro scale are put forward from the three aspects of land-use, blue-green networks, and coastline.

Q4: How is it possible to apply the theory of spatial planning and design for resilience to the PRD?

Chapter 4 selects the PRD as an empirical research case and discusses the application of the theory of spatial planning and design for resilience from the macro scale. Based on the in-depth analysis of the current spatial status of the PRD, the spatial planning and design for resilient strategies of the PRD are mainly put forward from the perspectives of land-uses, blue-green networks and coastline.

SQ4-1: What could be the overall framework of spatial planning and design for a resilient PRD?

The general framework includes the following:

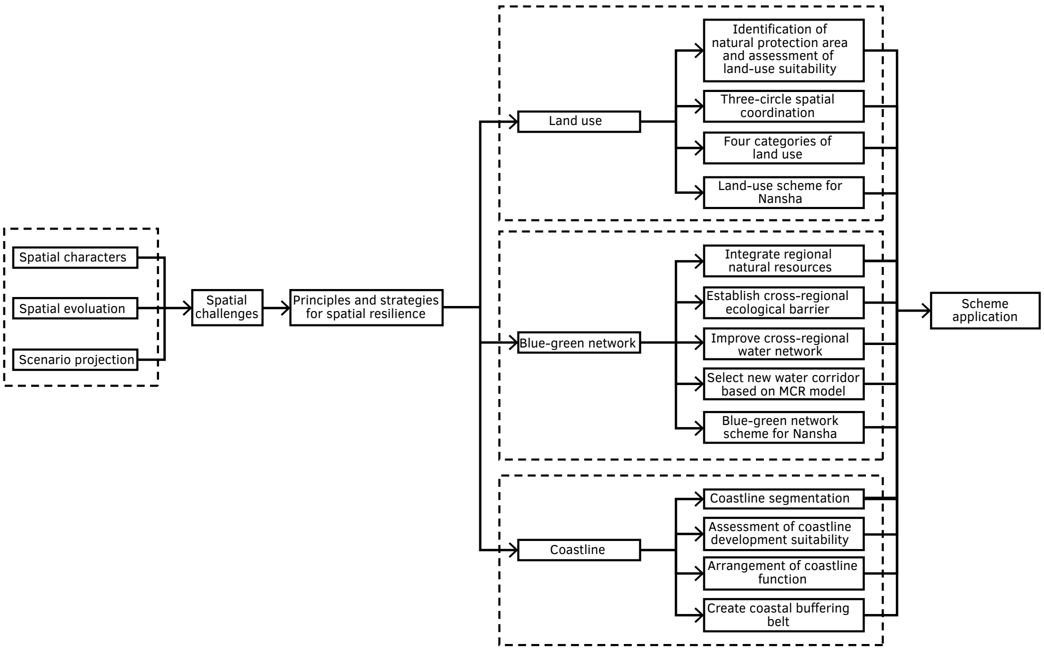

FIG. 6.2 Technic route of spatial planning and design for a resilient PRD

STEP 1 The spatial evolution characteristics of the PRD should be analyzed based on regional features.

STEP 2 The future scenarios of the PRD under climate change should be projected.

STEP 3 The distribution of potential flooding and land subsidence risk areas should be analyzed.

STEP 4 The principles and strategies for land-use in the PRD are researched according to the identification of natural protection areas, and the assessments of agricultural and urban land-use suitability.

STEP 5 The principles and strategies for improving blue-green networks in the PRD are put forward based on minimum cumulative resistance (MCR) model.

STEP 6 The principles and strategies for coastline in the PRD are researched. The arrangement of coastline function is conducted based on coastline development suitability assessment (Section 4.2).

The overall framework of spatial planning and design for resilient PRD is shown below.

SQ4-2: What are the characteristics of current spatial status in the PRD?

Urban space of the PRD is characterized as ‘dense and compact in the north and east part, sparse and loose in the south and west part’. Guangzhou city and Shenzhen city are always in the leading position in the regional development and play a decisive role as the radiation centers of the delta. The connection line between Guangzhou city and Shenzhen city has always been the most important social and economic channel in PRD.

The blue-green space is characterized by ‘strong and dense in the outer circle, weak and sparse in the inner circle’. Zhaoqing city -Guangzhou city, Dongguan city -Huizhou city and Zhongshan city -Zhuhai city serve as the radiative source and radiative corridors for the PRD. The main water corridors related with the West River and the North River are important ecological buffer corridors. Some of the ecological corridors between Guangzhou city and Foshan city, Guangzhou city and Zhongshan city, Zhuhai city and Jiangmen city, Dongguan city and Shenzhen city have been converted into urban lands.

At present, there are the following main problems in the whole region of the PRD.

Spatial development is inadequate and unbalanced. The west upstream region of the PRD has formed a highly integrated cross axis topological spatial network. The linear axis of the spatial structure has been basically formed in the eastern coast of the Pearl River. The West Bank downstream region of the Pearl River develops in a scattered layout spatial structure. The production, living and ecological functions are mixed in urban fringe areas in the PRD with extensive land-use situation.

Original blue-green space tends to deteriorate. Natural fragmentation index is increased, and the depths of riverbeds are changed so that the runoff and sedimentation diversion ratio of important branches are changed, which increases the flood control and drainage pressure of some branches. The average runoff of the West, North and East River are increased significantly. The water levels of waterways of Donghai, Dongping and Shunde, which are located at important branches of the West River and the North River, are generally raised. The effective crossing width of the channel becomes low, which reduces the storage capacity of the channel (Section 4.3).

SQ4-3: What could be principles for improving land-use distribution in resilient PRD?

Spatial planning and design for a resilient PRD are closely related to land-use distributions. The land-use distribution that adapts to ecological and hydrologic mechanisms can largely reduce the negative impacts from flooding, land subsidence and earthquake disasters under extreme climate condition. Therefore, resilient land-use strategies should fully reflect on the regional characteristics and coordinate the relationship between natural protection and urbanization. In the future, the land-use distribution of the PRD should attach importance to the results of land-use suitability assessment, and reasonably regulate the intensity of constructive lands in the coastal area, and advocate diversified, mixed and compact land-use distribution (Section 4.4.1).

The results of natural protection area identification have priority to the decision of future land-use distribution. The principle of natural priority should be maintained when there are contradictions in different types of land use. When there are ambiguities in the division of agricultural lands and urban lands, some important factors such as regional characteristics, development positioning, potential risk areas, ecosystem and water system conditions should be considered comprehensively.

SQ4-4: How can we improve land-use distribution based on land-use suitability assessment in resilient PRD?

The identification of natural protection areas, agricultural and urban areas is based on land-use suitability assessments in the PRD for preventing the potential negative impacts from flood and land subsidence under extreme climate change conditions. The strategic spatial pattern named by ‘three-circle space coordination and four land-use categories’ is generally formed.

Given the original circle-layout characters of the PRD, three-circle space should be developed coordinately. The first circle is the coastal belt. It is necessary to make full use of the advantages of ports to construct the coastal shoreline protection belt. The second circle is located between the coastal circle and the natural protection mountainous area. This circle provides the most mutual feedings between the urban and the blue-green space. The proposed -scheme focuses on the construction and restoration of urban internal ecological corridors and opening green spaces. The third circle is the natural protection mountainous, which is the key protection area of important vegetation, soil, water source reservation.

Four land-use categories are named as; natural protection area, agricultural development area, urban development space and coastline area. Each of the four land-use categories is arranged by corresponding strategies and measurements (Section 4.4.3).

The overall protection/development pattern is shown in Figure 4.16, and the possible land-use scheme is shown in Figure 4.17. The corresponding land-use scheme for Nansha District is shown in Figure 4.22.

SQ4-5: What could be the principles for improving blue-green networks in resilient PRD?

The regional blue-green networks can be regarded as backbones for the organization of different land-use in the PRD. The blue-green network strategies should fully reflect the principle of network connectivity. In response to the real situation of degradations of rivers, branches, waterways, tributaries and congestion at estuaries, it is necessary to integrate regional natural environment resources and focus on creating cross-regional ecological corridors and water corridors. It is possible to reconnect crucial cross-regional rivers (tributaries) by adding new passing water channels in the upstream nearby important cities to improve the flood safety of the whole PRD (Section 4.5.1, Section 4.5.2).

SQ4-6: How can we improve the blue-green networks based on the minimum cumulative resistance (MCR) model in resilient PRD?

On the basis of the existing water networks in the PRD, the minimum cumulative resistance (MCR) model is used to help select potential blue-green corridors with comprehensive least environmental cost and lowest average land resistance between aimed connecting points. According to the analysis, some rivers in the PRD have caused problems in the river reach, which has caused great pressures on the flood control of surrounding cities. These problems should be given prior attention in spatial planning and design. After analysing and simulation by the assistance of the MCR model, Line AB, Line CD and Line EF in the figure 4.24 are proposed as new connective water corridors to improve the performance of PRD's water networks (Section 4.5.4)

Meanwhile, the potential ecological barriers are built by using mountains, reservoirs, forest parks, wetlands, which can play roles in water conservation, biodiversity protection and soil and water conservation. In the coastal areas, marine barriers should be built on the basis of ecosystems such as bays, islands, coastal wetlands, mangroves and coral reefs. The distribution of water resources of the North, West and East Rivers should be improved to slow down the peak flood speed of the West River. The protection of Huangmao Sea should be strengthened to prevent the trend of further shrinkage of the gate. Qianhai and Houhai mangrove nature reserves in Shenzhen city need to be protected. It is necessary to strengthen the connectivity of the Olive River, the upper and lower waterways, the Hongqi waterway and the Jiao waterway. The large tidal flats should be protected beside Hu Estuary to reduce the flooding impact on Guangzhou City (Section 4.5.3).

The process and results of possible improved schemes for Nansha District blue networks can be seen in figure 4.31 and figure 4.32.

SQ4-7: What could be principles for improving coastline quality in the PRD?

The coastline is an important spatial factor to ensure the safety of flooding and improve the hydrologic and ecological environment of the PRD. Spatial planning and design for a resilient coastline of the PRD can focus on reasonably arranging the function of coastline and creating coastal buffer belts. Areas for development, controlled development or protection of each coastline segments should be determined based on the results of coastline development suitability assessment. Flood storage space and buffering areas need to be constructed by taking the advantages of elements such as tidal flats outside the dykes and public space inside the dykes (Section 4.6.1).

SQ4-6: How can we arrange the coastline function and create a buffering belt based on coastline development suitability assessment in resilient PRD?

The indicators such as the rate of land subsidence, the inundation depth under 200-year flooding, the steady state of the surrounding water (erosion and sedimentation) and the distribution of spatial natural resources are used, in order to make comprehensive evaluations of the suitability assessment of coastline development (Section 4.6.3).Based on the results of assessment , the coastline function of the PRD can be divided into an area for development, an area for controlled development and an area for protection, which is shown in figure 4.36. Corresponding strategies for resilience of coastline are proposed. Some coastline segments such as AB, CD, EF and GH in figure 4.36, whose existing functions are largely conflicts to the arranged function, should be adjusted with corresponding measurements. At the same time, it needs to actively use the intertidal lands, flood storage space to build a scoastline buffering belt so as to realize the combination of the functions in normal days and the functions in flooding days (Section 4.6.4).

Q5 is answered in Chapter 5. Hengli Island is selected as a case for empirical research. The principles, strategies and a new scheme of spatial planning and design for resilient flood control and drainage are proposed respectively.

Q5: How is it possible to apply the theory of spatial planning and design for resilience to address the flood control and drainage problem on Hengli Island?

In Chapter 5, Hengli Island in Nansha District of PRD is selected as a case for empirical research. The theory of spatial planning and design for resilience is applied to explore a resilient flood control and drainage system on Hengli Island.

SQ5-1: What can be the general framework of spatial planning and design for resilient flood control and drainage on Hengli Island?

In Chapter 5, the approach for spatial planning and design for resilient flood control and drainage systems are suggested. The technical route is shown below (Section 5.3.2)

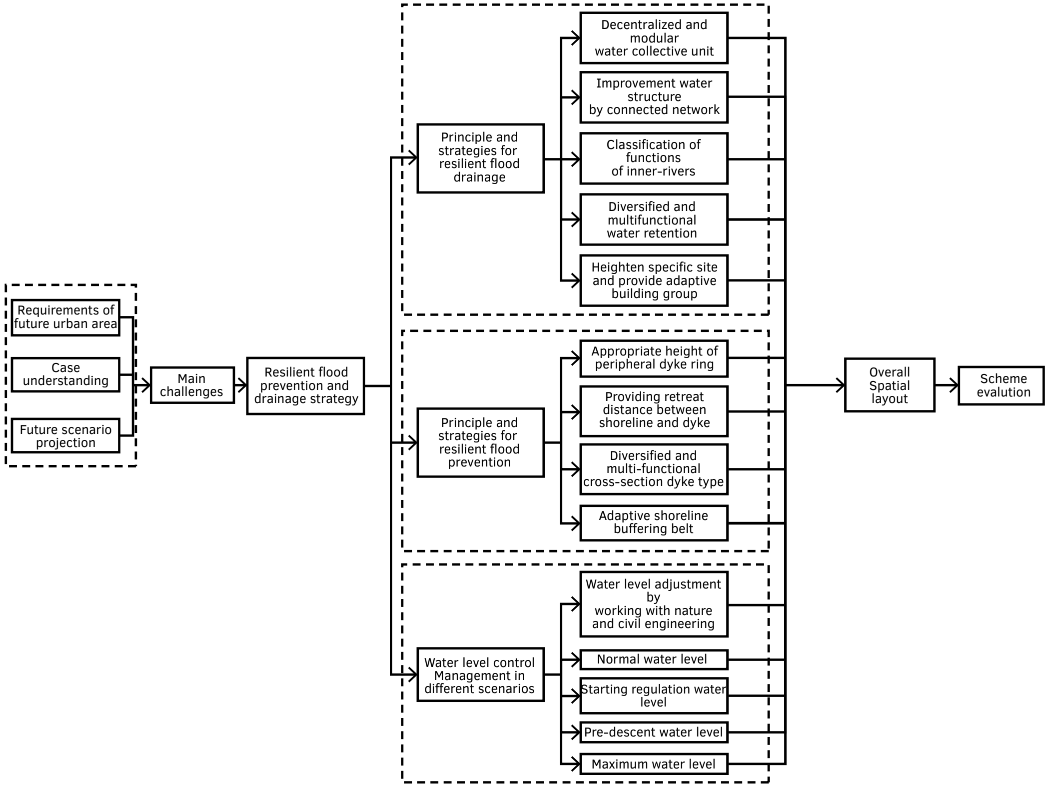

FIG. 6.3 Technic route of resilient flood control and drainage on Hengli Island

STEP 1 Based on regional characteristics of Hengli Island, it is necessary to analyze historical flooding disasters and the elevation relationship between outside waterways, inner-river and site surface. The existing problems of flood control and drainage are identified.

STEP 2 The potential impacts of the scenario of extreme climate change on Hengli Island need to be identified for rational spatial organization. It is important to conduct simulation analyses to evaluate whether the current waterways, inner-river system and each water collective unit have enough capability to store water, and whether the current dyke standards have enough ability to adapt flooding from outside waterways.

STEP 3 It is necessary to conduct evaluation and simulation to deeply discover the current spatial status. The items such as: (a) Analysis of water storage of each water collective unit, (b) Evaluation of the condition of each shoreline segment and (c) Spatial distribution of current elements for resilient flood control and drainage.

STEP 4 Research on principles and strategies for resilient flood drainage such as: (a) Decentralized and modular water collective unit, (b) Spatial organization of new water networks with the assistant elements of low-lying depression, lakes and wetlands, (c) Classification of the function of inner-rivers, (d) Diversified and multifunctional water retention spots and (e) Heightening spatial site and providing adaptive building groups.

STEP 5 Research on principles and strategies for flood prevention such as: (a) Appropriate height of peripheral dyke ring, (b) Creating retreat distance of dyke from shoreline, (c) Shaping diversified and multifunctional cross-section dyke shape and (d) Adaptive shoreline buffering belt.

STEP 6 Research on principles and strategies for water level management in different scenarios such as: (a) Adjusting water level based on working with nature and civil engineering, (b) Providing spatial carriers for self-discharge and artificial- extraction and (c) Providing four types of water level for different scenarios.

STEP 7 The effectiveness of the new scheme is analyzed with an evaluation framework.

SQ5-2: What spatial planning and design strategies and measures for resilience can be taken in resilient flood drainage on Hengli Island?

Facing continuous pluvial and fluvial impact and specific site conditions, the spatial characters of resilience, such as regionality, network, diversity, multifunctionality, redundancy and modularization, should be widely implemented to improve the robustness and adaptability of current flood drainage systems (Section 5.7.1).

The application of regionality refers to comprehensively considering the factors such as elevation, water level, dyke heights and properly exploring land-use suitability, 'source-confluence-runoff' water flow and water circulation.

The application of connectivity refers to improving current water networks with the combined spatial carriers of inner-rivers, regulation lakes, wetlands and low-lying depressions to form a better water storage network from a fragmented model to networked model. It is necessary to increase network density and network connectivity to increase current water storage.

The application of modularization refers to dividing existing water collective units from a centralized model to a decentralized model, for dispersing flood risk at the source. According to the calculated water storage gaps, the centralized surface water collective units need to be changed to decentralized water collective units.

TOC

According to newly distributed water collective units, the distance from each potential flooding and waterlogging points to adjacent water bodies can be reduced, which can ensure a smoother water circulation and greater water storage capacity.

The application of redundancy refers to providing buffering spaces along the shoreline and creating tidal flats to reduce the impact of outside waterways. The water level can be lowered below the normal water level in order to further increase the water storage capacity.

The application of multifunctionality refers to combining flood safety with irrigation, landscape-viewing, navigation, social communication, business and public life.

SQ5-3: What spatial planning and design strategies and measures can be taken in resilient flood prevention on Hengli Island?

The flood prevention organization should fully highlight the regional natural characteristics. The impact of water level of tidal influence can be reduced by means of increasing the height of the peripheral dyke ring and the length of the buffering area of shoreline (Section 5.8.1).

Application of redundancy refers to providing multiple redundant measures for flood prevention. By providing the appropriate height of the dyke, creating reasonable buffering areas and setting adaptive shoreline buffering belts, the negative impact of tidal influence can be reduced to ensure flood safety and landscape-viewing under extreme climate conditions.

Application of diversity refers to taking corresponding measures and choosing different cross-section dyke shapes for different shoreline sections based on the differences of functional characteristics and terrain conditions in order to fully respect the natural process and reduce the losses caused by tidal influence.

Application of regionality refers to giving full play to the coastal resources and realizing the prosperity of the water environment. It is important to combine the function of special safety and leisure, recreation, education and culture landscape.

Application of multifunctionality refers to providing adaptive shoreline buffering belts that can connect different cross-section dyke types and can function as a landscape belt in normal days and function as floodable spaces under extreme climate condition.

SQ5-4: How can the new scheme adapt to more severe extreme climate?

The key for effectively improving the adaptability of space to environmental changes is to adopt spatial characters of resilience that can be presented by planning and design as much as possible, such as regionality, redundancy, connectivity, multifunctionality, diversity, modularization, especially the spatial characteristics of redundancy and multifunctionality. Redundancy refers to the provision of space or facilities in advance that can be prepared for possible new changes in the future. It actively creates the conditions to address the new possible changes in the future and makes the existing space flexible and expandable. Multifunctionality can provide different services from the same space in different periods through the means of spatial stacking or time shifting. The spatial carriers such as tidal flats, floodplain space, and retention ground and shelter forest could be used to expand the floodable area for reducing the impact of tidal influence. The buffering area is reserved both on the inside and outside of dykes, which can be used as a landscape belt at normal times and becomes floodable areas if necessary. Wetland parks and artificial lakes are arranged in low-lying areas to serve as excessive water storage bodies under extreme climate conditions. Public space is combined with blue-green infrastructure to create multifunctional space. In areas with high elevation and dense population, emergency safe evacuation places can be set in advance to ensure traffic accessibility. Different water level control schemes are proposed under various scenarios, and adaptive buildings are suggested.

SQ5-5: How can one evaluate the scheme's effectiveness for resilient flood control and drainage?

Based on the core objective of improving the future water performance for resilient flood control, the following indicators could be selected to evaluate the feasibility and effectiveness of resilient flood control by simulations, including: (a) The size and the spatial distribution of potential flooding areas, (b) The number of gaps between the capacity of water storage and future precipitation, (c) Peak runoff speed in each new water collective unit, (d) Connectivity and the degree of spatial integration of a water system and (e) Landscape effects of important locations. The evaluation and simulation results all show the feasibility and effectiveness of the new scheme for flood resilience. (Section 5.10, Appendix D-12, Appendix D-13).

6.3 **Originality**

A Theoretical features of spatial planning and design for resilience

This doctoral dissertation proposes the theoretical features of spatial planning and design for resilience, including the core capabilities pursued by spatial planning and design for resilience and fundamental thinking characteristics of spatial planning and design for resilience. It proposes that robustness and adaptability are two core capabilities pursued by spatial planning and design, and systematic thinking, coordinative thinking, bottom-line thinking and foresight thinking are four fundamental thinking characteristics of spatial planning and design for resilience (Table 2.3). This doctoral dissertation also proposes an internal thinking logic of the approach of spatial planning and design for resilience (Figure 2.5). Different from other spatial planning and design methods, spatial planning and design for resilience emphasizes to pay more attention to expound the understanding of driving forces such as nature, ecology, society and economy and to comprehensively grasp the harmonious relationship between natural base layer and socio-economic development. Spatial planning and design for resilience should be good at learning and drawing lessons from the world and translating them into the wisdom of planning and design. Spatial planning and design for resilience should focus on identifying external disturbances, developing spatial strategies and methods for coping with disturbances, and strengthening feedback assessment. The core of spatial planning and design for resilience is to give priority to ecology and make spatial development on the basis of ecological capacity and guarantee the bottom line.

B Main spatial characteristics of resilience presented by planning and design

The extraction of key spatial characteristics is of great significance to the formulation of principles and strategies for spatial planning and design for resilience. The commonly used spatial resilience assessment models (Rockefeller foundation model, HOSEI University model, RATA model, Chinese Resilient Assessment Framework, etc.) involve more than 20 indicators from the aspects of society, economy, environment, management, which lacks guidance and operability for spatial planning and design for resilience

This doctoral dissertation extracts main spatial characteristics presented by planning and design for resilience based on the understanding of the theoretical features of resilience. These main spatial characteristics are respectively regionality, connectivity, diversity, multifunctionality, redundancy and modularization. It is proved that these six spatial characteristics can become the common principles of spatial planning and design for achieving resilience. Regionality means that the planning and design scheme should be based on the site characteristics, fully respectful to the natural base layer and make use of regional resources. Connectivity refers to the strong connection and feedback among spatial elements. Diversity is the basic condition for resilient spatial system when facing external disturbances. It not only refers to the multifunction of a spatial system, but also refers to a variety of ways to achieve to the goal of spatial resilience. Redundancy refers to preparations provided in advance for future unpredictable changes in order to let the space to be extendable, which can provide possibilities for addressing uncertain risks. Modularization refers to divide the complex system into several controllable and reasonable modules in order to disperse potential risks and guarantee the smooth operation of a spatial system.

This doctoral dissertation elaborates why these six spatial characteristics can help to improve the resilient capacity of spatial system. The understanding of these six important spatial characteristics of resilience presented by planning and design is basis of proposing specific detailed planning and design principles and strategies for the PRD.

C Implementation method of spatial planning and design for resilience

This doctoral dissertation believes that understanding the mechanism of system evolution is the basis of spatial planning and design for resilience. Spatial planning and design for resilience should be based on the analysis of the hydro-ecological system, the assessment of land-use suitability, the projection of potential flooding and land subsidence risk areas. The main flooding risk area and key natural protection nodes should be identified and the corresponding database should be constructed. Based on above understanding, this doctoral dissertation formulates the implementation method of spatial planning and design for resilience, which includes several major phases such as target determination, system interpretation, main scenario projection, system planning and design, as well as evaluation and feedback. This doctoral dissertation elaborates key points of each phase in detail. In addition, the implementation principles, organization, and technical route are also put forward (Figure 3.2).

TOC

D Possible spatial planning and design schemes for the PRD from four aspects

Facing the serious situation of flooding, this doctoral dissertation firstly analyses the spatial characteristics, spatial evolution, and major scenarios of the future climate change in the PRD, and then some innovative schemes are proposed by using the theory and method of spatial planning and design for resilience put forward by this doctoral dissertation from four aspects. All these possible spatial schemes can reflect to the research gaps in section 1.1.2.

