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Adaptive Construction Strategy of Human Settlements under the Disaster Mechanism of Typhoon-Waterlogging: A Study Based on the Jiaxing, Zhejiang

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Abstract: Based on the waterlogging disaster caused by typhoon landing and affecting the human settlements in the coastal plain of northern Zhejiang in recent years, this study explores the disaster mechanism of typhoon waterlogging affecting the human settlements from the four dimensions of physical geography, social structure, economic development and built environment. Through regression analysis, it is clear that "the ineffectiveness of polder" is the most key factor, high-density depressions, high water retention of imperious surfaces, low GDP and imperfect rescue circle are also closely related to disasters, which reveals that the security of human settlements in coastal plain areas is subject to the action mechanisms of natural geographical characteristics, the nature of towns and "human settlements units" construction. Then, adaptive strategies such as the optimization of micro watersheds structures, the establishment of towns compensation mechanism, the multi-functional construction of polder and the division of "waterlogging-control units" are proposed on the three scales of micro watersheds, towns and human settlement units. The purpose is to provide technical support and decision-making basis for disaster risk reduction and quality improvement of human settlements in coastal plain areas of China.

1. Introduction

1.1. Research Background

Typhoon is one of the most dangerous hydro-meteorological disasters, which poses a great threat to the human settlements in the Pacific Rim coastal area. Due to global warming, Intergovernmental Panel on climate change (IPCC) pointed out that the annual frequency of typhoons may decrease but the intensity may increase in the future. At present, this trend has become a consensus in the academic community [1-2]. As an extremely complex and huge meteorological system, its extreme precipitation is the major hazard. Almost all the records of heavy precipitation worldwide are created by tropical cyclones represented by typhoons [3]. With the upgrading of typhoon intensity, studies have shown that the southeast coastal areas of China will face more extreme heavy rainfall until the mid-21st century [4].

Typhoon extreme precipitation usually produces structural differentiation at the end of the disaster chain due to different geomorphic characteristics. In the coastal plain area with the strongest population carrying capacity in China, urban waterlogging is the final manifestation, and its negative impact on human settlements is significantly higher than single rainstorm waterlogging [5]. For example, Typhoon Lekima (201909) caused widespread waterlogging in Wenrui Plain, Wenhuang Plain and Hangjiahu Plain, resulting in a direct economic loss of 40.72 billion yuan in Zhejiang Province; The accumulated precipitation of Typhoon In-fa (202106) within 4 days broke the historical record of Zhejiang Province. Moreover, the second landing in Jiaxing coincided with the astronomical tide, resulting in poor drainage and serious waterlogging. Therefore, based on the severe damage, reducing the risk of "typhoon-waterlogging" needs to become the key to improve the quality of human settlements in the coastal plain.

1.2. Literature Review

Typhoon-waterlogging in coastal plain area is a small-scale disaster field caused by large-scale man-land conflict. The existing adaptability research can be summarized from macro, meso and micro scales. On the macro scale, the prevention and control of typhoon-waterlogging is a sub part of the national, regional or urban flood management plan. Like Sponge Cities, which began in 2013, most of the research focuses on the construction, implementation and management methods of the overall planning [6,7]. Although collaborative governance still has a long way to go, "cognitive risk and its mechanism" can be used as the first step to support subsequent governance [8]. On the meso scale, on the one hand, low impact development can be used as a guideline to simulate and build drainage systems [9,10], but some researches pointed out that most of the methods developed so far are only effective for small-scale flood peaks [11], which means the necessity of building non engineering measures; On the other hand, many studies regard towns or communities as the basic unit of risk assessment, and comprehensively consider the risk driven by multi-dimensional factors such as environment, society and economy [12,13]. On the micro scale, it is manifested in the adaptive optimization of the built environment and construction mode. When the system responds to external interference, the purpose of adaptive construction is to generate new methods by transforming the structure to maintain functional stability. Nowadays, the hydrological situation has changed significantly [14]. The traditional construction methods need to be organically updated, and the clarification of disaster mechanism can provide a more scientific basis for adaptive construction [15].