Land use

Combining the spatial characteristics such as regionality, diversity, and multifunctionality, this doctoral dissertation proposes the general principles for future land use of the PRD. The principles of land-use schemes should fully reflect the regional natural elements that need to be considered in priority. Land use that conforms to natural conditions and adapts to hydro-ecological structure can possibly avoid being exposed to serious flooding and land subsidence. New possible land-use schemes for the whole PRD should consider the results of both the identification of natural protection area and the land-use suitability assessments of agricultural and urban lands. It is necessary to arrange a variety of mixed and compact land-use model and regulate the intensity of construction lands in the coastal area.

The results can be seen in the followings. First of all, the major scenario of future climate is projected. Evaluation maps of the risk areas of flooding and land subsidence are created. Secondly, supported by ArcGIS software, maps of the identification of natural protection area and the land-use suitability assessment of agricultural and urban lands are draw by overlaying multiple objective-related spatial indicators. It is proposed that the mapping result of the identification of natural protection area should have its priority to the future land-use scheme. Thirdly, a possible land-use scheme with the guidelines of ‘three-circle spatial coordination’ and ‘four categories of land use’ is proposed, which takes the mapping results of the identification of natural protection area and the land-use suitability assessments of agricultural and urban lands into considerations. Fourthly, supported by FLUS, Markov-CA chain and ArcGIS software, a possible land-use scheme in local context—Nansha is proposed with the considerations of both the identification of natural protection areas and the appropriate population that can be accommodated. A possible future land-use evolution pathway is simulated under different population numbers, in order to find out ‘tipping points’of land use and subsequently to determine the maximum amount of population.

It can be found that the land-use scheme in this research put more emphasis on protecting natural lands and avoiding potential flooding and land subsidence areas. The sizes of construction lands in this doctoral dissertation are smaller than those obtained from the documents of previous land-use scheme in the PRD. The spatial form of this possible land-use scheme that combines the factors of natural topography, potential flooding and land subsidence area, estuaries' tidal environment tends to be more organic. In this land-use scheme, the disordered reclamations in major estuaries are restricted and the silt-up areas are protected.

Blue-green network

Combining the spatial characteristics such as regionality, connectivity, and redundancy, this doctoral dissertation proposes the general principles for future blue-green situation. The principles for new possible blue-green schemes should fully reflect the spatial characteristic of network connectivity. In response to the challenges of the degradation of water environment and the congestion of estuaries, it is necessary to integrate regional natural resources and focus on creating cross-regional blue-green corridors. It is possible to reconnect crucial cross-regional rivers by adding new passing water corridors in the upstream location that closes to important cities. It is necessary to take the situation of topography, landform, elevation and natural resources into considerations and break the administrative boundary line to guarantee the integrity of the hydro-ecosystem.

The results can be seen in the followings. First of all, the major scenario of future climate is projected and maps of comprehensive risk areas are draw. Secondly, cross-regional ecological corridors are established based on existing natural resources like large mountains, wetlands and regional parks. Thirdly, cross-regional water network of the PRD is improved by adding new passing water corridors between three problematic rivers (the north river and its branches in the westside upstream region, the west river in the westside downstream region and waterways in Nansha), with the assistance of MCR model. Each possible option of this kind of new water corridor is analysed from both advantages and disadvantage aspects. Fourthly, blue network in local context—Nansha is improved. The new blue network consists of three types of water carriers, including large protected waterways, improved inner-rivers, and newly digging inner-rivers.

Coastline

This doctoral dissertation proposes ideas for future PRD's coastline such as the arrangement of coastline function and the creation of coastal buffering belt. The scheme of the arrangement of coastline function is based on the situation of hydro-ecological environment and the requirements of flooding defence on each coastline segment. According to the different characteristics of each coastline segment, different functions should be arranged and different type of dyke section should be proposed. The scheme of new coastal buffering belt should be based on factors such as hydrodynamic force and the tidal resources alongside the estuaries. When constructing the coastal buffering belt, the hydrodynamic force of the estuaries should be analysed. Both tidal resources outside the dyke and leisure parks inside the dyke can be used to construct coastline buffer belt for preventing tidal invasion.

The results can be seen in the followings. First of all, based on the results of the assessments of coastline development suitability of each coastline segment, the new scheme of the arrangement of the coastline function in the PRD is proposed. Secondly, some key coastline segments whose current coastline function and future arranged coastline functions that are not matched are selected and adjusted. Thirdly, combining the results of the calculations of hydrodynamic force, 100-200 meters width buffering belts inside of waterways of Hongqi, Shawan and Xiqiao are suggested, which have a fast low rate and scour significant watercourses.

Flood control and drainage

Based on the understanding of the complexity of flood control and drainage situation in the PRD, this doctoral dissertation puts forward a planning and design framework for multi-layer resilient flood control and drainage. The first layer of the framework is the drainage layer mainly consists of water network. The main objective of adjusting the spatial elements in this layer is to eliminate the gaps between current water storage capacity of the site and future precipitation by the means of decentralizing water collective units, connecting water corridors and adding more multifunctional water storage points. Rivers, lakes, depressions, ditch ponds can all be used as the spatial components for this layer. The second layer is the dyke infrastructure. The main objective of adjusting the spatial elements of this layer is to prevent uncertain tidal and pluvial influences by the means of setting appropriate height of dyke and creating diversified and multifunctional cross-section dyke shape based on the spatial analysis of coastline evolution, and the situation of erosion and sedimentation. The third layer is water level management in different scenarios. The purpose is to formulate water level control and the corresponding elevation values of both inner-rivers and outside waterways so as to ensure that the water system has sufficient resilient ability to adapt to various flooding scenarios.

The results can be seen in the followings. First of all, the framework of the multi-layer resilient flood control and drainage is proposed. The overall technical route for the spatial organization of resilient flood control and drainage is proposed from the aspects of flood drainage, flood prevention and water level management. Secondly, the spatial characteristics of resilience are integrated into the framework of multi-layer resilient flood control and drainage. The principles and strategies of resilient flood control and drainage are proposed. Thirdly, a possible new scheme of the spatial layout for resilient flood control and drainage systems is proposed with corresponding principles and strategies of resilient flood control and drainage. Spatial layout for flood control and drainage and new elevation relationships are proposed. Fourthly, key planning and design aspects for resilient flood control and drainage are researched, such as decentralized and modular water collective unit, improved water network, classified inner-rivers, diversified and multifunctional water storage spots, appropriate dyke's height, appropriate distance between dyke and shoreline, as well as diversified and multifunctional cross-section dyke shape.

6.4 Discussion

6.4.1 Value transformation: From resistance to adaptation

Compared with traditional planning and design, spatial planning and design for resilience can provide more possibilities to adapt to dynamic and uncertain environments. In the past, the main approach to address water-related issues in the delta was to build or heighten dykes into a fixed value alongside rivers, or set massive drainage pipes in the site. Static dykes with fixed heights break the current blue-green network and restrict water from entering into a certain range along riverbeds. A purely engineering-based approach often ignores the integrity, synergy, natural bottom –line and adaptability of the system, which causes the degradation of water and ecosystem. The alternative approach of spatial planning and design for resilience focuses on improving the capabilities of robustness and adaptability by

TOC

systematic, coordinative, bottom-line and foresight thinking during the process of planning and design. It widely uses spatial characteristics that can be presented by planning and design, such as regionality, connectivity, multifunctionality, diversity, modularization, and redundancy. Spatial planning and design for resilience can be a systematic approach with positive, foresight and targeted prevention when facing unexpected disturbances like flooding and land subsidence in the PRD.

6.4.2 Role of spatial planning and design in realizing resilience

The means of improving the capacity of resilience of the PRD are multiple, which can be studied from the aspects of technology, management and the social economy. Planners and designers can make their contributions to realize spatial resilience by setting out principles, strategies and proposing new spatial layouts. This doctoral dissertation focuses on improving the capacity of resilience from the perspective of spatial planning and design, with the assistance of corresponding data and relevant technical support. Guided by the theory of spatial planning and design for resilience, the implementation method of spatial planning and design can be organized through the process of system interpretation, system projection, planning and design for resilience, feedback and evaluation. Research by planning and design in empirical research is an effective way to test all the principles, strategies and measurements that could be learned from theoretical studies.

In this doctoral dissertation, the validity of the studied theories and methods in Chapter 2 and Chapter 3 is tested by empirical research of two different scales in the PRD in Chapter 4 and Chapter 5, which respond to the spatial problems of the PRD that are put forward in Chapter 1, from the aspects of improving land-use, blue-green networks, coastline, and flood control and drainage systems at different scales.

6.4.3 Deficiency in this doctoral dissertation and future works

This doctoral dissertation focuses on improving the capacity of resilience of the PRD, under the background of the negative disturbances caused by climate change, especially in flooding and land subsidence. It provides an alternative way to address the situation of unexpected climate change, which focuses on creating resilient principles and strategies of land-use, cross-regional blue-green networks, coastline, and flood control and drainage systems. This doctoral dissertation provides knowledge for linking theory, projection, planning and design schemes, evaluation and feedback. It attempts to reflect on all the research questions that are proposed in Chapter 1. However, because of limited time, insufficient precise database, there are still some deficiencies in this doctoral dissertation which needs to be further improved. The following points deserve to be further studied.

A The study of evaluation indicators of spatial planning and design for resilience

How to establish measurable indicators for evaluating spatial resilience is an issue that needs to be further studied. In this doctoral dissertation, six spatial characteristics for resilience that can be presented by planning and design, such as regionality, connectivity, diversity, multifunctionality, redundancy and modularization are proposed, which lays fundamental knowledge for the establishment of evaluation indicator systems. In the future, based on these spatial characteristics, the techniques for deepening these characteristics and set up sub-indicators and corresponding weights are worth further studies.

B The study of spatial life cycle and land carrying capacity threshold

This doctoral dissertation emphasizes the idea of natural priority and addresses the relationship between spatial elements. Spatial life cycle can explore the relationship between spatial elements. In order to create the new land-use scheme that has balance between natural and urban pattern, identifying land carrying capacity threshold value is important. It reflects the compatibility of urban development and resources of the environment. Understanding spatial life cycle and land carrying capacity provides the basis for achieving spatial resilience. Therefore, it is worth further studying spatial life cycle and land carrying capacity threshold in the PRD.

C The research on one scheme adapts to multiple scenarios

The future situations are uncertain in the PRD. In addition to extreme climate change, industrial transformation and population mobility in the PRD will become important uncertainties in the future. This doctoral dissertation emphasizes that the main scenario in the future has to be identified from a variety of possible scenarios, and for this main scenario, the theory of spatial planning and design for resilience can be widely applied by realizing spatial characters like regionality, connectivity, diversity, multifunctionality, modularization and redundancy, as much as possible. However, how to develop a type of spatial planning and design method which can allow one scheme to adapt to multiple scenarios simultaneously by combining theories of complex systems with uncertainty and adaptive pathway analysis is worth studying under the PRD context.

D The transformation ability of spatial planning and design for resilience needs to be strengthened

The learning and transformation ability of resilience in the PRD is mainly reflected in the non-spatial organizational and management of spatial planning and design processes. From a spatial governance point of view, spatial planning systems, policies and agenda are also important considerations for achieving resilience. Although this doctoral dissertation puts forward some basic ideas such as being good at learning from the experience of addressing disturbance around the world, drawing lessons and taking it as an important wisdom source of spatial planning and design are an important way of improving resilient abilities. However, it is worth further studying how to deepen and refine the management of processes in future research.

The theory and the method of spatial planning and design for resilient PRD takes systematic, coordinative, bottom-line and foresight as the thinking characteristics, and robustness and adaptability capacity of a system as the targets, consequently extensively applying characteristics such as regionality, connectivity, diversity, multifunctionality, modularization and redundancy to improve spatial resilience. Resilience not only conforms to the future requirements of spatial development in the PRD, but can also be an inevitable product for the field of spatial planning and design in the future.

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Appendices

APPENDIX A

The background of the PRD

A.1 The context of the PRD

The Great Pearl River Delta (GPRD) formed 340,000 years ago. The water source of GPRD is from the uplifting plate of the 'Qinghai-Tibet' Plateau. The estuary of PRD has experienced the processes of ascent and descent movement of the sea. Rivers formed by the processes of continuous sedimentation and erosion and gradually shaped the landscape of this complex river basin and delta.

As shown in figure app.A.1, the GPRD is mainly composed of the West River Basin, North River Basin, East River Basin, and other small basins of tributaries. The West, North and East Rivers flow across eight provinces in China, and eventually converge into the South China Sea. The West River is the longest river of the GPRD. It originates from the Maxiong Mountain and the Wumeng Mountain in Qujing City, Yunnan Province and flows across Guizhou Province, Guangxi Province, and Guangdong Province. The North River is the second longest river of the GPRD. It originates from Shijie Village, Xinfeng County, Jiangxi Province and flows to Guangdong province from Shaoguan city. The East River is the third longest river in the GPRD. It originates from Xunjing County, Jiangxi Province and flows to Guangdong Province from Longchuan County.

TOC

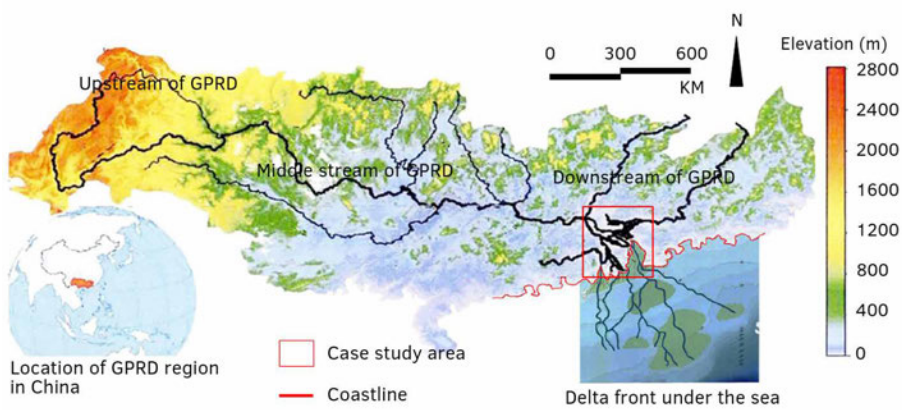


FIG. APP.A.1 The topography of the GPRD

The PRD discussed in this dissertation is located at the estuary of the GPRD. PRD's geographical location is between 23° 40'-21° 30 'North Latitude. It is surrounded by mountains and hills and it is an impacted plain formed by fluvial impact of West, North, East River, as well as tidal invasion from the South China Sea.

There are nine cities in the PRD, including Guangzhou city, Shenzhen city, Foshan city, Dongguan city, Zhongshan city, Zhuhai, Jiangmen city, Zhaoqing city and Huizhou city. After the rapid industrialization and urbanization brought about by the 'Open-door Policy' in 1978, the PRD became a world-famous manufacturing and export basement. In January, 2015, a report of the World Bank revealed that the PRD has surpassed Tokyo bay area, Japan, and became the world's largest metropolitan. It is one of the world's four major bay areas, together with New York Bay Area, the San Francisco Bay Area, and the Tokyo Bay Area in Japan (World Bank, 2015).

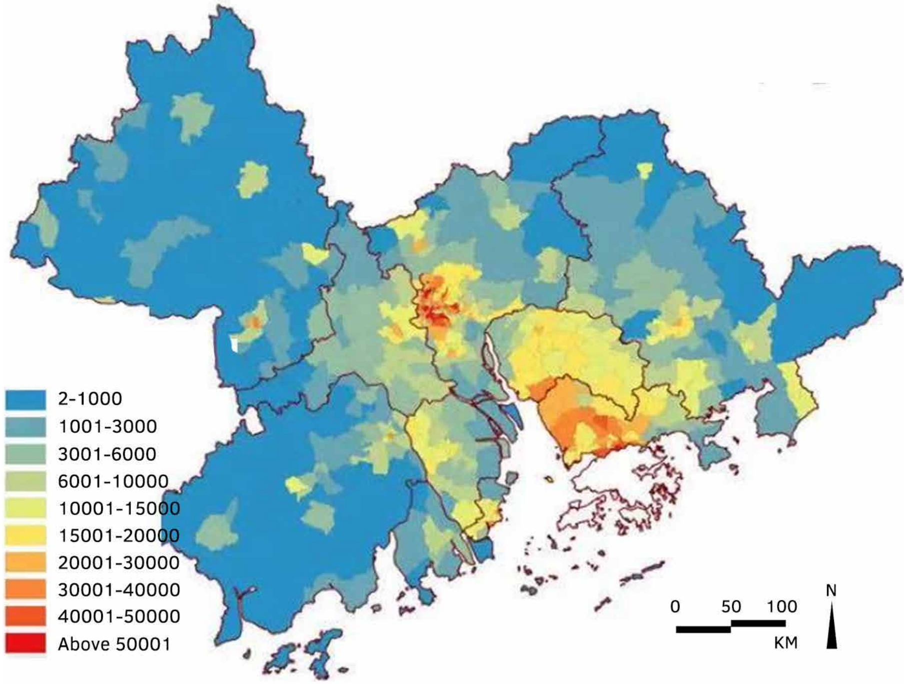


FIG. APP.A.2 Population density of the PRD (persons/square kilometer).
(Source: Guangdong institute of urban and rural planning, 2015)

The PRD is located in a subtropical climate area, which is humid, warm and moist all year round. The average annual temperature is 21-23°C. January has the coldest climate with a monthly average temperature of 13-15°C, while July has the hottest climate with a monthly average temperature of 28°C. The annual average amount of rainfall of the PRD is more than 1500 mm and annual average amount of evaporation of the PRD is about 900-1600mm. In addition, the amount of rainfall in the flooding seasons (April to September) accounts for more than 80% of the amount of rainfall in a year. The rainy season and high temperature season always occur at the same time. Humid climate is also a positive factor for forming fertile soils that can be cultivated.

TABLE APP.A.1 Basic information of the PRD

City	Area(km²)	Population (thousand people)	Density of population (people/km²)	GDP (billion RMB)
Guangzhou	7249.27	14904.4	2055.986	2285.935
Shenzhen	1997.47	13026.6	6521.550	2422.198
Zhongshan	1783.67	3310.0	1855.724	363.270
Dongguan	2460.08	8392.2	3411.352	827.859
Foshan	3797.72	7905.7	2081.696	993.588
Zhuhai	1736.46	1891.1	1089.055	291.474
Zhaoqing	14891.23	4151.7	278.802	220.180
Jiangmen	9506.92	4598.2	483.669	290.041
Huizhou	11347.39	4830.0	425.649	410.305
Hongkong	1106.7	7392.0	6679.316	2845.3
Macao	30.8	657.0	21331.169	440.316

(Source: China Statistics Press, 2019)

The geological conditions of the PRD are dominated by continuous land subsidence, with an average rate of about 1.5-2.0 mm/a. As shown in figure app.A.3, three groups of geological faults formed during the 'Yanshan movement' in the Mesozoic geological period. Powered by crustal movement, these geographic faults control the formation of the PRD's continental shelfs and coastline shape. Among these geographic faults, the Guangsan fault, Luofushan fault, West fault, and Shawan fault are more active than others.

The topography of the PRD consists of geological faults, mountains, hills and plains. It is a delta mainly dominated by large mountains in the north, west, and east side, hills and plains in the middle and a sea in the south side. The process of sedimentation and erosion creates transition zones between land ecosystems, intertidal ecosystems and marine ecosystems. The size of plain occupies 49.2% of the total area and is the main component of the topography of the PRD.

On the north, west, and east part, favorable conditions such as fertile soils provide material basis for the early agricultural civilization of the PRD. On the south part, the silt-up areas near the coastline of the Pearl River estuary are sufficient. In recent years, influenced by artificial activities such as sea reclamations and port constructions, the shape of PRD's coastline has experienced major changes.

The areas of soft soil (mainly clay and salty clay) of the PRD are widely distributed, which cover an area of nearly 8,000 km² and account for nearly 70% of the total delta area. As shown in figure app.A.4, the oldest soil in the PRD has a sedimentary age of 40,000 to 60,000 years that formed in the Late Pleistocene geographic period. The average thickness of soft soil is about 25-40 m, with a maximum thickness of more than 63 meters.

The quality of soil in the north of the Guangsan fault is better than that in the south. In the north of Guangsan fault, the soil mainly consists of sand whose particles are larger than 0.05 mm. The soil between the Guangzhou-Conghua fault and Shiqiao-Xinhui geographic fault is a transition zone between pluvial soil and coastal soil. The particles of pluvial soil and coastal soil are less than 0.002 mm, which are difficult to penetrate. The soil in the south of Shiqiao-Xinhui fault is coastal soft soil. Groundwater flow can be largely resisted by silt and clay, which can cause oversaturated soil moisture. This phenomenon is particularly typical in Shunde (Foshan city), South of Panyu (Guangzhou city), Nansha (Guangzhou city), North East of Zhongshan city, Southwest of Zhuhai city, and West Coastline of Shenzhen city.

As shown in figure app.A.5, the movement of PRD's coastline can be divided into six main periods: Neolithic (about 5,000 years ago), Qin and Han Dynasty (2200 years ago), Tang Dynasty (1400 years ago), Song Dynasty (1000 years ago), Ming Dynasty (700 years ago) and Qing Dynasty (300 years ago). During the first 4000 years, the PRD was at a stage of slow sedimentation, with 0.3 km^2 of new land created each year. In the later 2000 years, the speed of sedimentation accelerated, with an average of 0.55km^2 of new land creation in the Tang Dynasty to 1.78-2.41km^2 of new land creation in the present. Nowadays, the West River and North River move at a speed of 32.5 m/a towards Lingding sea and 47.2m/a towards Modao estuary. The East River flows at a speed of 13.4 m/a towards Lingding sea.

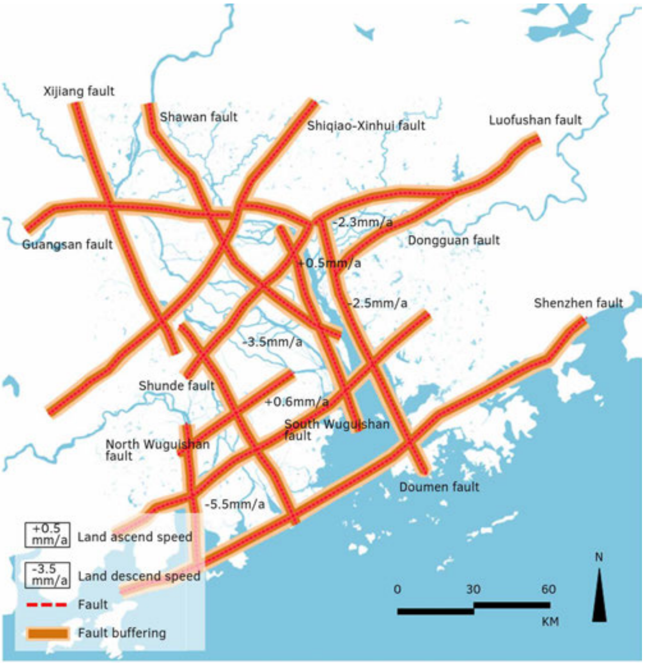


FIG. APP.A.3 The topology of the PRD . (Source: Author; Data from: Zhao, 2017)

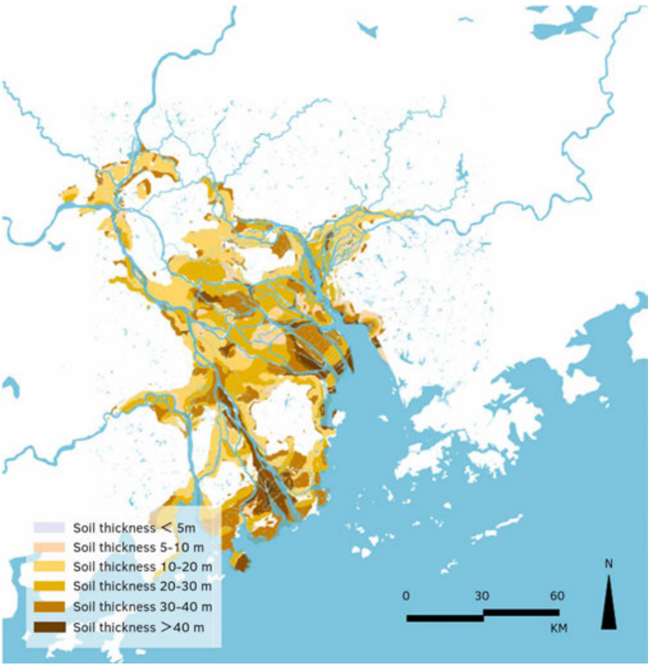
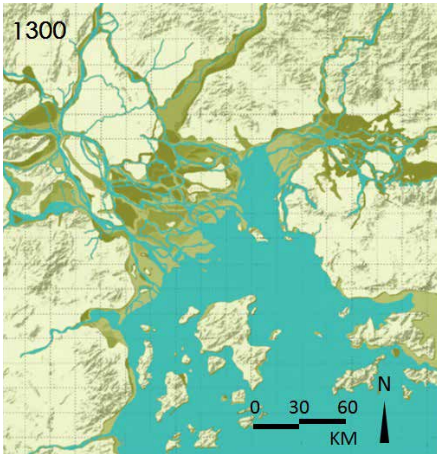
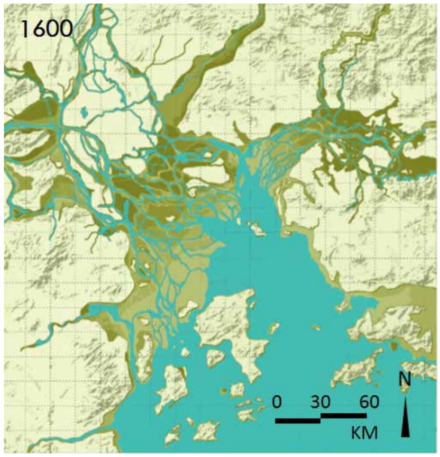


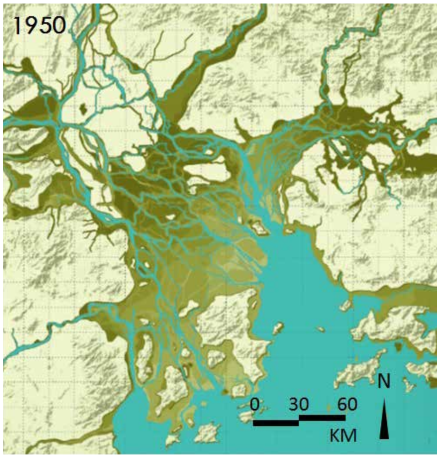
FIG. APP.A.4 Soft soil distribution of the PRD . (Source: Author; Data from: Dong et.al., 2012)



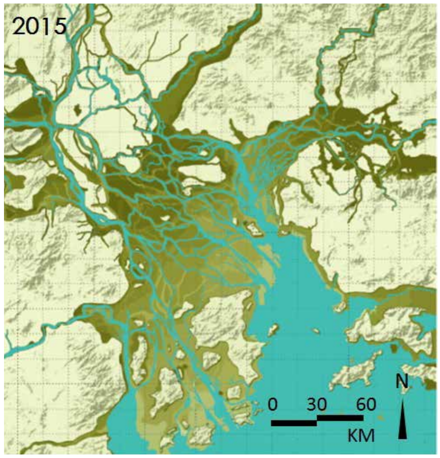
1 PRD coastline in 1300



2 PRD coastline in 1600



3 PRD coastline in 1950



4 PRD coastline in 2015

FIG. APP.A.5 The movement of PRD's coastline. (Source: Xiong & Nijhuis, 2019)

A.2 Crucial stages of spatial transformation of the PRD

A Before 1978: Agricultural stage

Before 1978, the PRD was dominated by the agricultural economy. The spatial structure is dominated by natural areas, farmlands and villages. Guangzhou city was the only urban center before Yuan Dynasty. The convenience of port traffic in Guangzhou city is the main reason.

In Ming and Qing Dynasty, Guangzhou city became the only foreign trade port in the south of China. After the 16th century, Macao was occupied by the Portuguese, which changed the spatial development tendency of the PRD from the single urban center of Guangzhou city, to the dual urban centers of Guangzhou city and Macao.

After the opium war, due to the rise of Hong Kong and the decline of Macao, the locations of dual urban centers changed, from Guangzhou city and Macao in the west coastline to Guangzhou city and HongKong in the east coastline. During this period, the function of Guangzhou city changed greatly. It gradually transformed into a modern industrial and commercial center, a trade and financial center and an international transportation hub.

B 1978—1992: Starting stage of urbanization

Since the Chinese Open-door Policy in 1978, policies, industries and transportation have greatly changed the process of the evolution of the spatial structure of the PRD. The PRD took its geographical advantages to fully absorb technology from HongKong and Macao. The rapid development of township enterprises, export-oriented industries and special economic zones led to the rise of a number of small and medium-sized cities and towns surrounding Guangzhou city, HongKong and Macao. On the one hand, the previous rural areas of the PRD were widely covered by the policy of ‘household contract responsibility’. A large number of surplus labors were released. On the other hand, due to the rising costs of land, HongKong’s manufacturing industry, capital and industrial structure have been largely transferred outward which generates another super urban center—Shenzhen city.

Industrialization has greatly promoted the urbanization process of the PRD. The number of cities increased from 5 to 12. Original small cities such as Shenzhen city, Zhuhai city, Zhongshan city, Dongguan city and Shunde gradually evolved into medium-sized cities. The number of towns increased from 32 to 374 and accounted for 31.7% of the total number of towns in the province at that time. In 1992, there were 21 cities with a population of more than 100000. The urbanization level reached 43%, which is 16% higher than the urbanization level in China.

C 1992-2002: Rapid development stage of urbanization

In 1992, the former president—Deng Xiaoping's speech in the south China accelerated the establishment of the economic system, and the PRD entered into the stage of rapid industrialization and urbanization. The PRD has largely shifted from an agricultural-based development model to an industrial-based development model.

In 1995, the PRD entered into a period of rapid industry and urbanization. The spatial structure changed. The cities and towns in the inner circle have been integrated into a whole, with the development axes of the east wing and west wing. The proportion of employment of the PRD increased from 32% to 37.3%.

D 2002-now: Steady development stage

After 2005, driven by factors such as the high technology and transportation network, the speed of urbanization has increased. During this period, the urban space of the PRD changed from the hinterland to the coastline, and the cross-sea spatial pattern gradually came into being.

The financial crisis in 2008 had a huge impact on the 'export-oriented' economy of the PRD. A large number of small and medium-sized township enterprises went bankrupt and many labor-intensive industries moved to the edge area of the PRD due to the gradually higher land price. In order to cope with the challenges of the financial crisis, the manufacturing industry of the PRD increased their investments in order to make innovation in both science and technology.

With the development of the regional economy, especially the construction of transportation infrastructure, the cities in the PRD are becoming integrated. Affected by the adjustment of the administrative boundary in Guangzhou city and Foshan city, the number of cities in the PRD reduced to 17. Compared with the previous stages, the model of spatial development has also changed from emphasizing socio-economic benefits to environmental protection. The implementation of policies such as greenway construction and ecological protection brought opportunities for the repair of blue-green networks and regenerated the new delta environment.

APPENDIX B

Literature Review

The delta is derived from the deposit of sediments. It is formed by interrelationships between land formation, fluvial and tidal process and is usually located at the end of estuary and has a unique landscape. Generally, the delta can be divided into three types, namely fluvial-dominated delta, tidal-dominated delta and wave-dominated delta (Galloway, 1975) (Table app.B.1). The shape of the delta is an aggregation of the specific topography, hydrology, ecology, soil, climate, and human activities. Low elevation is a common geographic feature of most deltas.

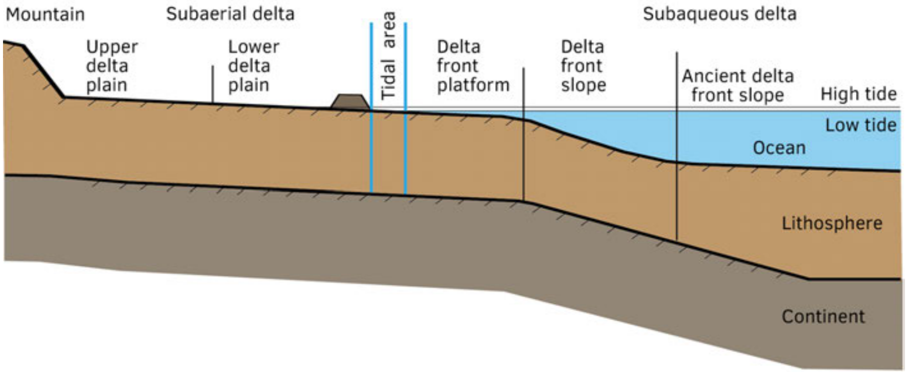


FIG. APP.B.1 The section of delta area

TOC

TABLE APP.B.1 Three types of deltas

The type of delta	Examples	Typical typology
Fluvial-dominated delta	Mississippi River Delta (USA), PRD (China), Elbe delta (Germany)	 Mississippi River Delta (USA),
Tidal-dominated delta	Rhine-Maas delta (Netherlands), Nile delta (Egypt), San Francisco Bay area (USA), Yellow River Delta (China)	 Rhine-Maas delta (Netherlands)
Wave-dominated delta	Mekong Delta (Vietnam), Yangtze River Delta (China), Amazon Delta (Brazil)	 Mekong Delta (Vietnam)

(Source: Author; Pictures from: Meyer et al., 2014)

B.1 Literature review on American and Dutch delta study

A Theoretical study

Combining the knowledge of geography, ecology, hydrology and landscape science is the main trends of research on delta interventions. The discussions of theories and methods for future delta interventions have become heated all over the world.

Being advanced countries in this field, America and the Netherlands have improved fruitful results and accumulated a lot of experience in delta planning and design. Both the American and Dutch scholars focus on the relationship between land and water, and between different scales.

Several important literatures in America influence the field of delta interventions. McHarg (1992) integrated spatial planning and design with the value of ecosystem by stating that spatial planning and design should be based on ecological principles. The method of 'overlapping layers' for multi-factor evaluation provided a significant impact on the planning and design in the last 50 years. Costanza et. al.(1997), Millennium Ecosystem Assessment (MEA) (2005) described the ways of understanding ecosystem service by providing measurable aspects of supply, regulation, providing and culture value with corresponding quantitative indicators, which further help many designers to link principles with the value of ecosystem. Alberti (2008) introduced landscape language, as well as hydrologic process, biochemical process and atmospheric process in details, in order to help people understand elements and processes behind urban ecosystems. Bosselmann (2018) systematically elaborated the adaptability of the metropolitan landscape in the delta from landscape, metropolitan, political, historical and cultural aspects by using comparative case studies of San Francisco Bay, Rhine-Mass Delta and the PRD. Kim et al. (2016) and Lin et al. (2020) combined the Landscape Dynamic Succession Analysis Model (SD) with the Cellular Automata (CA) to simulate the evolution characteristics of the New York Bay area.

The Netherlands is the world's lowest lying country, which is located at the lower reaches of the Rhine-Maas estuary. About a third of the lands is below sea level. The Dutch have a lot of experience in the study of water-related planning and design in the delta, with ecological wisdom and modern technology. Two major flooding issues in 1993 and 1995 led them to pay more attention to the 'spatial safety and landscape quality', from 'working against water' to 'working with water' in a systematic way. Sijmons (1991) proposed 'Casco concept' by paying attention to the different dynamics of landscape. Slow speed elements, such as water and agricultural pattern can function as spatial structure for preparing uncertainty. Tjallingii (2000) put forward 'Two networks' by proposing that traffic and water network should function as basic spatial structures with 'fast and slow' lanes for promoting mobility.

Meyer in his book *Delta Urbanism—the Netherlands* provided detailed descriptions of the spatial evolution and landscape changes in the Netherlands by applying the 'layer-model' (Meyer et al., 2010). It pointed out that delta planning and design should be combined with water management and ecological protection to realize a sustainable future. It built a bridge from the understanding of delta landscape to reasonably make a spatial layout in specific sites, such as Rotterdam. Then, his book *New perspectives on urbanizing deltas—a complex adaptive systems approach to planning and design* introduced the theory of complex adaptive systems and used the Southwest delta as a case study (Meyer et al., 2015). It explained the concrete contents of the way to research, planning and design in the delta, with retrospective analysis, future perspective, actor analysis, envisions and international comparisons. Another book named *Urbanized Deltas in Transition* uses 'Layer-model' as an analytical tool to conduct in-depth studies on the Mississippi River Delta, Mekong River Delta, Panama Delta and Venice, which provided sufficient fundamental database for further study (Meyeret al., 2014).

With the assistance of Meyer, Chung (2014), Nilesen (2019), Voorendt (2017), Tai (2018), Veelen (2016) all made theoretical contributions to this filed in recent years, with sufficient outcomes. Based on different research objectives and methodologies, there are several categories, especially focusing on the transformation of delta landscape, preparing for flooding disasters, adjusting blue-green networks, etc. in order to propose new inspirations for future planning in the delta. For instance, Lijdsman (2019) discussed the relationship between spatial element distribution and flood control effect in Rotterdam under multiple scenarios. Bacchin (2015) proposed the idea of regulating multi-scale blue-green network to deal with rainwater flooding. O 'Malley (2014) used the ENVI-MET model to study the impact of building forms on the mitigation of urban heat island effect and storm flood risk. Zeeliner (2016) analyzed the flood mitigation effect of green infrastructure in delta cities.

B Planning and design practice

Planning and design practices in deltas conducted in America and the Netherland have already attracted attention of scholars around the world.

Mississipi River Delta and New Orleans City

New Orleans is located in the swamp and clay area of Mississippi Estuary Delta. After Hurricane Katrina in 2005, The 'Dutch Dialogues' workshop was established with the support of the Dutch Embassy and American Planning Association (Meyer et al., 2009). The final outcome of this workshop—'The Great New Orleans Water Plan' created new blue-green networks in the city, in order to deal with the problems of serious flooding. The new planning and design scheme started from a regional perspective to understand the flooding vulnerable areas in New Orleans. Then, several key principles were made: (1) Re-planning the spatial distribution of water catchments from centralized model to decentralized model; (2) Applying water collective elements such as parks, wetlands, small ditches instead of drainage pipes to form a three-dimensional climate-responsive networks for absorbing excessive water; (3) Considering the existing situation of natural stratum; (4) Proposing mixed land-use strategies to promote the functions of land-use when flooding occurs (Great New Orleans Water Plan, 2012).

According to the topographic conditions, New Orleans was divided into four sub-areas, together with 40 water catchments with new blue-green infrastructures. After hydrological calculations, the rainwater carrying capacity of each water catchment was allocated (Figure app.B.2).

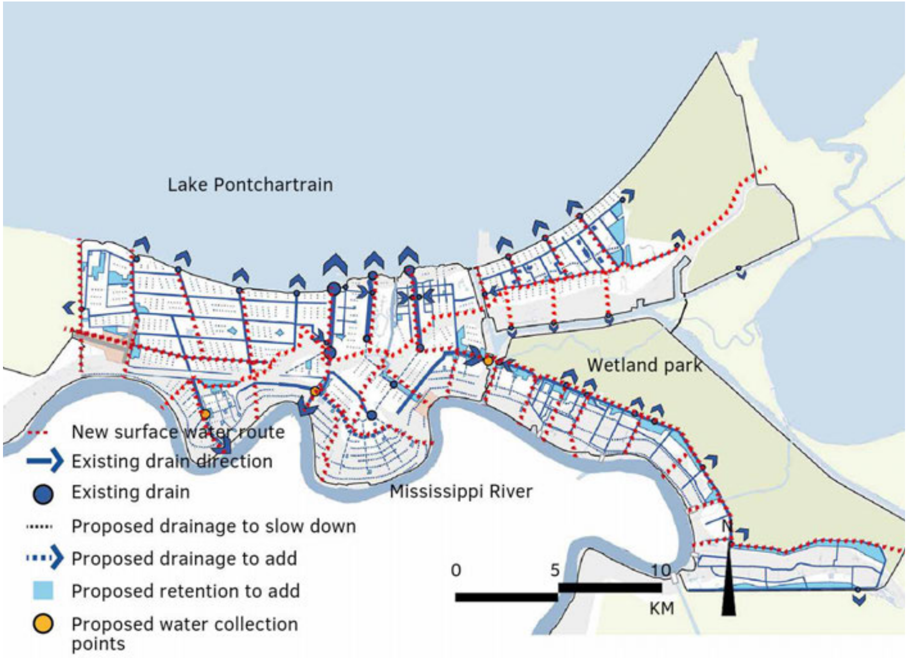


FIG. APP.B.2 New water system for New Orleans. (Source: Great New Orleans Water Plan, 2012)

New York Bay

Hurricane Sandy in 2012 caused flooding in 129km² of New York City, which led to direct economic losses of 20 billion dollars. In 2015, the competition of ‘Rebuild by Design’ for a new New York was conducted by the US Department of Housing and Urban Development, which attracted the attention of designers all over the world (New York Government, 2014). Designers tried to find solutions to adapt to flooding, as well as to find new opportunities for further development of New York. In competition, BIG Company systematically considered the uncertainties of rising sea level caused by future climate change, and proposed a multifunctional ‘U-Shaped’ flooding protection infrastructure for the waterfront of Manhattan Island (Zhan, 2016). The ‘U-Shaped’ flooding protection infrastructure not only responded to potential flooding issues caused by continuous sea level rise, but also created a diverse and vital waterfront space for citizens (Ingels et al., 2017).

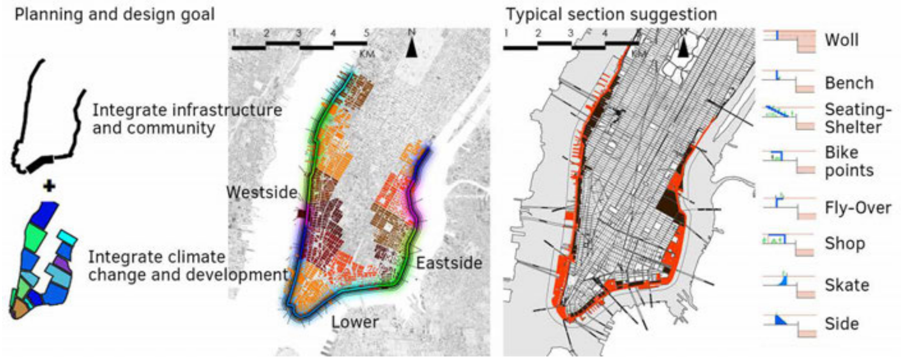


FIG. APP.B.3 BIG U Project. (Source: New York Government, 2014)

Dutch Delta—Room for river

In the 1930s, in response to continuous tidal invasion, hydraulic engineers shortened the Dutch coastline by nearly 700km with hard sea dykes, in order to reclaim lands for agricultural production. The establishment of the Afsluitdijk in the north part of the Netherland transformed the original Zuider Zee into three parts: the outer Zuider, the Ijsselmeer, and the Markenmeer. The construction of this world-class sea dyke triggered the constructions of the three new reclaimed provinces with huge farmlands and satellite cities. After the severe flooding disaster in 1953, the Dutch government made major adjustments to the overall spatial structure of the Netherlands. Many structural elements, such as storm surge, dykes, sluices, have become the main elements of the enclosed coastline.

In 1993 and 1995, the Netherlands experienced two other major floods. Afterwards, Designers transferred their design concept from 'working against water' to 'working with water'. Since 2011, the Delta Programme in the Netherland implemented projects for 'coping with climate change, optimizing natural process, and improving spatial security', in order to provide safety lands for the next 50-100 years, specialized in six typical zones based on the differences of landscape characters (Rijksoverheid, 2012). Each year, a clear theme with a series of spatial planning and design strategies were made (Ministry of Infrastructure and the Environment, 2018). Scenario simulations in the whole Netherlands were carried out for extreme situations such as heavy rainfall, geological subsidence, heat island, storm interference and sea level rise. Afterwards, the correlation models of development intensity, economic development and the number of potential disaster victims were constructed.

The regional projects, ‘Room for the rivers’, created lots of buffering zones near waterfronts with more than 18 prototypes of sections of new relationships between ‘land and water’. The project covered 35 sub-projects from 2005 (Figure app.B.4).

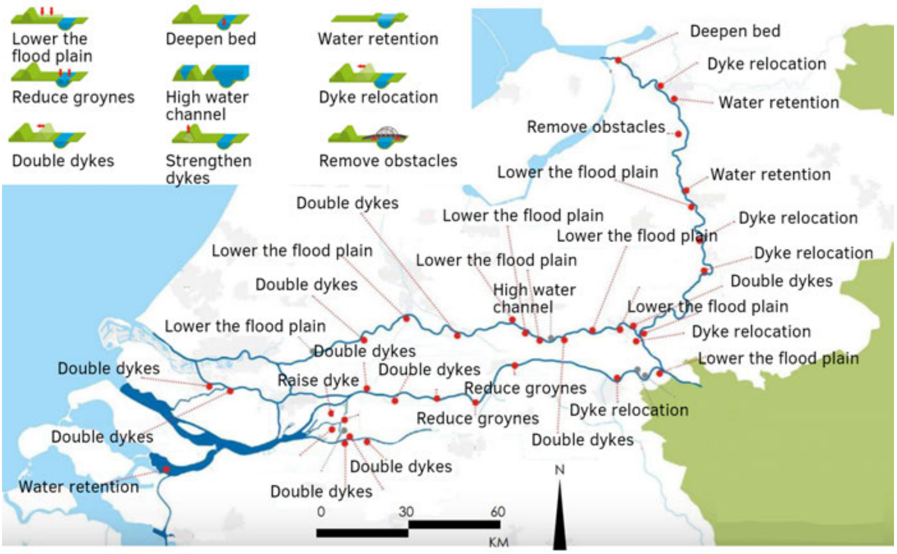


FIG. APP.B.4 Diversified sections applied in the project of ‘Room for Rivers’. (Source: Ruimtevoorderivier, 2014)

The Nijmegen strategic point is part of the Waal River extension project under the project of ‘Room for Rivers’ (Figure app.B.5). In order to prevent the erosion caused by the Waal River to the southern convex bank of Nijmegen during the heavy rain season, moderate increases in floodable spaces on the north bank are required. The project has pushed back original dykes on the north side of the Waal River by 350 meters and created a new bypass channel, with an overflow dyke. A number of controllable pipes were buried in the overflow dyke, and different numbers of connected pipes can be opened according to the water level of the Waal River.

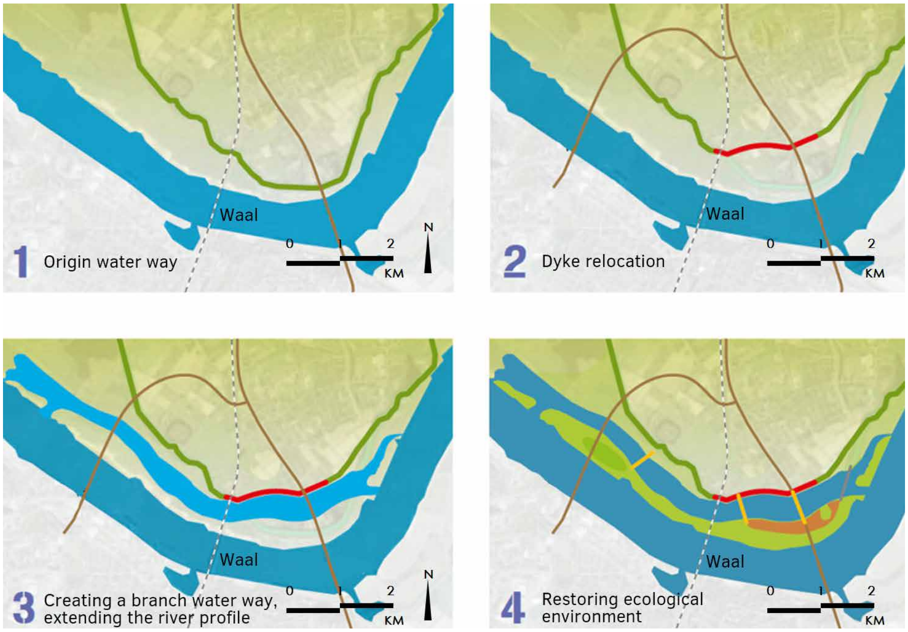


FIG. APP.B.5 Create bypass channel and retreat dyke in Nijmegen. (Source: Ruimtevoorderivier, 2014)

C Others

In addition to above practical explorations from spatial aspects, America and the Netherlands also explored optimized management in terms of governance, policies, legislation and intelligent facilities. For instance, the *Rotterdam Climate-Proof Strategy* developed adaptability plans in terms of five aspects—flooding management, accessibility, adaptive buildings, urban water systems and urban climate (Ward et al., 2013). *A strong, More Resilient New York* involved comprehensive intelligent scenario predictions such as coastline shock prediction, climate change prediction, flooding risk prediction, extreme high temperature prediction, in order to provide foundations for further decision-making process (Bloomberg, 2013). The report of *Climate Resilient Cities: A Primer on Reducing Vulnerability to Disaster* by the World Bank summarized how to measure vulnerability in cities by corresponding indicators (Prasad, 2009). Other documents, such as *Low Impact Development* by America, *Water Sensitive City* by Australia, etc. also provided the same directions.