1.3. Research Purpose and Significance

Through literature review and the overview of typhoon disasters in coastal plain areas of China, it can be seen that the current analysis of disaster mechanism cannot be effectively linked to the adaptive construction of human settlements. The terrain in the southeast coastal areas of China is broken, among which the Jiaxing plain in Northern Zhejiang is one of the coastal plains with the widest land area and the largest population. It is also a typical area seriously affected by the "typhoon-waterlogging" disaster, so it is worth studying as an object to explore the disaster mechanism affecting the human settlements, so as to improve the interpretation of adaptive construction. And then provide some technical support and decision-making basis for the disaster prevention and mitigation and quality improvement of the human settlements in the wider coastal plain area.

2. Study Area and Research Methods

2.1. Study Area

2.1.1. Geomorphic Features

Jiaxing, located in the north of Zhejiang Province and the hinterland of the Yangtze River Delta, is one of the coastal plains with the largest area and the largest population in Zhejiang Province. The land area of the whole territory is 3915 km^2, the terrain is low and flat, and the average altitude is only 3.7m. The plain accounts for 88.8% of the land area, and the open and flat coastline accounts for 67.2% of the total length (excluding a few Island coastlines) (Figure 1). Jiaxing is rich in groundwater, but excessive exploitation has caused land subsidence. By 2019, a total of 80.3% of the city's land areas have subsidence greater than 100mm, and 8.5% of it has subsidence greater than 500mm. The maximum is located in Pinghu county and the main urban area, up to 1045mm and 874mm respectively.

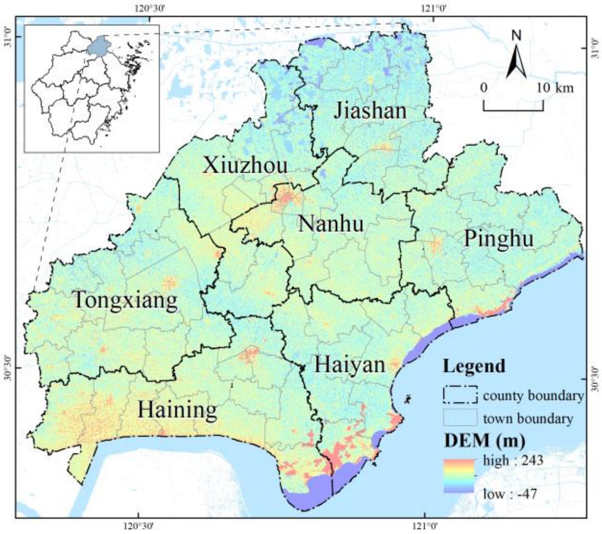


Figure 1: Geomorphic features of Jiaxing.

2.1.2. Typhoon Features

Statistics show that there were 135 tropical cyclones affecting Zhejiang from 1973 to 2015, and the precipitation intensity of 129 tropical cyclones strengthened again after weakening, and reached the rainstorm standard, which is called "heavy rainfall reinforcement ", accounting for 95.6%. Jiaxing is one of the high-frequency areas with "extreme rainfall reinforcement" of 3-12 hours [16]. Therefore, natural conditions and many social factors determine that Jiaxing is the worst-hit area in the disaster chain of "typhoon extreme precipitation - waterlogging in human settlements". The research shows that 94.4% of the towns in Jiaxing have medium and high levels of waterlogging risk, ranking first in Zhejiang Province [17].

2.1.3. Problems of Disaster Prevention and Mitigation of Human Settlements in Jiaxing

(1) High speed urbanization: focusing on agglomeration and neglecting quality

Jiaxing's urban-rural integration has achieved remarkable results after 2008. In 2020, the urbanization rate of Jiaxing's perennial resident population reached 71.34%, an increase of 18.01% compared with 2010, ranking first in Zhejiang Province. However, from the existing experience and practice, there are several problems.

① Development mode of most towns is guided by the rapid release of construction land. Typhoon prevention and disaster reduction strategies lack attention in the planning of new areas, and the extensive use of space and land has not fundamentally changed.

② Due to the broken landform in the riverine plain area, as well as historical reasons such as the small-scale farming and rural industrialization, there are still a large number of scattered plots, so it is difficult to find a suitable method to turn to the aggregation mode in a short time.