B.2 Literature review on the PRD

The delta interventions in the Chinese context are different. Compared with pioneer countries like America and the Netherlands, the number of literatures on delta interventions in China is less. The PRD is one of the most important, challenging and potential delta in China, which is always on heated debates.

Huang et al. (2000) shows evidences that the sea level in the PRD rose fast during the past century. The sea level of the PRD has accelerated from mm/a to cm/a in recent years. Zhi (2005) shows that due to PRD's distinct geological formation, the obvious regional characteristics can make the soft soil of the PRD encountered in national projects with low carrying capacity. Dong et al. (2012) analysed the geological disasters and their factors such as earthquake, geographical deformation in soft soil areas, Karst collapse, coastal anomalous changes, and sea level rise, from the perspectives of topography and geomorphology. Liu et al. (2016) proposes that in the future, the PRD should pay attention to the combination effects of fluvial and tidal influence. It is necessary to strengthen risk management, and appropriately increase the amount of water storage in the region. Tai (2018) expounded the mechanism of urban water system in response to climate change from the perspective of water system value by using Guangzhou, PRD as a case. Xiong (2020) proposed a planning and design drawing method based on multi-scale and multi-disciplinary interaction of th PRD. Cai (2018) proposed a research method of spatial evolution of PRD from three spatial scales and four elements.

Research on the natural base layer of the PRD focuses on changes especially in water and soil conditions. Most of the results show that there has been severe degrading of the natural environment, which causes reduced land carrying capacity. Meanwhile there is an urgent requirement to adjust the regional blue-green networks.

The research on the social-economic structure of the PRD focuses on socio-economic growth and the industrial structure. During the past 40 years, the urban form changes in the core areas of the PRD have undergone a dynamic evolution process from point expansion to linear expansion. From 1979-2008, the non-agricultural construction land in the PRD has increased by about 53 times, with the urban built-up areas having increased by about 65 times. The growth of urban space in the core area of the PRD has undergone a spatial transformation from 'decentralized and flatten' model to 'point-axis' model.

Since the late 1980s, six rounds of spatial planning and design researches have been conducted. They were all in combination with the specific development background of the PRD at the specific time and proposed the corresponding spatial layouts that guide the path for the future development of the PRD (Lai et al., 2015).

Urban system planning of the PRD (1991-2010) was conducted in 1989. The goal of the scheme was to establish a reasonable urban structure. The method was to focus on cultivating several central cities. It was the first time for the PRD to make a regional spatial layout from the scale of the delta. Based on that, the spatial distribution of regional infrastructure and social facilities were preliminarily planned and were divided into four central areas—Guangzhou city, Shenzhen city, Zhuhai city and Huizhou city. The spatial layout can be seen in figure app.B.6.

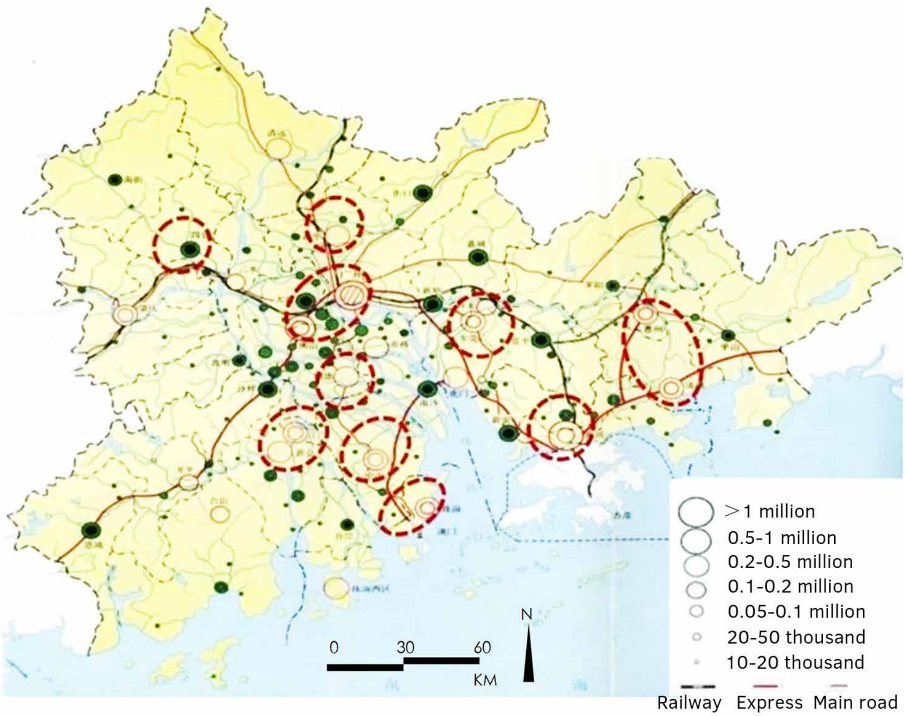


FIG. APP.B.6 Urban system planning of the PRD (1991-2010). (Source: Guangdong institute of urban and rural planning, 1991)

The scheme of economic metropolitan area in the PRD (1994-2020) was conducted in 1994. In order to make the urban system stronger, this scheme emphasized the application of ‘point-axis’ spatial model, and put forward the spatial structure development model of two main axes (Guangzhou city Shenzhen city, Guangzhou city Zhuhai city) and seven secondary axes. The main regional spatial layout can be seen in figure app.B.7.

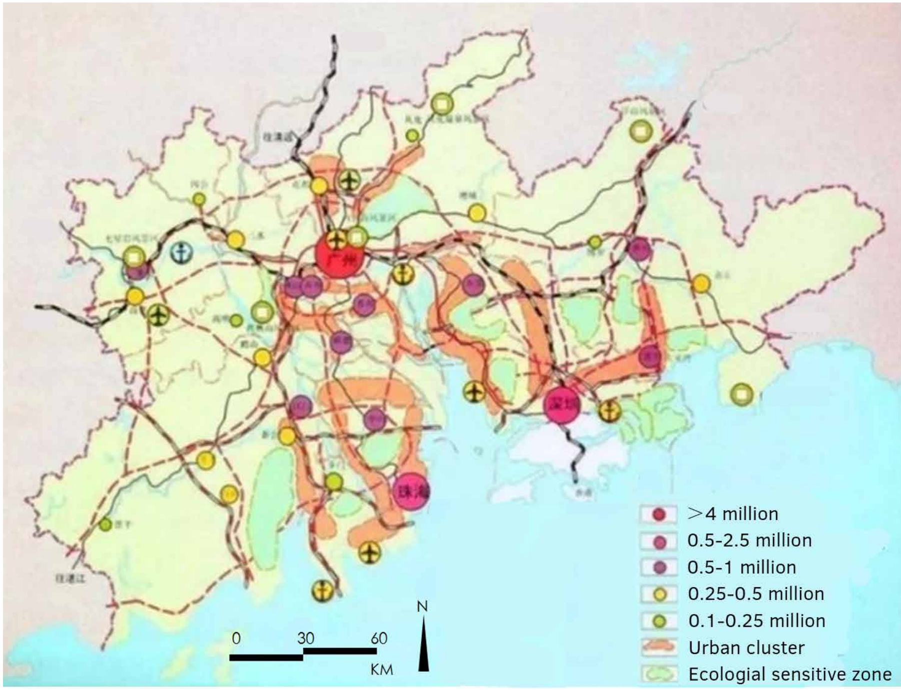


FIG. APP.B.7 The scheme of economic metropolitan area in the PRD (1994-2020). (Source: Guangdong institute of urban and rural planning, 1994)

The scheme for coordinated development of metropolitan areas in the PRD (2004-2020) was conducted in 2004. The goal of the scheme was to solve the negative impact caused by urban sprawl. The method was to find out the opportunities for fairness in the whole PRD through spatial policies and governance. According to the actual situation of the spatial structure of the PRD, nine zones were established, together with four levels of spatial governances and eight kinds of implemented actions. The main spatial layout can be seen in figure app.B.8.

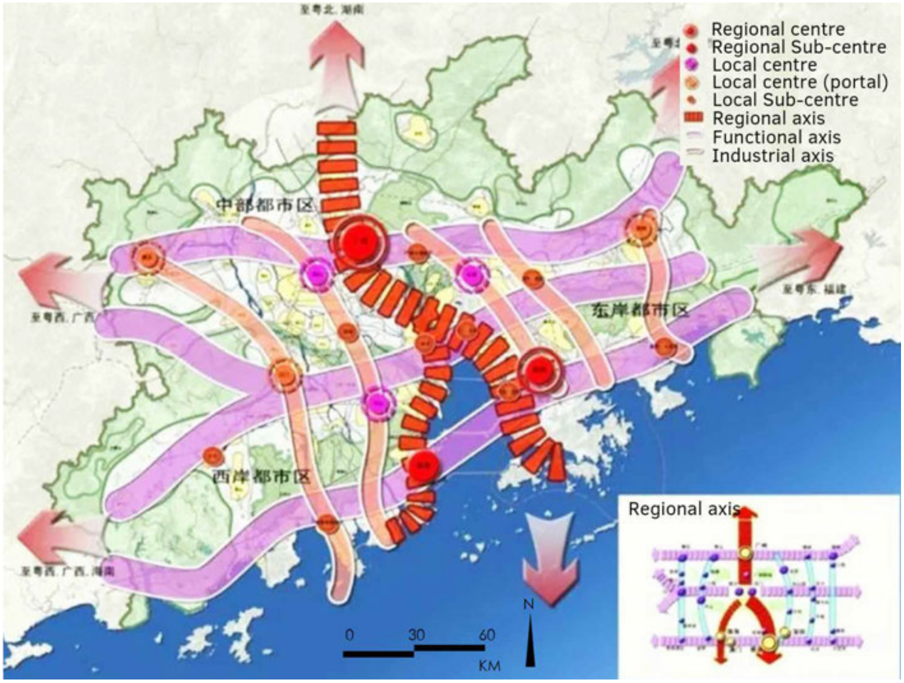


FIG. APP.B.8 The scheme for coordinated development of metropolitan areas in the PRD (2004-2020). (Source: Guangdong institute of urban and rural planning, 2004)

The reform and development planning for the PRD region (2008-2020) was conducted in 2008. The scheme aimed to maintain the integration and fairness of urban-rural space. As shown in figure app.B.9, the spatial layout of scheme mainly emphasized the contribution of the spatial 'axis' to create a coordinated and fair environment.

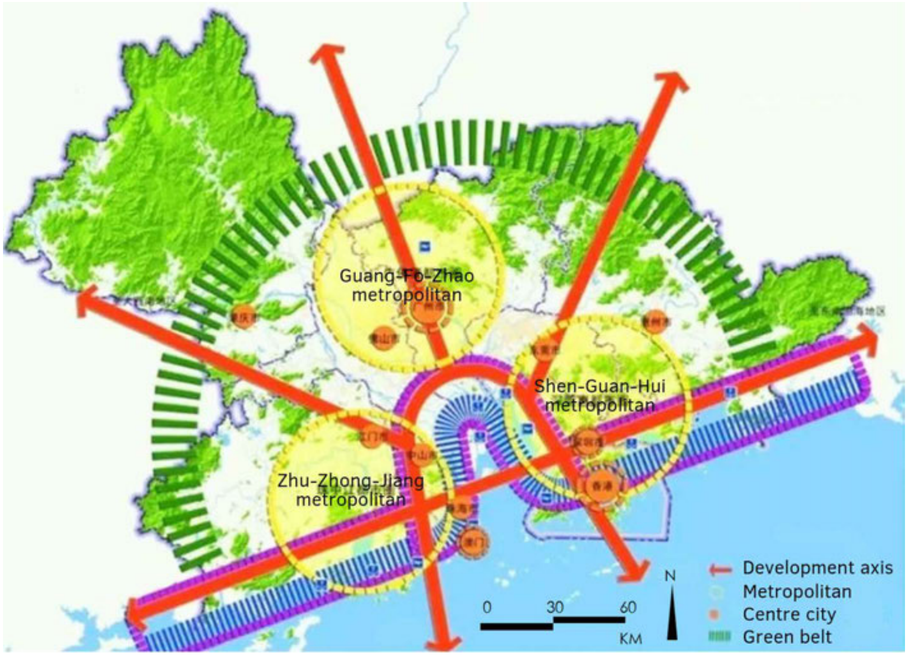


FIG. APP.B.9 Outline of the reform and development planning for the PRD (2008-2020). (Source: Guangdong institute of urban and rural planning, 2008)

The spatial planning of the PRD (2015-2020) was conducted. The goal of the scheme was to build a world-class ‘ecological-productive-living’ bay area. The scheme put forward the cooperation between Guangdong, Hong Kong and Macao by improving their regional coordination mechanism. The scheme focused on improving the function of a regional spatial structure, the efficiency of cross-border transportation and the action of regional cooperation. The scheme explored detailed ‘strategic points’ and ‘important projects’ for the whole delta. As shown in figure app.B.10, the scheme optimized the spatial structure by proposing the conceptual model of ‘one bay area, three axes, three zones and multiple points’.

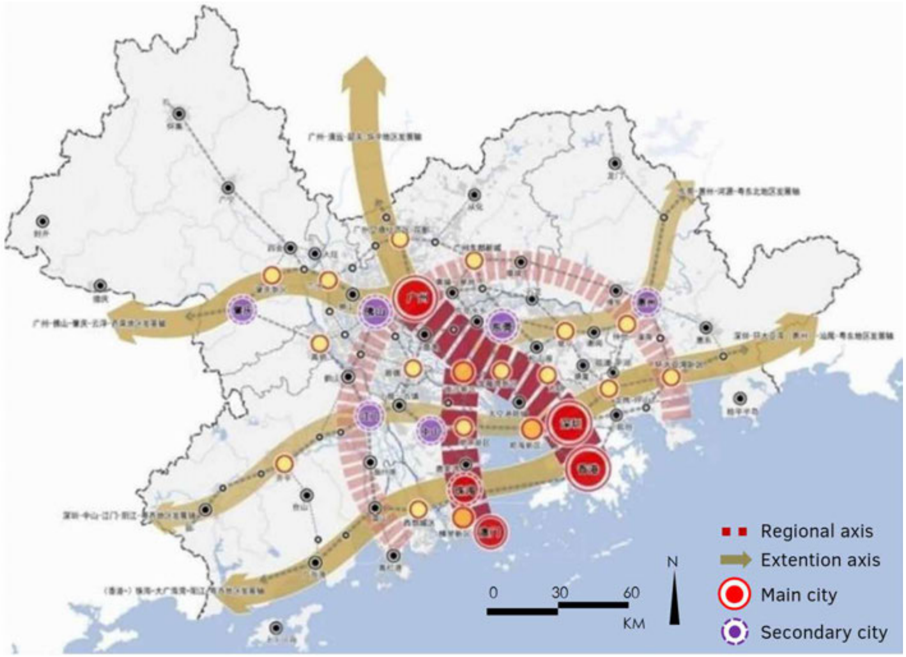


FIG. APP.B.10 Spatial planning of the PRD (2015-2020). (Source: Guangdong institute of urban and rural planning, 2015)

TOC

B.3 Practice of flood control and drainage system in the PRD

A Flooding disaster in the PRD

The PRD experienced severe flooding disasters in 1915, 1994, 1998, 2008, 2010, and 2018, which seriously affected the urban development. According to the hydrological characteristics of the PRD, when a 50-year flooding occurs upstream, 100-year or even 200-year flooding may appear downstream. The huge flooding in 1994 led to the collapse of Xiqiao dyke and other secondary dykes in Panyu, which caused more than 1-meter depth inundation in Zhongshan city, Shunde, Nanhai, Guangzhou city and other places. In 1998, some rivers in the PRD experienced 200-year flooding. In 2010, the huge precipitation in PRD lasted for more than 20 days. Guangzhou city, Yuexiu, Haizhu and other 8 districts and 102 towns (streets) were flooded. In 2018, the typhoon ‘Shanzhu’ transited and caused Nansha, Zhongshan city, Dongguan city and other cities to experience the highest water levels in history.

B The transformation of flood control and drainage system

The flood control and drainage system in the PRD can be regarded as an important part for consideration in spatial planning and design. With the improvement of productivity and technology, as well as the advancement of the understanding of the role of nature, flood control and drainage system in the PRD have undergone several major changes (Liu, 2014).

Traditional flood control and drainage system
Due to low productivity and immature engineering technology, people chose to develop lands in areas with higher elevations to avoid flooding disasters in important farmlands and cities. City walls, gates, channels and ditches were commonly used as spatial elements in flood control and drainage systems in the early urban areas of the PRD. For example, the early development of Guangzhou City was located at the foot of Baiyun Mountain, which was a relatively high-lying area.

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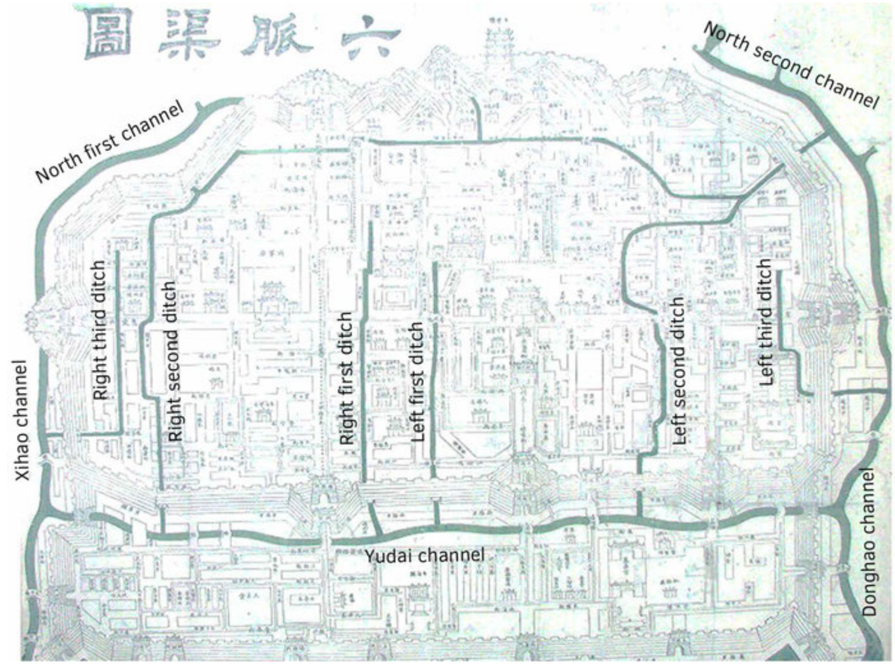


FIG. APP.B.11 Flood control and drainage system in ancient Guangzhou city
(Source: Liu, 2016)

City walls were built on the north bank of the Pearl River, Donghao channel and Xihao channel. At the same time, six important ditches, Yudai ditches were dug inside the city to form the primary water system. The surrounding large lakes, wetlands were also connected to the water system to play a role of forming more effective flood control and drainage system.

Engineering-based flood control and drainage system

With the improvement of productivity and the advancement of technology, the construction level of flood control and drainage infrastructure has gradually improved. The PRD has launched large-scale constructions of engineer-based flood control and drainage systems. Since the 1950s and 1960s, the constructions of dykes, dams and reservoirs led by the Pearl River Water Conservancy Department have been implemented on the whole region of the PRD. Original small dykes were combined into big ones to form dyke rings. Each island in delta and its inner-rivers were enclosed by dykes and sluices. Drainage pipe networks were set up inside the enclosed islands, and only some main rivers and waterways outside islands were left to discharge floods. Although the constructions of dyke rings prevent excessive

TOC

water, they actually separate the internal and external original water systems and blocks water circulation. Large dams across main rivers were constructed and artificial reservoirs were formed upstream to store water and product electricity, which can ensure the safety of important agricultural and urban areas downstream.

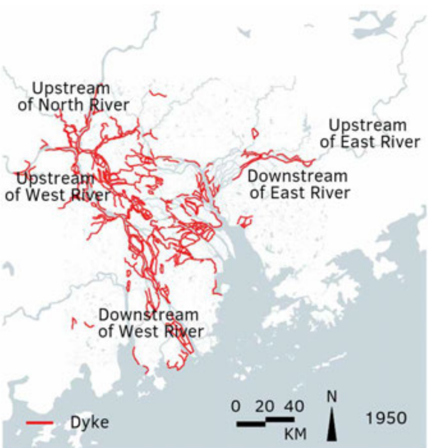
FIG. APP.B.12 Typical large water conservancy facilities in the PRD (Source: Flood control planning for the Pearl River Basin, 2010)

However, the engineer-based flood control and drainage system cannot adapt to future climate change in the PRD due to the excessive emphasis on the actions of heightening dykes. Dykes with fixed flooding protection standards cannot guarantee that the further urban development can adapt to the dynamic water environment.

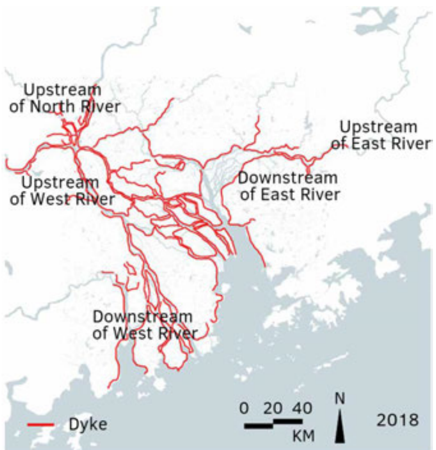
Ecological-based flooding control and drainage system

Large-scale human activities have changed the water environment. On the one hand, the activities of heightening dykes can limit the lateral expansion of flooding in the cross-section of important rivers. On the other hand, the construction of dams and reservoirs will lead to changes of diversion runoff and sedimentation ratio of the main rivers in the PRD, which can cause serious riverbed cuts and create an unstable water environment. Engineer-based flood control and drainage system is static and difficult to deal with uncertain flooding disasters. Therefore, for the sake of long-term development, although engineer-based flood control and drainage system is indispensable, an ecological-based flood control and drainage system that can actively improve blue-green networks by integrating consideration of upstream and downstream water environment is more suitable for long-term scenarios.

Influenced by strategies such as 'low impact', 'water-sensitive'' and 'sponge city' put forward in recent years, The PRD has begun to gradually attempt to integrate engineer-based flood control and drainage systems with ecological-based flood control and drainage systems, especially with important cities such as Guangzhou and Shenzhen as pilot cases. For example, *Special Planning for Sponge City in Guangzhou (2016-2030)* proposed to build a model of sponge city construction in high-density construction areas and build a livable city from water ecology, water safety, water environment and water resources. *Shenzhen City Flooding Control (Tide) Plan Revision and River Rehabilitation Planning (2014-2020)* proposed to create a safe, ecological and beautiful urban flooding control and drainage system and began to pay attention to the connection between flooding management and urban planning. The *Revised Report on the Comprehensive Planning of the Zhuhai City Watershed* took water security, flood control drainage and mitigation, water supply and aquatic environment as the entry points to promote comprehensive water management in Zhuhai City in order to improve harmony between human and water.



1 Dyke system in 1950



2 Dyke system in 2018

FIG. APP.B.13 Spatial distribution of dyke system in 1950 and 2018 in the PRD

C Current planning and design content of flood control and drainage system in the PRD

In the Chinese context, the situation of spatial planning and water management is separated without an integrated information platform. The planning and design approach of flood control and drainage in the PRD is mainly dominated by a water conservancy and management department, based on the outline of *Pearl River Basin flooding control and drainage scheme* that is still engineer-based. Most of the assessment contents for flood control and drainage systems were carried out from the aspects of shoreline utilization, electricity production, shipping and transportation, water resources protection and environmental impact. The content for flood control and drainage systems generally involves more spatial elements such as hydropower stations, dykes, dams and ditches, and less spatial elements of land-use, blue-green infrastructures and coastline.

APPENDIX C

Intermediate Research Outcomes of the PRD

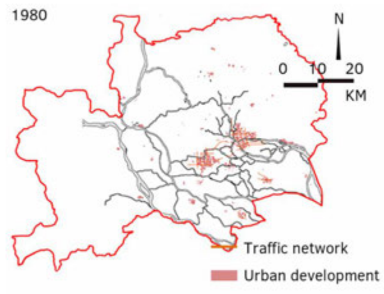
C.1 Evaluation of spatial connection between regions

Figure app.C.1 shows the four regions with sub-regions of the PRD from the delta scale. These four regions are named the Westside upstream region, Westside downstream region, East region and Central region in this research.

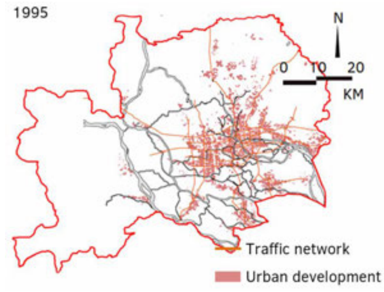
Due to the differences in geographical, historical, and development factors, the system mechanism and evolution pathway of these four regions are different. The Westside Upstream Region consists of the sub-regions numbered from WU-1 to WU-16. The Westside Downstream Region consists of the sub-regions numbered from WD-1 to WD-18. The East Region consists of the sub-regions numbered from E-1 to E-36. The Central Region consists of the sub-regions numbered from C-1to C-4.

FIG. APP.C.1 Four regions and its corresponding sub-regions of the PRD

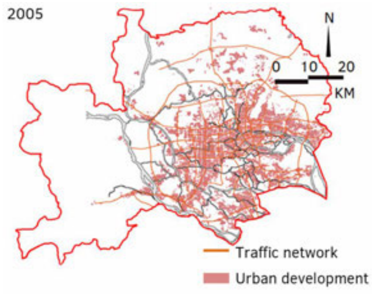
C.2 Spatial evolution and key indicators in each region



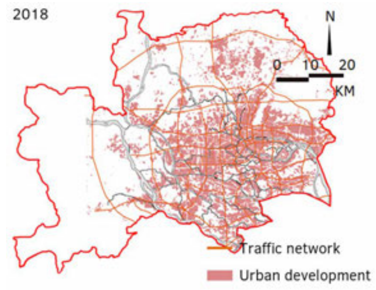
1 Urban pattern in 1980



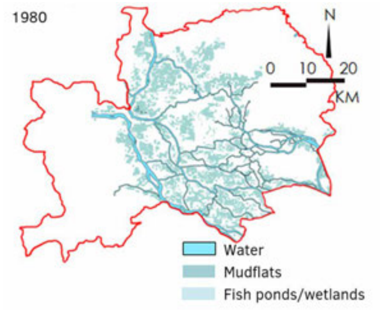
2 Urban pattern in 1995



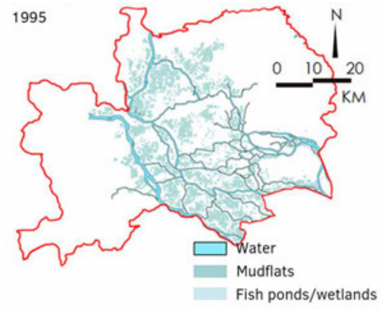
3 Urban pattern in 2005



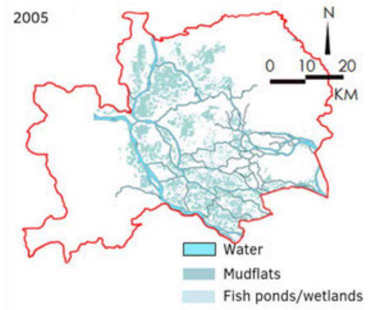
4 Urban pattern in 2018



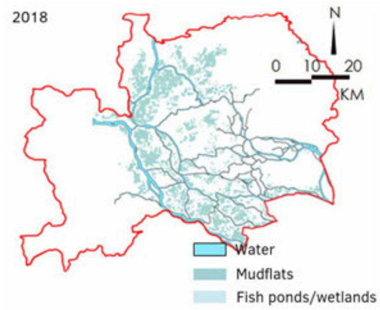
5 Blue-green pattern in 1980



6 Blue-green pattern in 1995



7 Blue-green pattern in 2005



8 Blue-green pattern in 2018

FIG. APP.C.2 Spatial evolution in westside upstream region

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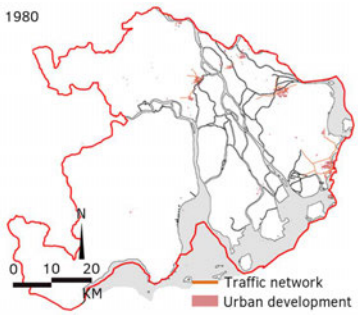
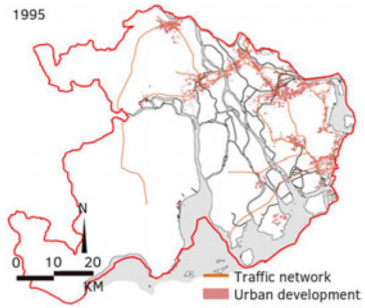
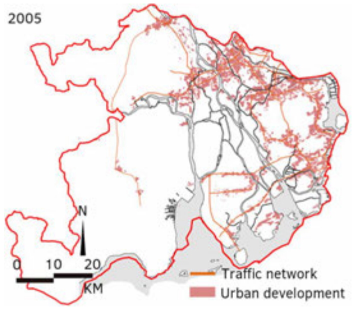


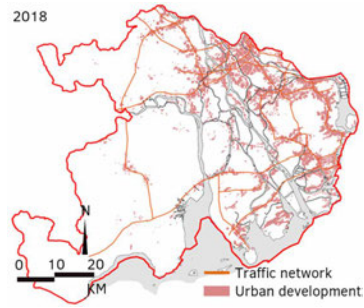
1 Urban pattern in 1980



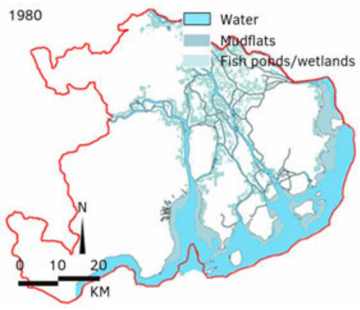
2 Urban pattern in 1995



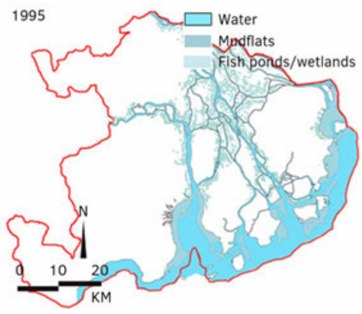
3 Urban pattern in 2005



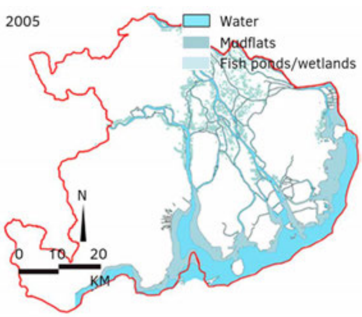
4 Urban pattern in 2018



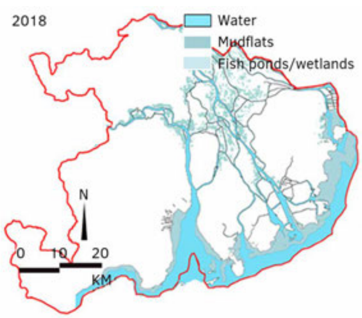
5 Blue-green pattern in 1980



6 Blue-green pattern in 1995

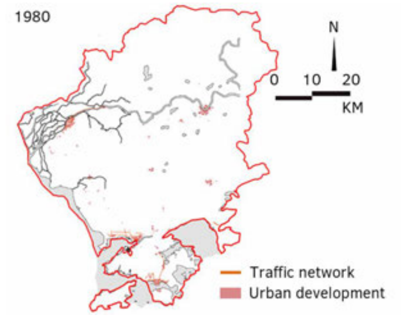


7 Blue-green pattern in 2005

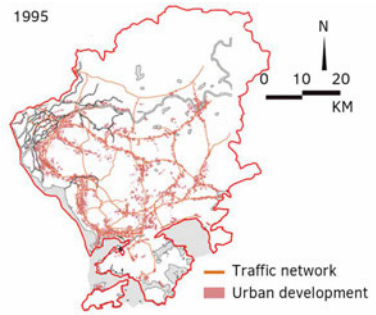


8 Blue-green pattern in 2018

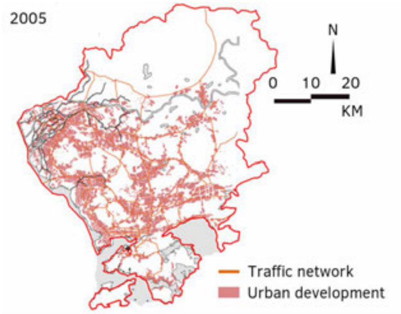
FIG. APP.C.3 Spatial evolution in westside downstream region



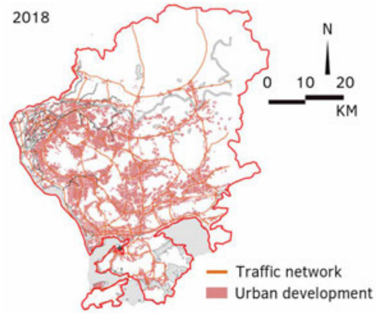
1 Urban pattern in 1980



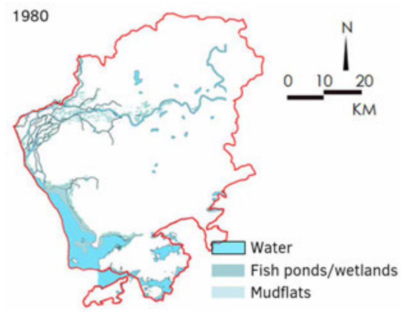
2 Urban pattern in 1995



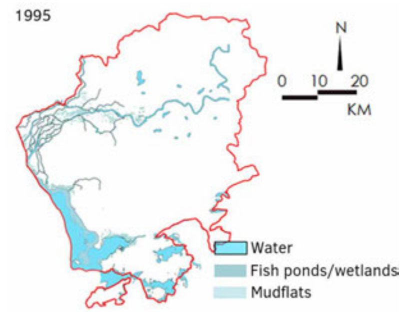
3 Urban pattern in 2005



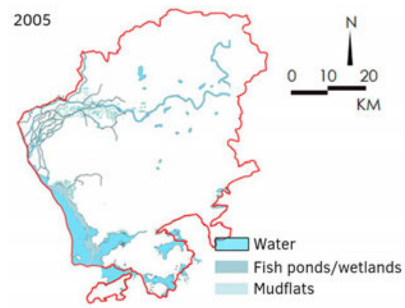
4 Urban pattern in 2018



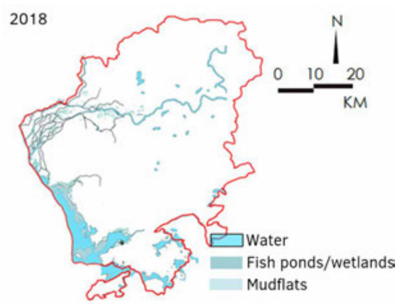
5 Blue-green pattern in 1980



6 Blue-green pattern in 1995

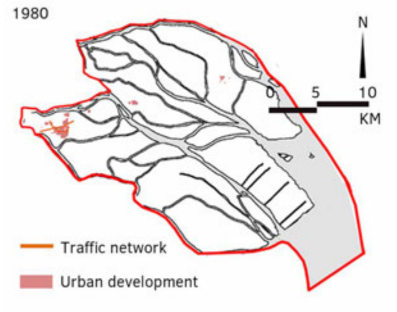


7 Blue-green pattern in 2005

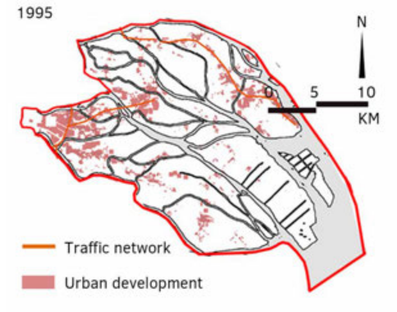


8 Blue-green pattern in 2018

FIG. APP.C.4 Spatial evolution in east region

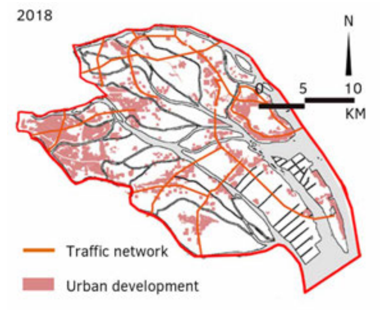


1 Urban pattern in 1980

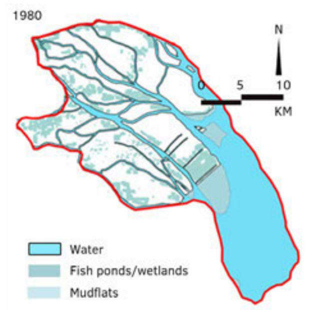


2 Urban pattern in 1995

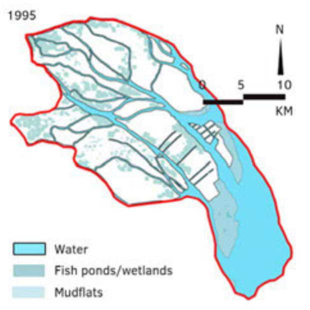
3 Urban pattern in 2005



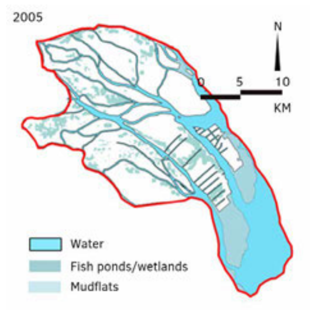
4 Urban pattern in 2018



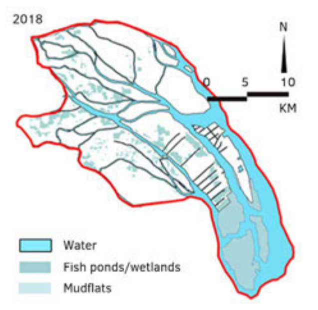
5 Blue-green pattern in 1980



6 Blue-green pattern in 1995



7 Blue-green pattern in 2005



8 Blue-green pattern in 2018

FIG. APP.C.5 Spatial evolution in central region

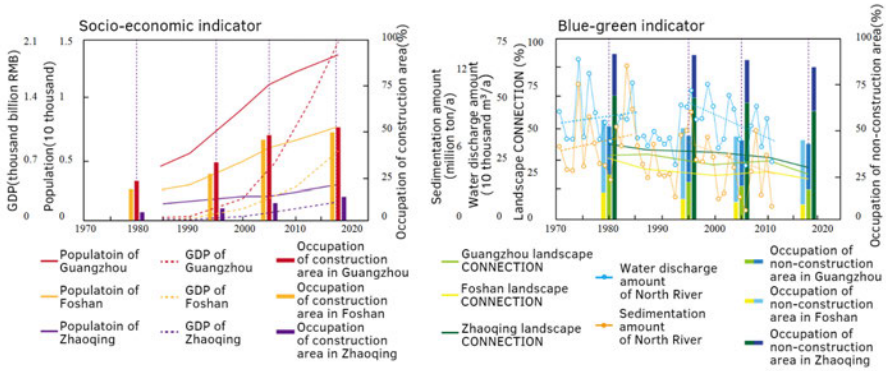


FIG. APP.C.6 The evolution indicators in the westside upstream region

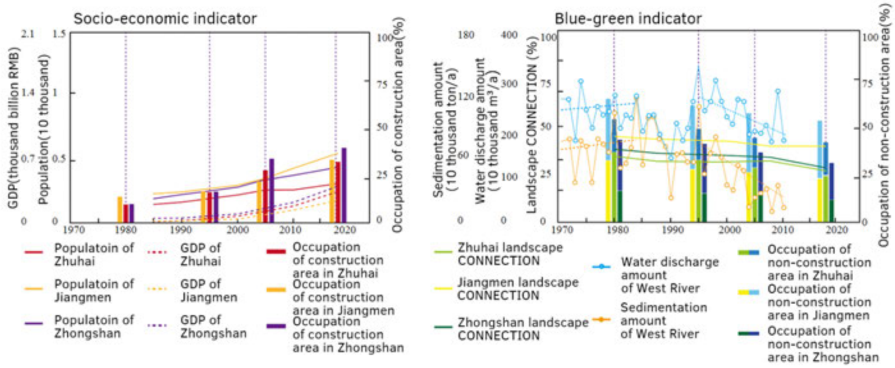


FIG. APP.C.7 The evolution indicators in the westside downstream region

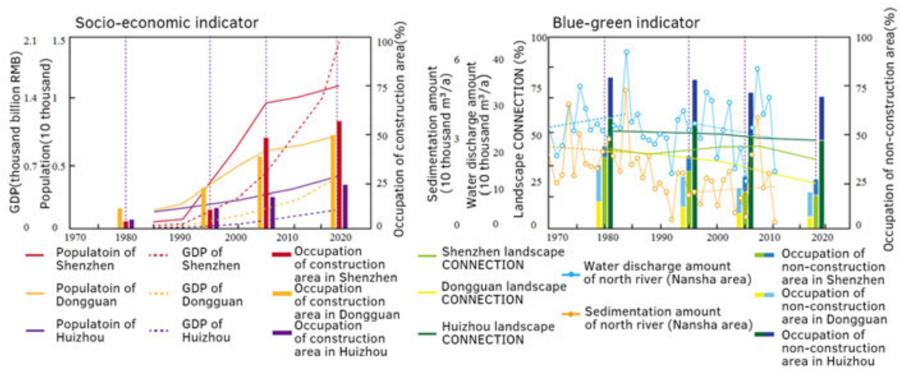


FIG. APP.C.8 The evolution indicators in the east region

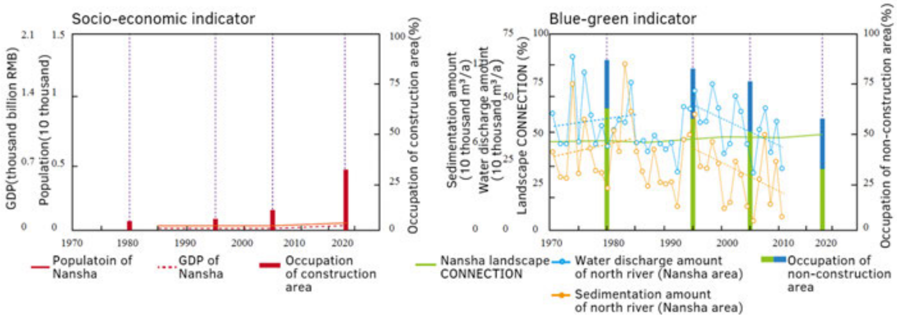


FIG. APP.C.9 The evolution indicators in the east region

C.3 Potential spatial resources in the PRD

The locations and density of the potential spatial resources can be seen in figure app.C.10, which is done by the tool of core density calculation from ArcGIS.

There are 85 existing regional nature reserves in the PRD. Among them, there are 5 national-level, 17 provincial-level, and 63 city-county-level nature reserves. Natural resources are mainly distributed in the outer circle mountains of the PRD. They are essential areas for water conservation, biodiversity protection and climate regulation. Some small shoals and silt-up areas in crisscross places of blue-green networks can function as important ‘stepping stones’ for establishing new blue-green connective networks. These important natural resources can be tapped and utilized as elements to form multi-layered ecological-hydrological barriers, which can not only provide spatial safety but also high perceptions of delta landscape in the PRD. Socio-economic resources are mainly distributed in the inner circle.

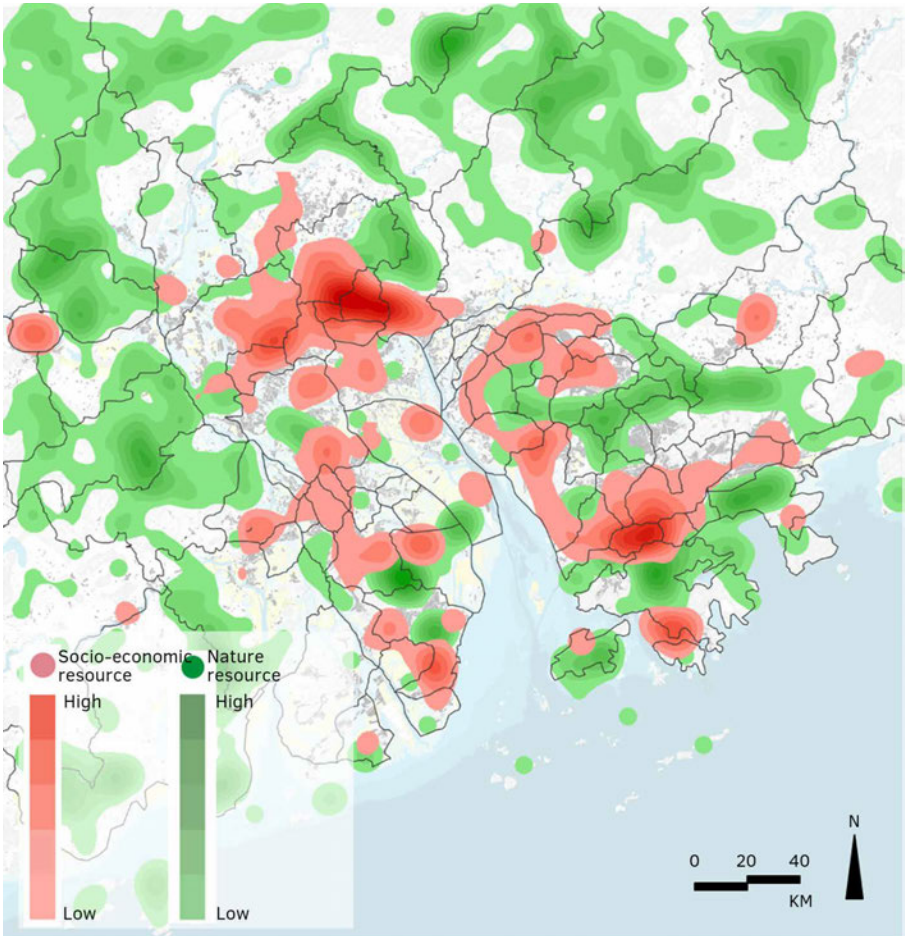


FIG. APP.C.10 The spatial distribution of important resources in the PRD. (Source: Author; Data from: Guangdong: institute of urban and rural planning and design, 2015)

TOC

C.4 Existing land-use situation in Nansha District

Nansha area can be divided into ten sub-areas, namely Nansha sub-area, Zhujiang sub-area, Longxue sub-area, Dongyong sub-area, Lanhe sub-area, Dagang sub-area, Huangge sub-area, Hengli sub-area, and Wanqingsha sub-area.