③ Policy restricts that old houses and dilapidated houses cannot be demolished and rebuilt, but can only be reinforced and repaired, which is difficult to ensure the safety of farmers who are unwilling to leave their hometown; There is also the problem of insufficient homestead in the reserved points, which makes it difficult to replace and contradicts the trend of spatial agglomeration.

(2) Sponge City Construction: fragmentation, invalidation, urban-rural differences

Jiaxing is one of the first sponge pilot cities in China in 2015, and the total annual runoff control rate in its main urban area is 75%. After five years of promotion, while achieving phased results, there are still some problems in engineering, ecology and life.

① Most local design institutes still don't understand the meaning and operation of sponge city. Although sponge projects should be declared for individual projects, they are not systematic as a whole and the sponge is fragmented. There are no detailed regulations on sponge facilities that jump out of the red line and are placed on the riverside green space.

② Since the limitation of groundwater exploitation in 2010, the groundwater level in Jiaxing has continued to rise, and there is no shortage of groundwater in general, so there is a certain waste of rainwater infiltration facilities.

③ Only sponge pedestrian roads are promoted, and little is known about sponge vehicle roads. Even ordinary C30 concrete is used to make sponge voids. When large vehicles cross the road, they often squeeze the road, causing the rupture of underground pipe network and further aggravating waterlogging.

④ Construction of the big sponge plan is limited to the main urban area of Jiaxing.

2.2. Research Methods and Data Sources

2.2.1. Risk Assessment for Human Settlement

For disaster management, risk assessment is an important non-engineering measure, which is the basis for the strategy. Waterlogging risk can usually be evaluated by submerged area, submerged depth and submerged duration [18-20]. Taking the town integrating administrative control and human settlement construction as the unit of measurement can more accurately express the characteristics of risk distribution. According to the waterlogging data caused by the five landfall and impact typhoons provided by Pinghu Emergency Management Bureau, the inundation depth is divided into 6 levels, and the inundation duration is divided into 5 levels (Table 1). The average inundation depth and average inundation duration risk level of each town are calculated, then calculate the proportion of the total maximum inundation area caused by five typhoons in the total land area of towns, describe the "typhoon-waterlogging" risk distribution of human settlements with Arcgis10.7, and then generate the spatial pattern of the overall risk with the same weight.

Table 1: Assignment of inundation depth and inundation duration.

Inundation depth (m)	Level	Inundation duration (h)	Level
<0.2	1	0~6	1
0.2~0.4	2	6~12	2
0.4~0.6	3	12~24	3
0.6~0.8	4	24~48	4
0.8~1	5	>48	5
>1	6		

2.2.2. Regression Analysis of Disaster Mechanism

Disaster risk is a composite function of natural disasters and the vulnerability of people exposed to natural disasters in time and space [21]. Regression analysis is usually needed to explain many factors behind the observed distribution characteristics. This study adopts the ordinary least square method, considering the universality of the man-land system and the periodicity of disaster management, and selects 11 explanatory variables from four dimensions: physical geography, social structure, economic development and built environment for data processing (Table 2), in order to obtain a more comprehensive understanding.

Table 2: Selection and description of explanatory variables.

Dimension	Explanatory variables	Variable description	Data source
Physical geography	Average cumulative precipitation in summer (June-September) over the years (0.1mm)	Total precipitation in summer. Using IDW	Monthly precipitation data of Jiaxing and its surrounding areas from 1981 to 2010. China Meteorological Data Service Center (http://data.cma.cn/)
	Summer (June-September) Rainstorm Day (0.1 day) over the years	Rainstorm Day: daily precipitation≥ 50.0mm. Using IDW	
	Kernel density of low-lying land	Low-lying land: a terrain that is lower than the surrounding area. Using FocalFlow	SRTM30 meter resolution DEM USGS (https://earthexplorer.usgs.gov/)
	Proportion of poorly drained soil	/	National Earth System Science Data Center - Soil Sub Center (http://soil.geodata.cn)
Social structure	Permanent resident population	Seventh national population census	Jiaxing Municipal Bureau of Statistics
	5-minute fire circle coverage	Using Network Analyst	POI data
	3-minute police circle coverage		
Economic development	GDP	GDP in 2020	Jiaxing Municipal Bureau of Statistics
Built environment	Growth rate of built environment in towns	Ratio of newly built environment in 2015-2020 to total built environment in 2015	GLC_FCS30_2015 and 2020 [22-23]
	Transfer area from paddy field to built environment	Using transition matrix	
	Ineffectiveness of polder	Waterlogging area caused by low efficiency of polder or no polder. Polder: common closed residential unit in riverine plain area	Pinghu Emergency Management Bureau