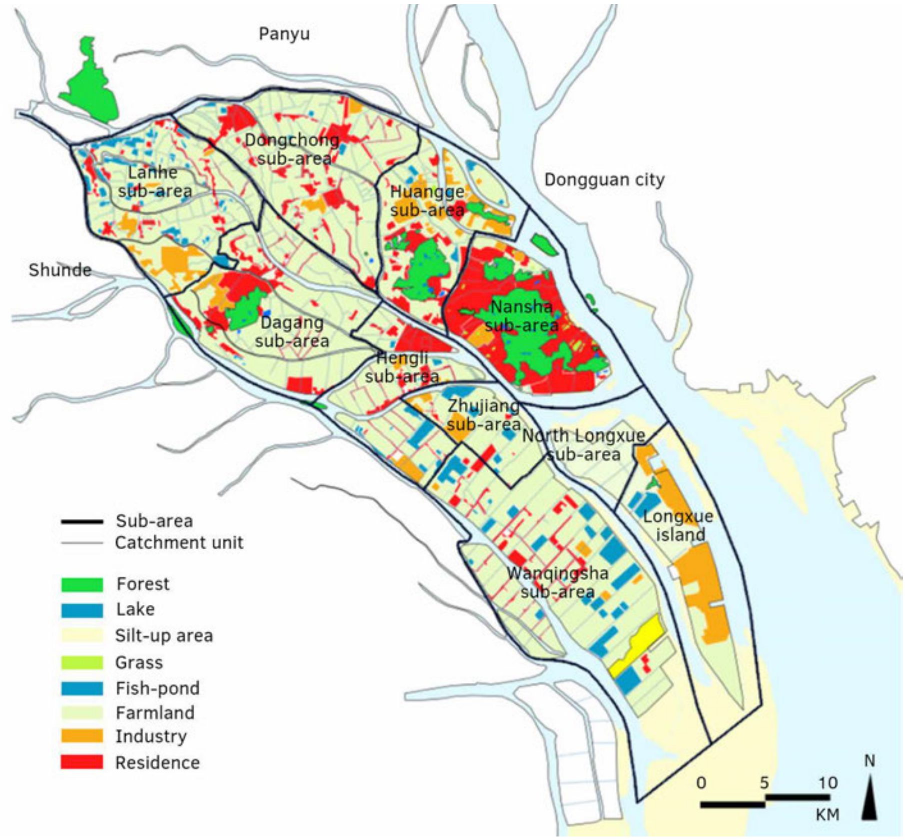


FIG. APP.C.11 Current land-use pattern of Nansha area

Current land-use pattern can be seen in figure app.C.11. Forest land accounts for 4.31%, grassland accounts for 0.23%, pond/lake area accounts for 0.21%, and silt-up area accounts for 8.3%. The forest land is mainly distributed in Nansha sub-area and Huangge sub-area. The silt-up area is mainly distributed in Nansha sub-area, north of Longxue sub-area and south of Wanqingsha sub-area. Forest land and silt-up area can provide a lot of hydro-ecosystem services. Farmland accounts for 46.15%, fish-pond accounts for 3.71%. The farmland is mainly distributed in Dongchong sub-area and Dagang sub-area. Fish ponds are mainly distributed in Lanhe sub-area, Dagang sub-area, Dongchong sub-area and Wanqingsha sub-area. Residential lands account for 11.8%, and industrial lands account for 5.5%. Residential lands are mainly distributed in Nansha sub-area, Dongchong sub-area and Dagang sub-area. Industrial lands are mainly distributed in Huangge sub-area and Longxue sub-area.

TABLE APP.C.1 Statistics of land-use in Nansha area (unit: ha)

Part	Sub-area	Natural land				Agricultural land		Urban land		Blue-green network	Total area
		Forest	Grassland	Pond	Silt-up	Fish-pond	Farmland	Residential	Industry		
North	Huangge	827.11	26.20	53.45	112.79	120.55	2635.16	886.88	841.53	1185.24	6688.90
	Dongchong	2.95	4.52	7.12	46.41	74.70	6366.63	1536.87	171.44	1040.78	9251.43
West	Dagang	370.78	5.81	36.15	9.50	12.77	6074.37	1035.30	231.79	1492.37	9268.84
	Lanhe	0.00	4.96	0.00	26.14	672.57	5107.12	598.52	645.61	954.30	8009.23
South	Wanqingsha	0.00	3.51	0.00	2927.71	1264.72	7950.91	1042.38	43.49	2907.50	16140.23
	South longxue	0.00	0.00	0.00	2250.77	188.06	1870.21	0.00	1265.94	2487.67	8422.65
Middle	Nansha	2128.91	108.64	32.40	190.76	9.89	73.70	3198.96	205.51	2682.81	8631.57
	Zhujiang	0.00	2.18	0.00	180.39	246.30	1781.02	107.68	292.36	443.79	3053.72
	Hengli	21.87	28.20	0.00	85.22	309.48	2843.22	847.01	254.62	1202.01	5591.62
	North longxue	23.59	0.00	0.00	679.17	8.01	1477.67	0.00	0.00	1142.46	3330.90

APPENDIX D

Intermediate Research Outcomes of Hengli Island

TOC

D.1 Related elevation data

Elevation data of Hengli Island can be seen in Table app.D.1.

TABLE APP.D.1 Elevation data of Hengli Island (Pearl River Datum, unit: m)

Number	Name	Data	Note
1	**The elevation of current agricultural land**	-1.6~ 0.3	The surface elevation of current agricultural land of Hengli Island
2	**The elevation of current constructed land**	0.7~1.8	The surface elevation of current constructed land of Hengli Island
3	**The elevation of water surface of inner-river**	-1.8~0.3	The elevation of the current water surface of inner-river of Hengli Island
4	**The elevation of the top of dyke of inner-river**	1.9~2.6	The elevation of the top of dyke on the both side of inner-river of Hengli Island
5	**The elevation of the deepest point of riverbed of outside waterway**	-18.7~ -7.6	The elevation of the maximum deep point of each cross-section of outside waterways (Jiaomen waterway, Shengheng waterway, Xiaheng waterway)
6	**Average elevation of the riverbed of outside waterway**	-15.4~ -10.9	Average elevation of the riverbed of outside waterways (Jiaomen waterway, Shengheng waterway, Xiaheng waterway)
7	**The elevation of the top of the dyke of outside waterway**	3.2~ 3.8	The elevation of the top of the dyke on the both side of outside waterway (Jiaomen waterway, Shengheng waterway, Xiaheng waterway)
8	**The elevation of the bottom of the dyke of outside waterway**	0.8~1.2	The ground elevation of the dyke of outside waterway (Jiaomen waterway, Shengheng waterway, Xiaheng waterway)
9	**Historical average elevation of the water level of the daily high-high tide of outside waterway**	1.7~2.1	Average elevation of the daily higher high tide (can represent as highest water level in a day) of outside waterway (Jiaomen waterway, Shengheng waterway, Xiaheng waterway) from the calculation of a long time historical period
10	**Historical average elevation of the water level of the daily low-low tide of outside waterway**	-1.5~ -1.1	Average elevation of the daily lower low tide (can represent as lowest water level in a day) of outside waterway (Jiaomen waterway, Shengheng waterway, Xiaheng waterway) from the calculation of a long time historical period
11	**Historical average elevation of the normal water level of outside waterway**	-0.3~0.3	Average elevation of the daily water level of outside waterway (Jiaomen waterway, Shengheng waterway, Xiaheng waterway) that can be maintained longer than 6.5 hours during half-day tidal situation
12	**The elevation of 2018 typhoon 'Shanzhu' water level of outside waterway**	3.16	The Water level of the high tide of outside waterway (Jiaomen waterway, Shengheng waterway, Xiaheng waterway) brought by 2018 typhoon 'Shanzhu'

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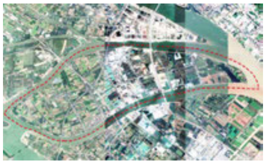
TABLE APP.D.1 Elevation data of Hengli Island (Pearl River Datum, unit: m)

Number	Name	Data	Note
13	**The elevation of the water level of high-high tide under different accumulated percentage (P)**	3.22 (P=0.1%, recurrence period is 1000 years) 2.93 (P=0.5%, recurrence period is 200 years) 2.80 (P=1%, recurrence period is 100 years)	The elevation of the water level of high-high tide under different accumulated percentage (P)
14	**The Height of sea level rise under moderate climate change**	0.25m	The height of sea level rise under moderate climate change in 2100
15	**The height of sea level rise under extreme climate change**	0.50m	The height of sea level rise under extreme climate change in 2100
16	**The proposed elevation of dyke for 100-year flooding**	Calculated value	The proposed elevation of dyke=Water level of 100-year flooding+ Height of wave run-up+ Height of wind banked-up+ Height for safety redundancy (Height for safety redundancy is 0.8m)
17	**The proposed elevation of dyke for 200-year flooding**	Calculated value	The proposed elevation of dyke=Water level of 200-year flooding+ Height of wave run-up+ Height of wind banked-up+ Height for safety redundancy (Height for safety redundancy is 1.0 m)
18	**The proposed elevation of dyke for 1000-year flooding**	Calculated value	The proposed elevation of dyke=Water level of 1000-year flooding+ Height of wave run-up+ Height of wind banked-up+ Height for safety redundancy (Height for safety redundancy is 1.2 m)

D.2 Land-use change and its influence on water system

TABLE APP.D.2 Impact of land-use change on water system

	Time	Satellite Image	Land-use change compared with last satellite image	Issues of water system
1	11/12 2009		– Farmland in Lingshan Island (north of Shangheng Waterway) remained unchanged; – Main development areas were in the middle of the site around Hengli road; – There were some factories and fishing villages on the south side of the site.	– Frequent waterlogging occurred in rainy seasons; Flooding occurred mainly from the outside waterway ; – Low-lying lands caused land subsidence to continue in the central and the eastern parts of the site.
2	21/10 2015		– Rapid urbanization started in Lingshan Island; – Fenghuang road, Fenghuang second bridge and Fenghuang third bridge that connected Lingshan Island and Hengli Island was under construction.	– Pumping caused the physical changes of underlying surface and natural surface runoff in the eastern and the central parts of the site, leading to serious water and soil loss; – Congestion at the Shangheng Waterway and Jiaomen Waterway severely affected the safety of land-use on the northeast side of the site.
3	11/03 2018		– Fenghuang road, Fenghuang second bridge and Fenghuang third bridge were completed; – Ground filling began on the southeast side of the site for urbanization (near the Fenghuang third bridges); – Ground filling began on the south side of the site for urbanization. Future Hengli subway station was located here, with adjacent large residential area.	– Affected by the development of the central and southern areas, the physical condition of the underlying surface changed with decreasing number of natural surface runoffs and increasing peak runoff speed during heavy precipitation. – As buildings on Lingshan Island on the north side began to increase, congestion at the Shangheng Waterway and Jiaomen Waterway during the flooding peak period severely affected the safety of land-use on the northeast side of the site.
4	15/06 2019		– A large amount of land development began in the central part near Hengli road; – Metro No. 18 was under construction with Hengli subway station.	– The current standard of peripheral dyke ring cannot meet the needs for future urban development. – The number of natural surface runoff decreased, with increasing peak runoff speed; – Land subsidence occurred seriously in the central and the eastern part of the site.

D.3 Data of erosion (sedimentation) of waterways

In order to understand the process of erosion (sedimentation), '1999 Topographic Map of Hengli Island' and '2008 Pearl River Navigation map' (compiled by the Guangdong Maritime Affairs Bureau of the People's Republic of China) are applied. 16 major sections of Jiaomen Waterway, Shangheng Waterway and Xiasheng Waterway are precisely compared from four indicators. Table app.D.3 shows the precise data of each section.

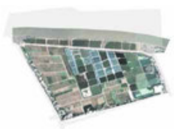
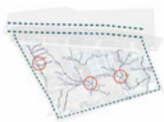
TABLE APP.D.3 Data of erosion (sedimentation) outside waterways

Section	Data time	The deepest point of riverbed (m)	Average elevation of riverbed (m)	The size of the section of passing water (square meter)	The width of outside waterway (m)
#1	1999	-11.5	-8.2	2618.6	403.1
	2008	-12.1	-8.4	2718.1	402.7
#2	1999	-13.4	-10.2	2552.6	301.1
	2008	-13.8	-10.5	2631.3	300.8
#3	1999	-10.8	-7.9	2454.1	397.2
	2008	-10.7	-8.0	2371.2	376.1
#4	1999	-12.1	-9.4	2254.2	291.2
	2008	-12.7	-9.7	2297.5	287.1
#5	1999	-13.5	-9.3	2407.2	317.0
	2008	-13.0	-9.2	2181.1	291.1
#6	1999	-13.5	-10.0	2447.9	294.3
	2008	-12.5	-9.5	2269.2	288.7
#7	1999	-12.3	-9.2	2507.6	333.4
	2008	-12.7	-9.3	2450.7	322.1
#8	1999	-7.3	-5.2	1378.4	390.7
	2008	-9.5	-6.7	1822.7	364.5
#9	1999	-9.5	-7.5	1420.5	242.7
	2008	-12.2	-9.3	1769.4	232.7
#10	1999	-10.7	-7.2	1479.6	268.4
	2008	-11.4	-8.4	1786.0	267.4
#11	1999	-9.7	-6.4	1441.6	307.2
	2008	-10.1	-7.0	1741.6	331.3
#12	1999	-7.3	-5.7	1194.5	295.2
	2008	-7.5	-6.3	1396.1	298.1
#13	1999	-11.7	-6.7	1323.3	263.1
	2008	-12.2	-7.1	1577.3	289.8
#14	1999	-10.9	-7.2	3271.6	600.6
	2008	-11.7	-8.5	4443.8	653.9
#15	1999	-7.1	-4.7	3710.7	1226.4
	2008	-11.8	-7.4	7174.7	1257.6
#16	1999	-7.6	-5.2	2030.1	577.9
	2008	-7.8	-5.2	2164.2	609.1

D.4 The basic parameters and the characters of each water collective unit

Table app.D.4 shows the basic parameters and the current characters of each water collective unit. Among them, the elevation, the slope and the inner-rivers of the site are calculated automatically by computer. Natural surface runoffs and potential depression (below -1.5meters) for storing water during high precipitation are also calculated.

TABLE APP.D.4 The basic parameters and the characters of each water collective unit

Name	Current land-use situation and water system	Basic parameters	Characters
East1	 	Size:1.8km² Elevation:-1.4~3.6 Slope:0~37° Number of adjacent outside waterways:2 Number of adjacent inner-rivers:1 Number of natural surface runoffs:38 Number of important hydrological points:5 Size of low-lying depressions (percentage):0.04km² (2.2%)	The frontier of island plans to be a high-level construction area. The dyke does not attain the standards for future urban areas yet. There is a reserved riverside buffering zone on the north side. There are excellent landscape resources, with the largest water storage lake, natural depression, and tidal flat. The site has many natural surface runoffs, which can be provided for future flooding prevention and regulation.
East2	 	Size:1.1 km² Elevation:-2.0~3.6 Slope:0~28° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:35 Number of important hydrological points:3 Size of low-lying depressions (percentage):0.09km²(8.1%)	Fish ponds are main elements on the east side. The cultivated land on the west side tends to be filled in to construction. The dykes do not attain standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources in the area are sufficient. The natural surface runoffs on the east side are more than those on the west side.

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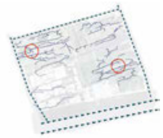
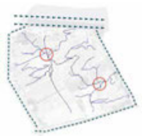
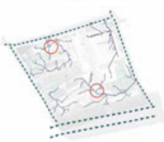
TOC

TABLE APP.D.4 The basic parameters and the characters of each water collective unit

Name	Current land-use situation and water system	Basic parameters	Characters
East3	 	Size:1.1km² Elevation:-1.7~3.6 Slope:0-22° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:33 Number of important hydrological points:2 Size of low-lying depressions (percentage):0.07km²(6.4%)	There are large industrial areas in the southwest side. The dykes do not attain standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources in the area are middle. The number of natural surface runoffs on the north and east sides is far more than those on the west and south sides, resulting in uneven circulation of local water system.
East4	 	Size:1.3km² Elevation:-0.3~3.7 Slope:0-21° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:18 Number of important hydrological points:2 Size of low-lying depressions (percentage):0.09km²(6.9%)	Most lands are filled, and the average elevation of the site is the highest in Hengli Island. The dyke attains the standard for future urban area. The northern part of the riverside buffering zone is reserved. The landscape resources are insufficient. The number of natural surface runoffs is the lowest in Hengli Island. Elevation difference is obvious here.
East5	 	Size:0.9km² Elevation:-2.7~3.6 Slope:0-26° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:20 Number of important hydrological points:2 Size of low-lying depressions (percentage):0.07km²(7.7%)	Part of the land on the northeast side is filled, and some factories are on the southwest side. The dykes attain the standard for future urban area. There is no reserved riverside buffering zone. The number of natural surface runoff in the area is small, and they are distributed only on the northwest and southeast sides. The size of potential depressions in the area is small.
Mid 1	 	Size:1.6km² Elevation:-2.2~3.6 Slope:0-24° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:18 Number of important hydrological points:3 Size of low-lying depressions (percentage):0.04km²(2.2%)	The central part has been developed on both sides around Fenghuang road. The dykes do not attain standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources on the site are middle, and the size of potential depressions is small. The natural surface runoffs on both sides was not connected due to the ground filling of the central part

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TOC

TABLE APP.D.4 The basic parameters and the characters of each water collective unit

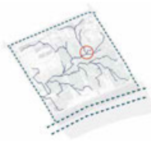
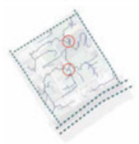
Name	Current land-use situation and water system	Basic parameters	Characters
Mid2	 	Size:0.9km² Elevation:-1.7~3.8 Slope:0-27° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:21 Number of important hydrological points:1 Size of low-lying depressions (percentage):0.03km²(3.3%)	The Hengli subway station of Metro Line 18 has a large socioeconomic value. The dykes do not reach standard for future urban area yet. There is no reserved riverside buffering zone. There are very few potential depressions on the field. Although the distribution of the natural surface runoff is relatively even, the number is not sufficient.
Mid3	 	Size:0.8km² Elevation:-2.7~3.6 Slope:0-22° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:42 Number of important hydrological points:4 Size of low-lying depressions (percentage):0.06km²(7.5%)	The situation of land-use is basically cultivated land. The dykes do not attain standard for future urban area yet. There is no reserved riverside buffering zone. There are many natural surface runoffs in the field with high density. The potential water storage and transportation capacity is strong.
Mid4	 	Size:1.0km² Elevation:-2.5~2.9 Slope:0-18° Number of adjacent outside waterways:0 Number of adjacent inner-rivers:4 Number of natural surface runoffs:22 Number of important hydrological points:3 Size of low-lying depressions (percentage):0.05km²(5.0%)	The situation of land-use is basically cultivated land. The dykes do not attain standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources on the site are middle. There are insufficient potential depressions. Natural surface runoffs are evenly distributed and highly connected.
Mid5	 	Size:0.8km² Elevation:-1.7~3.5 Slope:0-27° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:18 Number of important hydrological points:2 Size of low-lying depressions (percentage):0.08km²(10.5%)	The situation of land-use is basically cultivated land, with villages located in the south part. The dykes do not attain standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources on the site are middle, but the potential depressions are abundant. The number of natural surface runoffs is insufficient with even distribution.

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TABLE APP.D.4 The basic parameters and the characters of each water collective unit

Name	Current land-use situation and water system	Basic parameters	Characters
West 1	 	Size:1.2km² Elevation:-2.2~3.3 Slope:0-23° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:28 Number of important hydrological points:5 Size of low-lying depressions (percentage):0.09km²(7.5%)	The situation of land-use is basically cultivated land. The dykes do not reach standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources on the site are middle. There are insufficient potential depressions. Natural surface runoffs are evenly distributed and highly connected.
West 2	 	Size:1.6km² Elevation:-2.3~3.6 Slope:0-26° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:35 Number of important hydrological points:4 Size of low-lying depressions (percentage):0.08km²(5.0%)	The situation of land-use is basically cultivated land, with villages located in the south part. The dykes do not reach standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources on the site are middle, but the potential depressions are abundant. Natural surface runoffs are evenly distributed and highly connected.
West 3	 	Size:1.5km² Elevation:-2.3~3.4 Slope:0-21° Number of adjacent outside waterways:1 Number of adjacent inner-rivers:3 Number of natural surface runoffs:33 Number of important hydrological points:5 Size of low-lying depressions (percentage):0.07km²(4.6%)	The situation of land-use is basically cultivated land. The dykes do not reach standard for future urban area yet. There is no reserved riverside buffering zone. The landscape resources on the site are middle. There are insufficient potential depressions. Natural surface runoffs are evenly distributed and highly connected.
West 4	 	Size:1.7km² Elevation:-2.0~3.5 Slope:0-30° Number of adjacent outside waterways:2 Number of adjacent inner-rivers:4 Number of natural surface runoffs:35 Number of important hydrological points:4 Size of low-lying depressions (percentage):0.08km²(4.7%)	Except constructed land on northwest side, the rest are cultivated lands. The dykes do not reach standard for future urban area yet. There is no reserved riverside buffering zone. There are large strip-shaped depressions in the center for future use. The landscape resources in the site are middle. Natural surface runoff is evenly distributed and highly connected.

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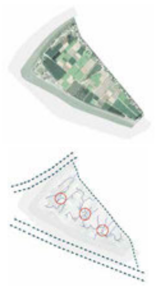
TABLE APP.D.4 The basic parameters and the characters of each water collective unit

Name	Current land-use situation and water system	Basic parameters	Characters
West 5		Size:0.6km² Elevation:-0.8~3.6 Slope: 0-22° Number of adjacent outside waterways:2 Number of adjacent inner-rivers:1 Number of natural surface runoffs:23 Number of important hydrological points:3 Size of low-lying depressions (percentage):0.02km²(3.3%)	The situation of land-use is basically cultivated land. Affected by the sedimentation process of the outside waterways, the average elevation remains the highest of Hengli Island. The dykes do not reach standard for future urban area yet. There is no reserved riverside buffering zone. Due to its proximity to the estuary, the view of the delta landscape is excellent. There are insufficient potential depressions. Natural surface runoff is evenly distributed.

D.5 The water level of waterways from 1950s to 2010s

According to data from Nansha Hydrological Station, Figures app.D.1shows the water level of outside waterways from 1950s to 2010s. When the 2018 typhoon 'Shanzhu' landed, the water level of outside waterways reached a historical highest level of 3.16 meters.

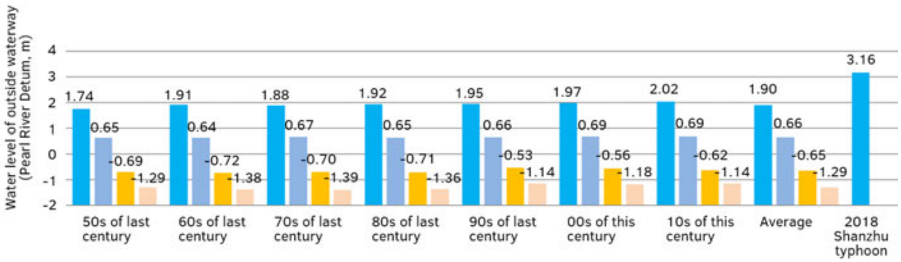


FIG. APP.D.1 The water level of waterways from 1950s to 2010s. (Source: Author; Data from: Nansha Hydrological Station)

TOC

D.6 The Gaps between Current Water Storage and Future Precipitation under Different Climate Scenarios

According to the information from 'Contour Map of Heavy Precipitation Parameters for Planning and Design', 5-year precipitation (in 24 hours; P=20%) is estimated to be 203.9 mm. 10-year precipitation (in 24 hours; P=10%) is estimated to be 246.2 mm. 50-year precipitation (in 24 hours; P=2%) is estimated to be 339.3 mm. 100-year precipitation (in 24 hours; P=1%) is estimated to be 377.1 mm. 200-year precipitation (in 24 hours; P=0.5%) is estimated to be 415.0 mm (Figure app.D.2).

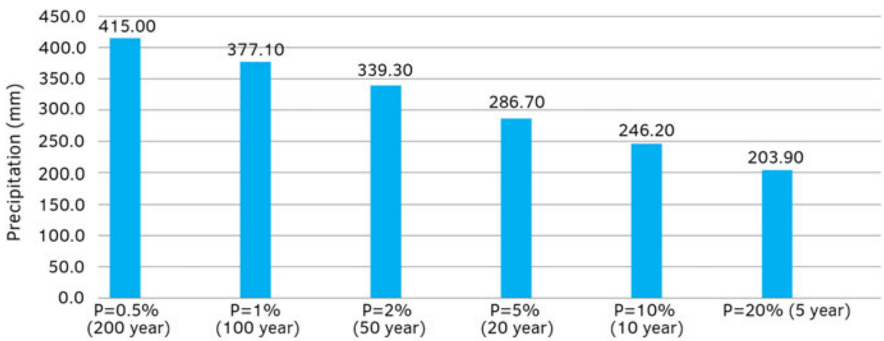


FIG. APP.D.2 The prediction of max daily precipitation under different climate scenarios . (Source: Author mapped based on Contour Map of Heavy Precipitation Parameters for Planning and Design, 2018)

The existing site of the Island is 17.9 square kilometers. Therefore, under 50-year precipitation, the total amount of precipitation in 24 hours is 6.109 million cubic meters. Under 100-year precipitation, the total amount of precipitation in 24 hours is 6.748 million cubic meters. Under 200-year precipitation, the total amount of precipitation in 24 hours is 7.428 million cubic meters. Table app.D.5 shows the amount of precipitation in each water collective unit with different precipitation scenarios.

TABLE APP.D.5 The amount of precipitation in each water collective units under different scenarios (unit: thousand m^3)

Number of water collective unit	Percentage of size	The amount of 50-year precipitation in 24 hours	The amount of 100-year precipitation in 24 hours	The amount of 200-year precipitation in 24 hours
East 1	10.1%	617	681	750
East 2	6.1%	373	412	453
East 3	6.1%	373	412	453
East 4	7.3%	446	493	542
East 5	5.0%	305	337	371
Mid 1	8.9%	544	601	661
Mid 2	5.0%	305	337	371
Mid 3	4.5%	275	304	334
Mid 4	5.6%	342	378	416
Mid 5	4.5%	275	304	334
West 1	6.7%	408	452	498
West 2	8.9%	544	601	661
West 3	8.3%	507	560	617
West 4	9.5%	580	641	706
West 5	3.5%	214	236	260

The amount of precipitation needs to be effectively stored or smoothly transported to outside waterways by connective water systems, natural surface runoffs, rainwater pipelines and other water storage carriers in the site. Table app.D.6 shows the current number of water storage elements in each water collective unit.

TABLE APP.D.6 Current water storage elements in each water collective unit

Number of water collective unit	Size of inner-river(thousand m²)	Size of potential low-lying depressions (floodable space) (thousand m²)	Number of natural surface runoff	Number of pumping station	Number of sluice
East 1	44	424	38	1	1
East 2	103	68	35	0.5	1
East 3	108	73	33	0.5	1
East 4	116	164	18	0.5	1
East 5	97	67	20	0.5	1
Mid 1	101	45	18	0.5	1
Mid 2	90	13	21	0.5	1
Mid 3	96	57	42	0	1
Mid 4	91	45	22	0	0
Mid 5	90	162	18	0	1
West 1	119	116	28	0.5	0.5
West 2	139	78	35	0.5	0.5
West 3	149	66	33	0.5	0.5
West 4	110	175	35	0.5	0.5
West 5	47	16	23	1	1

The mission of flood control and drainage responds to future precipitation to ensure that the amount of site's precipitation can be equal to the amount of site's water absorption. The mission of flooding control is to completely absorb the amount of precipitation in each water collective unit within 24 hours. Therefore, in order to improve this mission, the following formula can be applied.

$$V_r = V_a + V_b + V_c + V_d + V_e + V_f$$

Among them:

- V_r : The amount of precipitation to the site in 24hours
- V_a : The amount of water that can be stored in inner-rivers
- V_b : The amount of water that can be stored in low-lying depressions (floodable land)
- V_c : The amount of water that can be stored by the process of soil infiltration
- V_d : The amount of water that can be stored by other water bodies such as lake, ponds, wetlands
- V_e : The amount of water that can be extracted from site to outside waterways by pumping stations in 24 hours
- V_f : The amount of water that can be discharged from site to outside waterways by sluices in 24 hours

It is proposed that inner-river can store water for an average depth of 1.5 meters ((The average height of dyke alongside inner-rivers) - (Height for safety redundancy) - (Normal high water level)), in order to ensure that water will not overflow dykes to the site during extreme climate. The average width of the middle east-west inner-rivers (Zhengfeng Waterway) is 40 meters. The average width of the rest inner-rivers is 20 meters. At the same time, potential low-lying depressions that can be used as floodable lands that have an average depth of 0.6 meters for water storage.

Since there are two times of high tides and two times of low tides in a day, all sluices can only be opened when the water level of inner-rivers is higher than the water level of outside waterways (during the periods of normal water level and daily low tide). Each sluice has an average width of 6 meters with a discharge speed of 1 cubic meter/s. During normal water level's situation, sluice can discharge 0.2-meter depth water ((inner-river water level) - (outside waterway water level)) for 6.5 hours. During daily low tide's situation, sluice can discharge an average 0.6-meter depth water for 7 hours. Therefore, it can be calculated that each sluice can discharge 111.8 thousand cubic meters in 24 hours.

Each pumping station can work for 18 hours a day due to its intermittent operation, with the average extraction capacity of 1.84 cubic meters /s. Therefore, it can be calculated that each pumping station can extract 119.2 thousand cubic meters in 24 hours.

Urbanization will further affect the underlying surfaces of the land and influence the function of water storage and the process of infiltration. Simulations show that under the scenarios of future urbanization rate by 50% and by 80% (already, except the size of construction lands and hard pavements), the size of underlying surfaces that can be infiltrated are 8.56 and 3.42 square kilometers, respectively with reduced natural surface runoffs (Figure app.D.3, Figure app.D.4). The infiltration rate of soil is related to several physical characters such as composition, particle size, and viscosity. The infiltration rate of 100 to 500 mm / hour indicates that the soil has good infiltration capacity. Similarly, 70 to 100 mm / hour indicates moderate infiltration capacity, 30 to 70 mm / hour indicates weak infiltration capacity, and less than 30 mm / hour indicates poor infiltration capacity.

According to the simulation results of the site, the infiltration rate can be very large in the initial stage because of dry and unsaturated soil. When precipitation process continues and soils become wet and saturated, the infiltration rate gradually decreases, and finally maintains into a stable level until the process of infiltration stops. Combined with the physical characters of the soil of Hengli Island, the initial infiltration rate can reach to 45 mm/ h, with 2 hours effective infiltration time. Then the infiltration rate decreases to 9 mm/ h, with 10 hours effective infiltration time. For the remaining 12 hours, the process of infiltration stops.

Based on above data and formula, Table app.D.7 shows the number of gaps between the capacity of water storage and precipitation in each water collective unit, under different future scenarios. The table provides the basic knowledge for creating a resilient flood control and drainage system in the site.

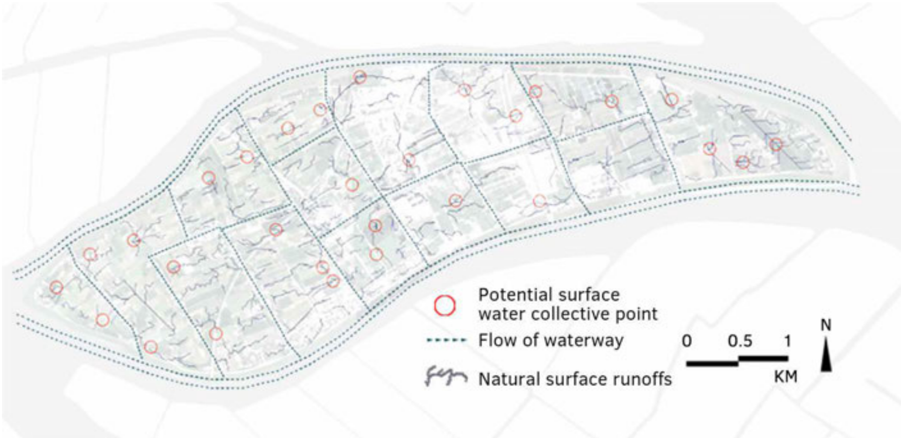


FIG. APP.D.3 The simulation of natural surface runoffs under 50% land development situation

FIG. APP.D.4 The simulation of natural surface runoffs under 80% land development situation

TABLE APP.D.7 The amount of gap in each water collective unit (Unit: thousand m³)

Number of water collective unit	Volume of water storage of adjacent inner-river (V_a)	Volume of water storage of low-lying depressions (V_b)	Volume of water discharge through sluice (V_f)	Volume of water extraction by pumping station (V_e)	Volume of soil infiltration under 50% (80%) of urbanization (V_c)	The amount of gaps of 50-year precipitation scenario, under 50% (80%) of urbanization (U)	The amount of gaps of 100-year precipitation scenario, under 50% (80%) of urbanization (U)	The amount of gaps of 50-year precipitation scenario, under 50% (80%) of urbanization (U)
East 1	307.5	27.6	111.8	119.2	144.2(57.7)	-79.5(15.3)	-15.0(79.8)	53.8(148.6)
East 2	59.2	52.8	111.8	59.6	94.7(37.8)	20.9(93.6)	59.9(132.5)	101.4(174.1)
East 3	62.2	43.8	111.8	59.6	94.5(37.8)	22.6(92.4)	61.5(131.4)	103.1(172.9)
East 4	64.8	53.4	111.8	59.6	113.7(45.5)	69.4(153.6)	116.0(200.2)	165.7(250.0)
East 5	59.1	40.2	111.8	59.6	77.1(30.8)	-22.1(36.1)	9.8(68.1)	43.8(102.1)
Mid 1	72.2	21.1	111.8	59.6	139.1(55.6)	150.8(240.5)	207.6(297.3)	268.2(358.0)
Mid 2	57.1	19.8	111.8	59.6	77.1(30.8)	-10.1(42.1)	21.8(74.0)	55.9(108.1)
Mid 3	32.1	34.2	111.8	0	71.5(28.2)	43.3(96.0)	72.1(124.7)	102.7(155.3)
Mid 4	81.1	27.1	0	0	85.3(34.1)	162.3(221.6)	198.0(257.3)	236.2(295.5)
Mid 5	58.8	49.2	111.8	0	68.9(27.5)	10.8(66.9)	39.5(95.6)	70.1(126.3)
West 1	65.7	51.6	55.9	59.6	103.9(41.5)	98.3(176.2)	141.1(219.0)	186.7(264.6)
West 2	68.8	46.8	55.9	59.6	139.2(55.6)	196.7(294.3)	253.6(351.2)	314.2(411.8)
West 3	78.1	39.6	55.9	59.6	129.0(51.6)	164.6(253.9)	217.6(306.9)	274.1(363.4)
West 4	69.7	45.5	55.9	59.6	148.8(59.5)	223.8(326.6)	284.5(387.3)	349.1(452.0)
West 5	34.6	9.6	111.8	119.2	54.3(21.7)	-110.9(-75.5)	-88.6(-53.1)	-64.7(-29.3)

Note: The amount of gap $U = V_r - V_a + V_b + V_c + V_d + V_e + V_f$

D.7 Indicators for evaluating shoreline condition

Shoreline condition is important for dyke construction and waterfront plan and design. There are several indicators to be considered for evaluating the shoreline condition in each section, as shown in table app.D.8.

TABLE APP.D.8 Indicators for evaluating shoreline condition

Item	Indicator to be measured	Classification	Indicator value
Flooding defense requirement	Flooding vulnerability: The ratio of the size of flooding areas (200-year) to the size of 100m width shoreline in each shoreline section	High	Flooding vulnerability > 70%
		Moderate	50% < Flooding vulnerability≤70%
		Low	Flooding vulnerability≤50%
Slope	Slope: The value of average slope on both sides of the shoreline in each shoreline section	Large	Slope > 10°
		Moderate	5° < Slope≤10°
		Small	Slope≤5°
The situation of land subsidence	Annual land subsidence: The value of average speed of annual land subsidence in each shoreline section	Extreme	Annual land subsidence > 4mm/a
		Middle	2mm/a < Annual land subsidence≤4mm/a
		Moderate	Annual land subsidence ≤2mm/a
Erosion (sedimentation)	Degree of Erosion (Sedimentation): The ratio of the distances that increase or decrease in 10 years of a river to the original width of a river	Erosion	Degree of Erosion (Sedimentation) > 5%
		Stable	-5%≤Degree of Erosion (Sedimentation)≤5%
		Sedimentation	Degree of Erosion (Sedimentation) < -5%
The condition of delta landscape	Landscape visual permeability: The ratio of the length that can visualize water to the total length of shoreline in each shoreline section	Good	Landscape visual permeability≤50%
		Moderate	50% < Landscape visual permeability≤75%
		Bad	Landscape visual permeability > 75%
The situation of reserved land	Existing buffering distance: Average distance from building to shoreline in each shoreline section	Insufficient	Existing buffering distance≤10m
		Moderate	10m < Existing buffering distance≤30m
		Sufficient	Existing buffering distance > 30m

D.8 Calculation for Peripheral Dyke's Height against 200-year flooding

The new elevation formula for flood control in peripheral dyke can be seen in the following.

$$H = h_1 + h_2 + h_3 + h_4 + h_5 + h_6$$

Among them:

H : The height of peripheral dyke ring
h_1 : Water level of 200-year (P=0.5%) high tide
h_2 : Sea level rise in 2100
h_3 : The height of wave run-up when flooding
h_4 : The height of wind banked-up when flooding
h_5 : The height of land subsidence of the site
h_6 : Height for safety redundancy

Based on historical data and the standard of dyke, the reserved height of land subsidence that prepares for concrete dyke foundation can be taken as 3% ~ 8% of the height of new dyke. Because the duration of the situation of extreme high tide is usually very short (only a few hours from the historical data), new peripheral dyke ring is proposed to be allowed to be partially overflowed by a small amount of waves that can be later absorbed by sufficient well-prepared water bodies and buffering zones on the site, in order to avoid poor landscape-viewing caused by 'too-high and wall-liked' dykes. Therefore, the calculation of the elevation of peripheral dyke ring here can use the indicator of height for safety redundancy (h_6) to replace the indicator of the height of wave run-up (h_3) and the indicator of the height of wind banked-up (h_4). According to the standard of dyke, when facing 200-year (P=0.5%) flooding, the value of h_6 can apply 1.0 meter.

Under the situation of overlapping sea level rise, 200-year (P=0.5%) high tide, and land subsidence, the proposed height of the new dyke can be seen in the following;

$H|_{p=0.5\%}$=2.93m (water level of 200-year (P=0.5%) high tide) + 0.5 m (sea level rise in 2100) + 1.0 m (safety redundancy) + 5.0m * 6% (reserved height for land subsidence) = 4.73 m. This new height is 1.53m higher than the lowest point of current dyke, 4.7m higher than current agricultural land, 3.5m higher than current constructed land.

Similarly, under the situation of overlapping sea level rise, 100-year (P=1%) high tide, and land subsidence, the proposed height of new dyke can be seen in the following.

$H|_{p=1\%}$=2.72m (water level of 100-year (P=1%) high tide) + 0.5 m (sea level rise in 2100) + 0.8 m (safety redundancy) + 5.0m * 6% (reserved height for land subsidence) = 4.32 m. This new height is 1.12m higher than current lowest point of dyke, 4.3m higher than current agricultural land, 3.1m higher than current constructed land.

Based on above calculations, proposed elevation of new dyke that can defend the situation of overlapping sea level rise, 200-year (P=0.5%) high tide, and land subsidence can be 4.73 meters.

D.9 Calculation for dyke retreat distance from shoreline

Figure app.D.5 shows the spatial models of dykes without retreat distance (proposal 1) and dykes with retreat distance (proposal 2). The purpose is to further explore the relationship between the width of buffering areas (W) and the reducing height of the water level of outside waterways (Δh).

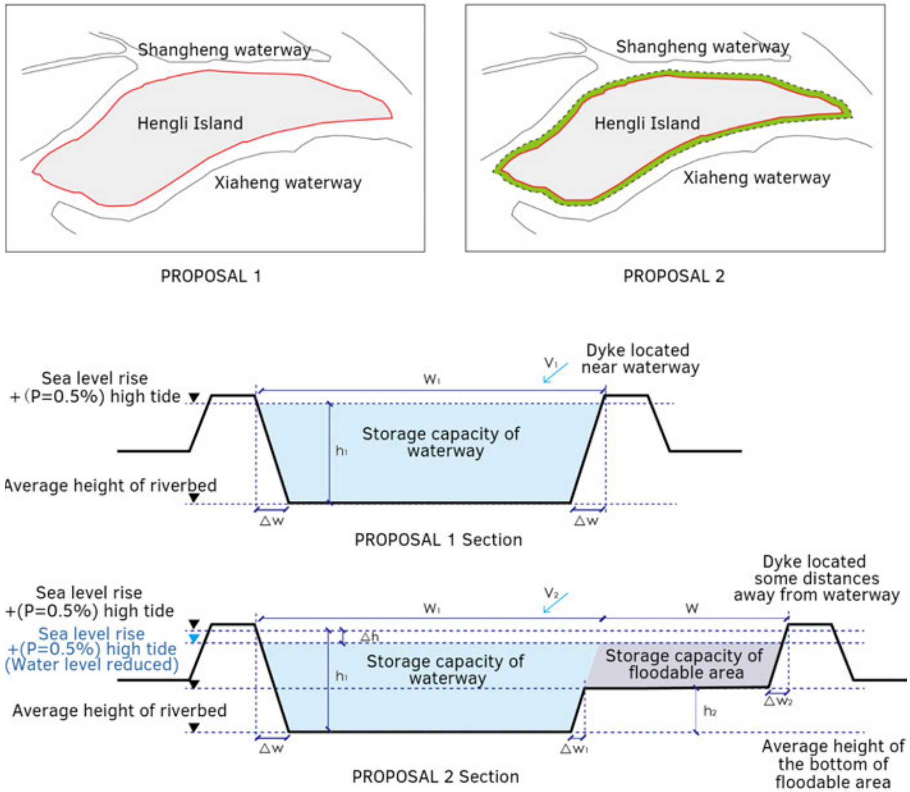


FIG. APP.D.5 The spatial models of two proposals of dyke location

TOC

As for estimation, it can be assumed that $\Delta w_1=0$, $\Delta w_2=0$, $\Delta w=0$. According to hydrodynamics' principle that the volumes of water go across a river section should be equal in a river channel, the following formula can be obtained.

$$W_1V_1h_1=\left[W_1\left(h_1-\Delta h\right)+W\left(h_1-\Delta h-h_2\right)\right]V_2$$

Among them:

W_1 : The average width of outside waterway,
V_1 : The flow velocity of outside waterway under extreme situation,
V_2 : The flow velocity of outside waterway after considering buffering areas under extreme situation,
h_1 : The average depth of outside waterway plus water level of extreme high tide,
h_2 : The average depth of outside waterway minus average depth of buffering area

After transforming, the following formula can be obtained.

$$\Delta h=h_1-\frac{Wh_2V_2+W_1V_1h_1}{\left(W_1+W\right)V_2}$$

Reviewing the data of Hengli Island, it can be found that h_1 = 16 m, h_2 = 12 m, W=300m (the width of outside waterways is from 200~400, so the average width is 300m). The circumference of the shoreline is 21.8 kilometers. According to formula, it can be seen that when the value of W increases, the value of $V_2:V_1$ decreases. According to the record value of the flow velocity of passing water in 2018 typhoon 'Shanzhu' (historical fastest), V_1 = 12 m / s can be taken for extreme climate condition in the future. Substituting all above data into formula and after calculating 11 possible scenarios, Table app.D.9 can be obtained for understanding the relationships between the width of buffering areas (W) and the reducing height of the water level of outside waterways (Δh).

TABLE APP.D.9 TABLE APP. D.9 The relationship between the width of buffering areas (W) and the height of water level reducing (Δh) under extreme climate condition

The width of buffering areas *W* (m)	The size of sacrificed land in each square kilometer (thousand m^2)	The height of water level reducing under extreme climate condition Δh (m)	$V_2 : V_1$
5	5	0.013	0.997
10	10	0.051	0.995
20	20	0.086	0.989
30	30	0.117	0.983
40	40	0.146	0.978
50	50	0.172	0.972
60	60	0.183	0.965
70	70	0.193	0.958
80	80	0.212	0.953
90	90	0.253	0.948
100	100	0.268	0.943

D.10 Diversified and Multifunctional Dykes

According to the terrain characters of the Island, several cross-section dyke shapes are proposed (Figure app.D.6 ~ Figure app.D.13). Table app.D.10 shows the advantages and the disadvantages of all these dyke shapes, as well as the suggestions of appropriate applicable shoreline conditions. Reasonable selections of different cross-section dyke shapes should be created according to the terrain conditions and future requirements of each shoreline section.

Proposals for cross-section dyke shapes are drawn. They are upright dyke shape, slope dyke shape, dual-upright dyke shape, dual-slope dyke shape, mixed dyke shape, super widen dyke shape, retreated dyke shape and spur dyke shape.

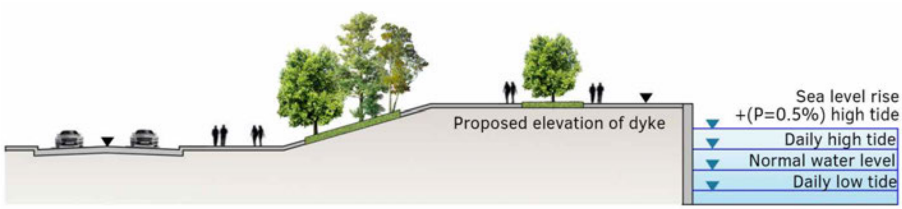


FIG. APP.D.6 Upright dyke shape

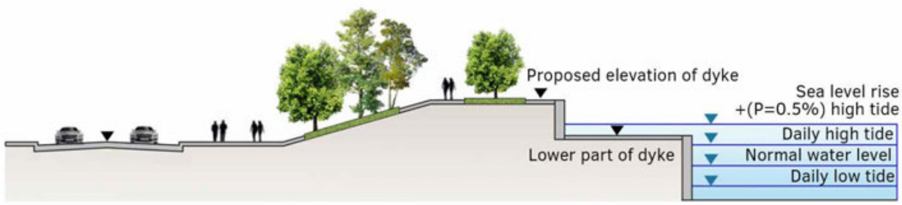


FIG. APP.D.7 Dual-upright dyke shape

FIG. APP.D.8 Slope dyke shape

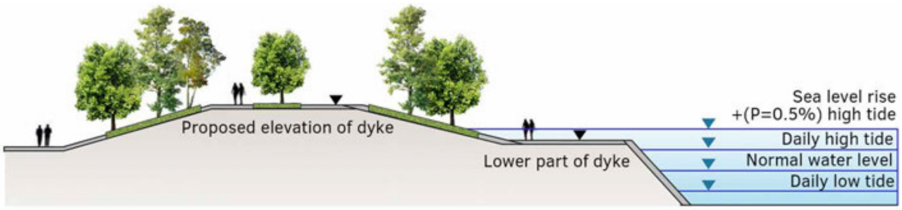


FIG. APP.D.9 Dual-slope dyke shape

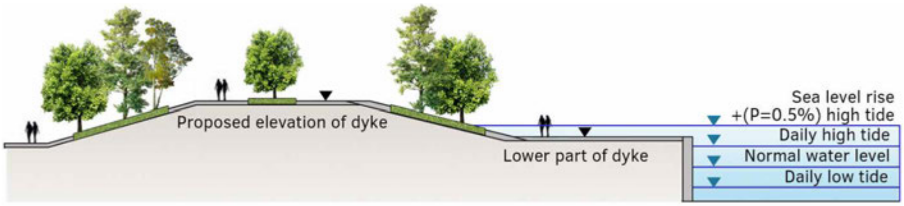


FIG. APP.D.10 Mixed dyke shape

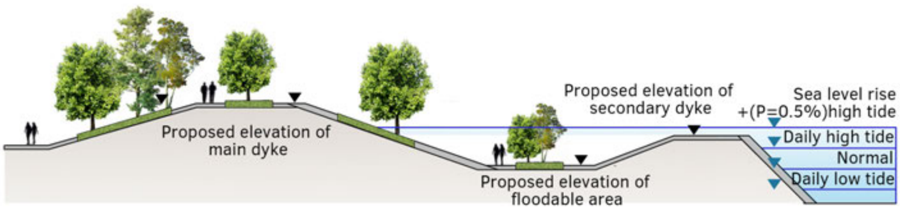


FIG. APP.D.11 Retreated dyke shape

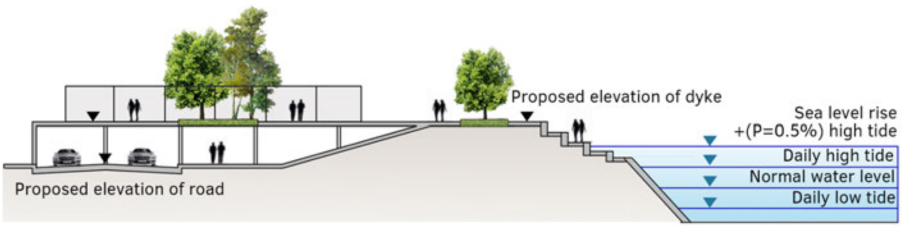


FIG. APP.D.12 Super widen dyke shape

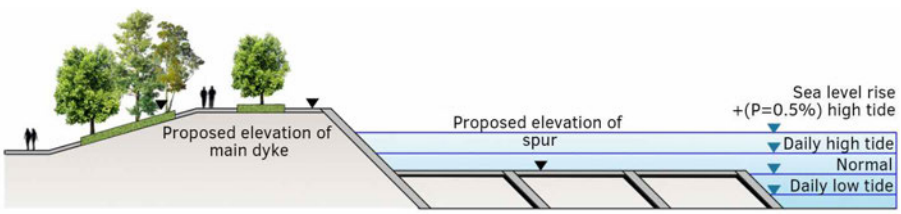


FIG. APP.D.13 Spur dyke shape

TABLE APP.D.10 Advantages and disadvantages of various cross-section dyke shapes and proposal for applicable shoreline section