3. Risk Assessment Result and Disaster Mechanism Analysis

3.1. Spatial Distribution Characteristics of Disasters

The basic characteristics of the five landfall and impact typhoons 1812, 1822, 1909, 2004 and 2106 are shown in Table 3. Except for 1822, the tracks of the other four typhoons passed directly or wiped Jiaxing from the edge, and the combination of typhoon inverted trough and weak cold air was the main reason for the increase of long-distance rainstorm caused by 1822 in Jiaxing [24].

Table 3: Basic characteristics of five typhoons related to Jiaxing.

	Landing place	Landing level	Warning duration (day)	Process areal precipitation
Typhoon Jongdari (1812)	Jinshan, Shanghai	Tropical storm	2018.8.2-8.3(2)	180.3mm
Typhoon Mangkhut (1822)	Jiangmen, Guangdong	Severe typhoon	2018.9.17(1)	145.2mm
Typhoon Lekima (1909)	Taizhou, Zhejiang	Severe typhoon	2019.8.8-8.9(2)	200.1mm
Typhoon Hagupit (2004)	Wenzhou, Zhejiang	Typhoon	2020.8.3-8.5(3)	87.5mm
Typhoon In-Fa (2106)	Zhoushan; Jiaxing, Zhejiang	Severe tropical storm	2021.7.23-7.26(4)	160.5mm

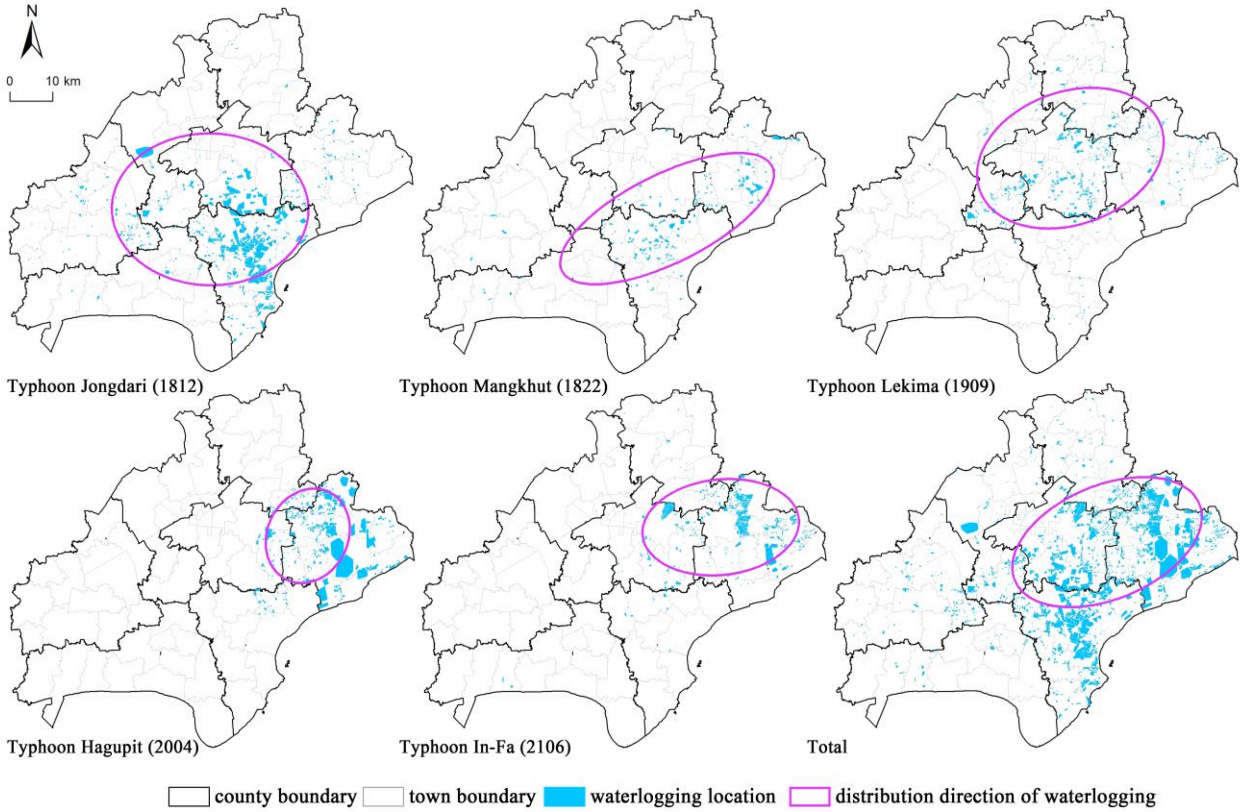


Figure 2: Spatial distribution characteristics of disasters under the coupling of typhoon-waterlogging.

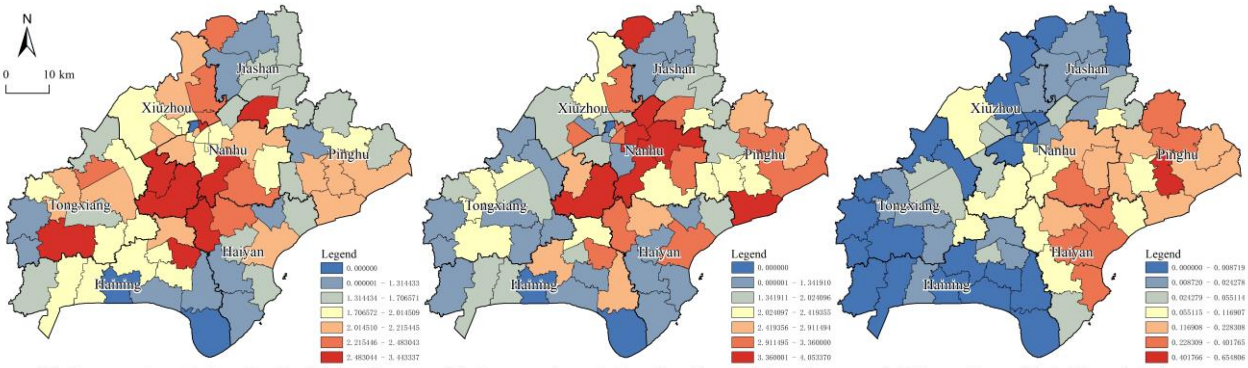
Using arcgis10.7 to process the original data, the spatial distribution characteristics of five typhoons and their total waterlogging are obtained. Blue represents the distribution position of waterlogging space, and purple standard deviation ellipse represents the overall distribution direction of 63% of waterlogging space (Figure.2). The data shows the following characteristics:

① Waterlogging caused by typhoon 1822 is relatively scattered and small in area. This is because the typhoon is too far away, causing only a one-day early warning, and the disaster effect is difficult to accumulate. In addition, the other typhoon tracks are closely related to the height of Jiaxing, so the waterlogging space is relatively concentrated, and the longer impact time leads to a relatively large area.

② The scope of waterlogging caused by the first three typhoons is wide, and the last two are small.

③ The spatial total map of waterlogging shows that Pinghu County, Haiyan County and Nanhu District, which are closer to Hangzhou Bay, are the worst-hit areas of typhoon-waterlogging in Jiaxing.

3.2. Risk Assessment Result



(a) Average inundation depth risk level (b) Average inundation duration risk level (c) Proportion of total inundated area

Figure 3: Subitem risk distribution of typhoon-waterlogging.