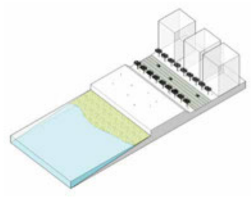
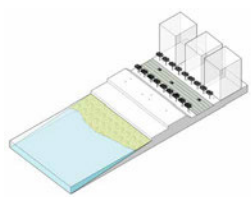
3D Perspective	Character	Disadvantage	Suggestions for applicable shoreline section
 Upright dyke shape	(1) A small amount of areas will be occupied for construction (2) When there are sufficient reserved lands, the width of dyke can be expanded to facilitate other functions (landscape leisure, fitness, etc.) (3) The flooding control standard can be reached easily behind the wave barrier, which is beneficial to the protection of the landscape-viewing site behind the dyke. (4) The cost of the construction of dyke is low.	(1) The tide can directly hit the dyke body without a slope, which can cause high wave height. It is not conducive to defend against the serious impact from huge wind and wave. (2). There are a large height distances between normal water level and dyke, which is not conductive to the need of feeling of water (3) Engineering traces on the waterfront can be obvious (4) High standard of foundation requires high cost of construction (5) It is not conductive to the layout of the buffering areas	It is suitable for shoreline section which has low flooding defense requirements, insufficient reserved lands, low impact from tide, and small degree of land subsidence
 Dual-upright dyke shape	(1) Dual sense of space can provide good landscape-viewing with wide sight (2) The lower part of dyke can be beneficial to the need of feeling of water (3) The flooding control standard can be reached easily behind the wave barrier, which is beneficial to the protection of the landscape-viewing site behind the dyke.	(1) The tide can directly hit the dyke body without a slope, which can cause high wave height. It is not conducive to defend against the serious impact from huge wind and wave. (2) Engineering traces on the waterfront can be obvious (3) High standard of foundation requires high cost of construction (4) A large amount of areas will be occupied for construction	It is suitable for shoreline section which has a high landscape-viewing requirements, low flooding defense requirements, sufficient reserved lands, low impact from tide, and small degree of land subsidence

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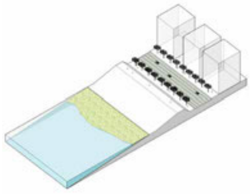
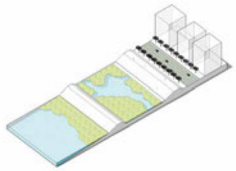
TABLE APP.D.10 Advantages and disadvantages of various cross-section dyke shapes and proposal for applicable shoreline section

3D Perspective	Character	Disadvantage	Suggestions for applicable shoreline section
 Slope dyke shape	(1) A small amount of areas will be occupied for construction (2) The dyke slope is more natural, with a better sense of space, wide sight and good landscape-viewing (3) It is beneficial to create a waterfront leisure landscape belt on the slope, which can provide space that is close to water (4). It requires low cost for construction (4) The slope can provide function of flooding prevention by buffering zone, which is conductive to defending against the impact of wind and wave	(1). There are a large height distances between normal water level and dyke, which is not conductive to the need of feeling of water (2) There can be waterlogging on the dyke slope	It is suitable for shoreline section which has high flooding defence requirements, high landscape-viewing requirements, insufficient reserved land, high impact from tide and moderate degree of land subsidence
 Dual-slope dyke shape	(1) The dyke slope is more natural, with a better sense of space, wide sight and good landscape-viewing (2) The lower part of dyke can be beneficial to the need of feeling of water (3) It is beneficial to create a waterfront leisure landscape belt on the slope, which can provide space that is close to water (4) The dual- slope can provide function of flooding prevention by buffering zone, which is conductive to defending against the impact of wind and wave	(1) A large amount of area will be occupied for construction (2) High standard of foundation requires high cost of construction (3) Under extreme climate condition, there can be waterlogging on the lower part of dyke	It is suitable for shoreline section which has high flooding defence requirements, high landscape-viewing requirements, sufficient reserved land, high impact from tide and small degree of land subsidence

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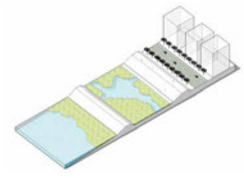
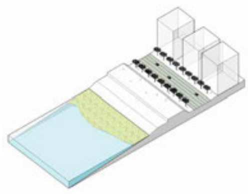
TOC

TABLE APP.D.10 Advantages and disadvantages of various cross-section dyke shapes and proposal for applicable shoreline section

3D Perspective	Character	Disadvantage	Suggestions for applicable shoreline section
 Retreated dyke shape	(1) The retreated dyke can largely protect the side from direct impacts of tide, wave and wind due to its buffering areas between first and second dyke; (2) Buffering area between first and second dyke can be beneficial to nourish new floodable area for the requirement of landscape-viewing	(1) A large amount of area will be occupied for construction (2) Sometimes low connectivity between first and second dyke can lead to 'dead water' (3). It will cost a high amount of money to maintain the quality of new floodable area	It is suitable for shoreline section which has high flooding defence requirement, high landscape-viewing requirement. It is especially suitable for the frontier part of the island which usually has sufficient reserved land and sufficient width of riverbed, where there always has a large amount of aquatic habitat, wetlands that have high conservation value
 Mixed dyke shape	(1) The mixed application of upright and slope form is more interesting, with a better sense of space, wide sight and good landscape-viewing (2) The mixed shape can provide function of flooding prevention by buffering zone, which is conductive to defending against the impact of wind and wave (3) Smaller amount of occupation of land compared with dual-slope dyke	(1) High standard of foundation requires high cost of construction (2) It is greatly affected by the effect of land subsidence (3) There can be waterlogging on the back part of upright platform	It is suitable for shoreline section which has high flooding defence requirements, high landscape-viewing requirements, sufficient reserved land, high impact from tide and small degree of land subsidence

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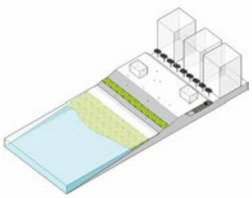
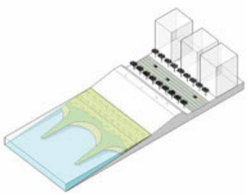
TOC

TABLE APP.D.10 Advantages and disadvantages of various cross-section dyke shapes and proposal for applicable shoreline section

3D Perspective	Character	Disadvantage	Suggestions for applicable shoreline section
 Super widen dyke shape	(1) Applying an extra-wide dyke structure can provide a good buffer against tide, wind and wave. Even if the situation of overflowing of water from outside occurs, the velocity can be reduced by widened dyke thus will not cause serious damage to the shoreline (2). The water facing surface usually adopts step-shaped structure, which can help to gradual adaptability to the situation of sea level rise by gradually increasing the height of dyke (3) Because the dyke is super wide, it can be coordinative constructed with surrounding roads, subway station and buildings to improve multifunctionality (4) Large space of platform can provide with a better sense of space, wide sight and good landscape-viewing	(1) A large amount of area will be occupied for construction (2) Complex construction structure will cost large amount of money (3) Under extreme climate condition, there can be waterlogging on the platform of dyke	It is suitable for shoreline section which has high flooding defence requirements, high landscape-viewing requirements, sufficient reserved land, high impact from tide and small degree of land subsidence. It is especially suitable for the high-density area with adjacent tall buildings, emergency route, and subway station. It is especially suitable for current step-shaped waterfront that can be gradually increasing the height of dyke
 Spur dyke shape	(1) With spur, the original hydrodynamic characters of waterways can be changed. The waterfront can be protected due to largely reduction of the negative impacts of tide, wave and wind (2) With low impact, it is beneficial to nourish new floodable areas in the riverbed	(1) Complex construction structure will cost large amount of money (2) A large amount of area will be occupied for construction (3) Because the dyke structure can penetrate into the riverbed, it will affect the original hydrodynamic characters of waterways which can cause uncertain water performance	It is suitable for shoreline section which is located adjacent to super wide waterways, and has huge impact from tide, wave and wind. It is especially suitable for shoreline section that needs to be nourished. Due to its uncertain negative effects to the original hydrodynamic characters of waterways, it is not recommended for common use.

TOC

D.11 Water Level Control Strategies in Different Scenarios

The water level of inner-rivers can be divided into four categories which include normal water level, starting regulation water level, pre-descent water level, and maximum water level.

- Normal water level refers to water level intervals at which the requirements of shipping and landscape-viewing of inner-rivers can be improved. The normal water level can be maintained by opening or closing sluices.
- Starting regulation water level is not only the upper limit of normal water level but also the initial water level for starting regulation. During normal days, when inner-river's water level is higher than starting regulation water level, sluices are opened and excessive water can be self-discharged to the outside waterways. Because of daily tidal time, sluices can be opened at night when the water level of outside waterways is low.
- Pre-descent water level is another type of start regulation water level, but this water level is lower than normal starting regulation water level. It is necessary to further lower the water level of inner-rivers in advance before extreme precipitation arrives, in order to leave more water storage space. Too low pre-descent water level can influence shipping and landscape-viewing.
- Maximum water level refers to the highest water level that needs to be controlled of inner-rivers when extreme precipitation occurs. Maximum water level is related to the proposed height of dykes of inner-rivers. Only when the water level of inner-river is lower than maximum water level, the site will not be flooded and waterlogged.

According to the data record, the average normal water level of outside waterway in the future will be '0.0 + 0.50 meters (sea level rise)', the average daily high-high tide will be '2.00 + 0.50 meters (sea level rise)', the average daily low-low tide is ' -1.5 + 0.50 meters (sea level rise) ', the normal high water level will be' 0.3 + 0.50 meters (sea level rise) ', and the normal low water level will be' -0.3 + 0.50 meters (sea level rise) '.The pre-descent water level is proposed to be '-0.3 + 0.50 meters (sea level rise)' when the requirements of both flooding control, landscape-viewing and shipping are considered. The pre-descent water level is equal to the normal low water level of the outside waterway, in order to guarantee that boats will not strand (lower water level will cause easier strand), as well as guarantee self-discharge and artificial-extraction can be conducted successfully (lower water level will cause more difficult self-discharge and artificial-extraction because of higher elevation difference). The maximum water level for preventing floods from come into the site from inner-river is proposed to be '2.0+0.50 meters (sea level rise)', which is equal to average daily high-high tide of outside waterway and has 0.6m safety redundant elevation difference between dyke height of inner-river and the site.

The elevation relationships for water level control, as well as the corresponding elevation values of both outside waterways and inner-rivers are shown in Figure app.D.14. (Note: The elevation in the figure is not added with sea level rise data because the actual sea level rise can be changed annually. For actual water level control process, the actual sea level rise data for that year should be added).

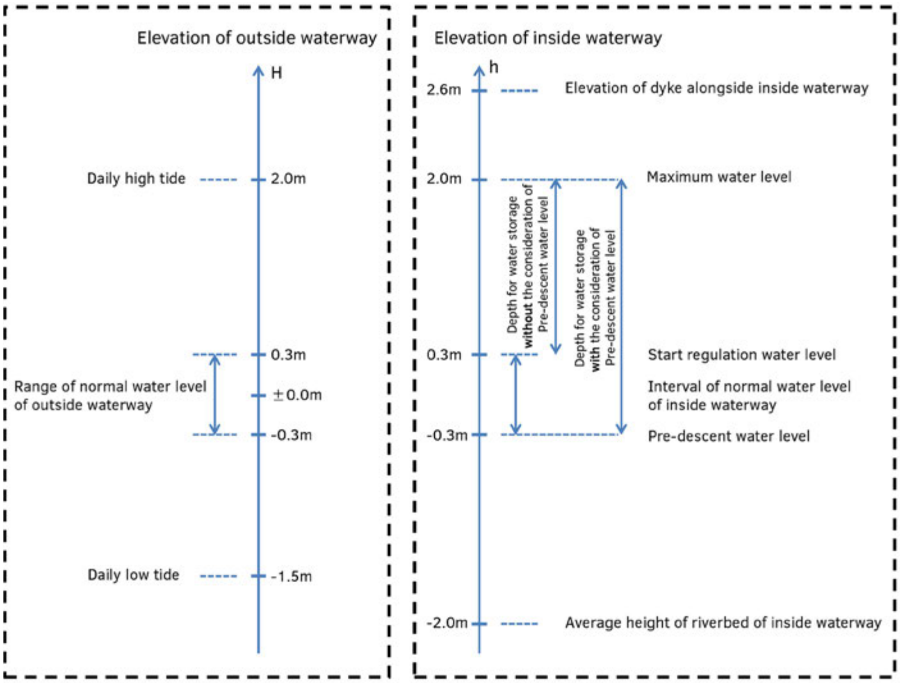


FIG. APP.D.14 Water level control and the corresponding elevation values of both inner-rivers and outside waterways

Based on the situation differences between normal and flooding days, the regulation of water level of inner-river can be divided into two further situations—regulation in normal situation and regulation in flooding situation.

A Measures for regulation in normal situation are in the followings.

With the opening and closing of the sluice, the interval of the normal water level of inner-rivers should be kept from -0.3m to 0.3m to maintain the functions of landscape-viewing and shipping. Therefore, further two scenarios for normal situation can be seen in the followings.

Scenario 1:
If h <-0.3 meters and h < H,

Then sluices will be opened. Water flow from outside waterway to inner-river until h = -0.3 m.

Otherwise, Sluices will be closed.

Scenario 2:
If h> 0.3 m and h **>** H,

Then sluices will be opened. Water flow from inner-river to outside waterway until h = 0.3 m.

Otherwise, Sluices will be closed.

B Measures for regulation in flooding situation are in the followings.

When flooding occurs, combination strategies of regulation, self-discharge, and artificial-extraction can be used. When start regulation water level of inner-rivers is taken to be 0.3 meters, further two scenarios for normal situation can be seen in the followings.

Scenario 3:
If h $>$ 0.3 meters and h $>$ H,

Then sluices will be opened. Excessive water can flow from inner-river to outside waterway by self-discharge to maintain the water level $<$ 2.0 meters.

Otherwise, sluices will be closed.

Scenario 4:
If h $>$ 0.3 meters and h $<$ H,

Then pumping stations will be opened. Excessive water can be extracted from inner-river to outside waterway by artificial-extraction to maintain the water level $<$ 2.0 meters.

Otherwise, pumping stations will be closed.

D.12 Spatial integration of key hydrological points evaluation

Table app.D.11 compares the degree of spatial integration of key hydrological points before and after planning and design.

TABLE APP.D.11 Comparison of the degree of spatial integration of key hydrological points before and after planning and design

Number of key hydrological point	Before	After	After: Before
#1	0.50	0.56	1.12
#2	0.57	0.65	1.14
#3	0.63	0.71	1.12
#4	0.48	0.59	1.22
#5	0.52	0.68	1.30
#6	0.69	0.78	1.13
#7	0.70	0.80	1.14
#8	0.59	0.71	1.20
#9	0.67	0.75	1.11
#10	0.68	0.79	1.16
#11	0.53	0.68	1.28
#12	0.63	0.73	1.15
#13	0.48	0.65	1.35
#14	0.64	0.73	1.14
#15	0.50	0.66	1.32
#16	0.50	0.68	1.36
#17	0.54	0.68	1.25
#18	0.60	0.66	1.10
#19	0.57	0.69	1.21
#20	0.46	0.49	1.06
#21	0.66	0.69	1.04
#22	0.51	0.58	1.13
#23	0.52	0.57	1.09
#24	0.68	0.69	1.01
#25	0.66	0.69	1.04
#26	0.70	0.73	1.04
#27	0.67	0.70	1.04
#28	0.44	0.51	1.15

D.13 Peak runoff speed of each water collective unit evaluation

According to the standard of flooding control and drainage, formula for calculating peak runoff speed can be seen in the followings.

$$Q_m = \varphi * q * F$$

$$q = \frac{5534\left(p^{0.3} - 0.42\right)}{\left(t + 10 + \log P\right)^{0.82 + 0.07\log P}}$$

Among them:

Qm: Peak runoff speed(L/s)
q : The intensify of precipitation(L/s·ha)
F : The size of each water collective unit (ha),

φ :The coefficient of peak runoff speed. φ =0.2(Underlying surface is park or other water-permeable green space) ;φ =0.4(Underlying surface is half-water-permeable space), φ =0.7(Underlying surface is concrete or other water-impermeable space)

P:The recurrence period of precipitation

t:The duration of precipitation

Table app.D.12 compares peak runoff speed in each water collective units before and after planning and design.

TABLE APP.D.12 Comparison of peak runoff speed in each water collective units before and after planning and design

Before planning and design			After planning and design			Peak runoff speed (after planning and design): Peak runoff speed (before planning and design)(%)
Number of water collective unit	Size of water collective unit(ha)	Peak runoff speed(m^3/s)	Number of water collective unit	Size of water collective unit(ha)	Peak runoff speed(m^3/s)	
East 1	180.79	12.62	East 1-1	47.00	5.74	45.5%
			East 1-2	47.02	5.75	45.6%
			East 1-3	86.77	10.60	83.4%
East 2	109.19	7.62	East 2-1	59.29	7.24	95.0%
			East 2-2	55.76	6.81	89.3%
			East 2-3	23.53	2.87	37.7%
East 3	109.19	7.62	East 3-1	42.19	5.15	67.6%
			East 3-2	34.20	4.17	54.7%
			East 3-3	32.80	4.08	53.2%
East 4	130.67	15.96	East 4-1	40.30	8.61	53.9%
			East 4-2	43.36	9.26	58.0%
			East 4-3	47.01	10.04	62.9%
East 5	89.51	6.25	East 5-1	33.25	2.32	37.1%
			East 5-2	23.86	1.66	26.6%
			East 5-3	32.40	2.26	36.2%
Mid 1	159.31	11.12	Mid 1-1	61.23	7.48	67.2%
			Mid 1-2	35.69	4.47	40.2%
			Mid 1-3	32.84	4.13	37.1%
			Mid 1-4	29.55	3.95	35.5%
Mid 2	89.51	10.94	Mid 2-1	49.45	6.04	55.2%
			Mid 2-2	40.06	4.89	44.8%
Mid 3	80.55	Mid 3-1	9.83	40.68	4.91	49.9%
		Mid 3-2		39.87	4.85	49.3%
Mid 4	100.24	Mid 4-1	7.00	12.42	1.51	21.6%
		Mid 4-2		37.02	4.59	65.6%
		Mid 4-3		37.29	4.61	65.9%
		Mid 4-4		13.51	1.68	24.0%
Mid 5	80.55	Mid 5-1	5.62	40.27	4.92	87.5%
		Mid 5-2		40.28	4.92	87.5%
West 1	119.93	West 1-1	8.37	28.78	3.51	41.9%
		West 1-2		31.19	3.80	45.4%
		West 1-3		59.96	7.32	87.5%
West 2	159.31	West 2-1	11.12	30.24	3.70	

>>>

TABLE APP.D.12 Comparison of peak runoff speed in each water collective units before and after planning and design

Before planning and design			After planning and design			Peak runoff speed (after planning and design): Peak runoff speed (before planning and design)(%)
Number of water collective unit	Size of water collective unit(ha)	Peak runoff speed(m^3/s)	Number of water collective unit	Size of water collective unit(ha)	Peak runoff speed(m^3/s)	
		West 2-2		34.82	4.26	38.4%
		West 2-3		38.92	4.76	42.3%
		West 2-4		33.25	4.06	36.6%
		West 2-5		22.08	2.70	24.1%
West 3	148.57	West 3-1	10.37	28.69	3.86	37.2%
		West 3-2		26.78	3.68	35.5%
		West 3-3		32.87	4.12	39.7%
		West 3-4		34.08	4.15	40.0%
		West 3-5		26.15	3.53	34.0%
West 4	170.05	West 4-1	11.88	35.36	4.32	37.0%
		West 4-2		43.87	5.13	43.2%
		West 4-3		51.47	7.44	62.6%
		West 4-4		15.68	1.94	16.3%
		West 4-5		23.67	2.95	24.8%
West 5	62.65	West 5	7.37	62.65	4.37	59.3%

Curriculum Vitae

Wei Dai was born in Hangzhou city, Zhejiang Province, P.R.China in March 25th, 1991. He obtained his bachelor degree from architecture at South China University of Technology (SCUT) in 2014. In the summer of 2014, he participated in the doctoral programme conducted by European IDEA league named ‘Making Urban System Adaptive and Resilience’, which provided him with motivations to think about a new way to improve the quality of our city in the future, especially under the pressure of climate change. Afterwards, he directly started his Ph.D research in the school of architecture, SCUT. In 2016, he received a scholarship from China Scholarship Council and continued his Ph.D research in the department of urbanism, Faculty of architecture and built environment, TUDelft, and began to obtain his double Ph.D. degree under the contract between TUDelft and SCUT. In 2017, he joined an International (Regional) joint project ‘Adaptive Urban Transformation-Territorial governance, spatial strategy and urban landscape dynamics for a more resilient Pearl River Delta’, which conducted among TUDelft, The university of Sheffield and South China University of Technology (SCUT). During his Ph.D research, he has been teaching in planning and design studios in the Master Program.

Besides Ph.D research, Wei Dai has also participated in many real urban planning and design projects from 2015-2019, such as Urban design and management optimization of Pazhou West District, Guangzhou, Urban planning and management optimization of C2 Unit, Pearl Bay, Nansha District, Guangzhou, Urban design consultation for Huangpu District, Guangzhou, Urban design consultation for Xiangmi Lake Area, Shenzhen, etc. All these experience obtained from real projects provide new insights for supporting his Ph.D research.

Being a curiosity-driven and internationally oriented person, Wei Dai is always delighted and enthusiastic to work together with his colleagues. After 10 years studying in the field of architecture, urban planning and design, he systematically grasped knowledge from this field, especially have interests in spatial planning and design for resilience.

List of Publications

Dai, W., Sun, Y., Meyer, H.,et.al. (2017). Resilient Planning of Delta Cities under Climate Change. *City Planning Review,* 41(12), 26-34.

Dai, W., Sun, Y., Meyer, H.,et. al. (2018). Towards Resilience: The Research on Resilient Delta Urban Planning from International Perspective. *Urban Planning and Design International*, 33(3), 83-91.

Dai, W., Sun, Y. (2018). Research of Land Use and Biodiversity Performance and Its Reference to Landscape Planning. *Landscape Architecture,* 25(4), 79-84.

Dai, W., Sun, Y., Meyer, H. (2019). Resilience as a New Concept of Planning Transformation in Delta Areas. *Landscape Architecture,* 26(9), 83-92.

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Dai, W. (2019). Understanding Effects of Urban Expansion on Natural Environment by Morphological Study. *Third International Conference on Energy Engineering and Environmental Protection,* 227(5).

21#04

Spatial Planning and Design for Resilience

The Case of Pearl River Delta

Wei Dai

Faced with the highly overlapping factors of the external disturbances -- natural disasters caused by extreme climate change, and internal interactions -- the contradiction between natural conditions and rapid urbanization, traditional spatial planning and design used to pursue economic development could not be flexible enough to respond to the dynamic and uncertain future of the Pearl River Delta (PRD).

Therefore, spatial planning and design should pay great attention to the fragile natural base layer and unexpected external disturbances that will negatively impact the PRD caused by increasing natural disasters, such as flooding and land subsidence situation. Based on the idea of spatial resilience, this doctoral dissertation aims to give an answer to the research question:
What are the theories and methods of spatial planning and design for resilience? How is it possible to apply the theory and method of spatial planning and design for resilience to the PRD?
Five major research contents are conducted. First of all, literatures on exploring the physical context, the crucial stages of spatial transformation, as well as spatial planning and design practices of the PRD are reviewed. Secondly, the theory of spatial planning and design for resilience is systematically researched. Thirdly, implementation method for spatial planning and design for resilience is provided. Fourthly, the empirical research of the theory and method of spatial planning and design for resilient PRD is conducted and possible new schemes are produced. Fifthly, the corresponding principles and strategies of resilient flood control and drainage on Hengli Island are proposed. The research outcomes obtained from this doctoral dissertation can be possibly applied to the further spatial planning and design practice for establishing a resilient PRD.

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