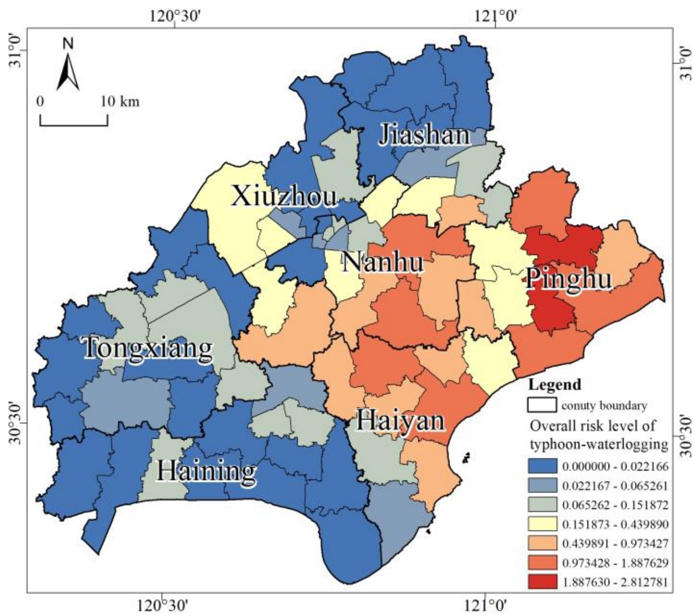


Figure 4: Distribution of town risk rank under the overall typhoon-waterlogging effect.

Mapping the real waterlogging space to the towns, the results are shown in Figure 3. The sub item risk maps of "typhoon-waterlogging" in Jiaxing towns show different results. The towns with high risk level of average inundation depth are most concentrated at the junction of Xiuzhou District, Nanhu District and Haiyan County, and are distributed in all districts and cities of Jiaxing plain, indicating that the risk of inundation depth is a universal problem. The towns with high risk level of average inundation duration are concentrated in the middle east of Jiaxing plain, and the towns within the municipal area are the most serious. The distribution difference of the total maximum inundation proportion is obvious. The towns with high proportion are all located in the eastern coastal area, and even as high as 65.5% in Lindai Town, Pinghu County.

Figure 4 shows the distribution of township risk levels under the overall "typhoon-waterlogging" after sub item weighting. The overall layout of high-risk areas is similar to that of the total maximum inundation area, which is concentrated in the eastern coastal areas. In addition, it covers a wider range of towns, including the southwest of Xiuzhou District and the south of Jiashan County.

3.3. Explanation of Regression Results of Disaster Mechanism

First of all, after regression analysis of typhoon-waterlogging risk in 73 towns in the city, the overall risk and inundation area risk are in an unsteady state, indicating that there is a lack of consistent relationship between explanatory variables and dependent variables in geographical space, that is, some explanatory variables may be very important in some towns, but not in others. In addition, the regression results of inundation area also show that the prediction of this model is one-sided. However, from a macro point of view, summer precipitation, low-lying land density and built environment growth rate can show the impact on typhoon-waterlogging, confirming the coupling effect of climate, landform and human settlements in disaster events.

In order to modify the model, the regression analysis was carried out again for 28 towns in the high-risk area. The results showed that the model was in a stable state, and the explanatory variables could better reveal the disaster mechanism in the high-risk area. The model performance of the overall risk and inundation area risk reached 71.21% and 92.70% respectively (Table 4). Further explain the analysis results:

① "Ineffectiveness of polder" is the most critical explanatory variable, showing a high positive correlation, indicating that the governance of human settlements represented by polder obviously lags behind the development of high-speed urbanization. Low-lying non-polder area, insufficient drainage capacity of polder area, flood overflow of outer river polder area, dike collapse, failure or damage of drainage facilities in polder area are all urgent problems to be solved.

② Proportion of poorly drained soil is negatively correlated with the risk of inundation depth, indicating that poorly drained soil cannot become a powerful factor for rainwater accumulation in towns in the study area, suggesting that the stagnancy of the impervious surface formed by urbanization, or the inefficiency of the artificial drainage system, is more dangerous. For example, the investigation shows that the cause of waterlogging in Jiaxing urban area with the highest urbanization rate is often caused by the adverse drainage of pipe network.

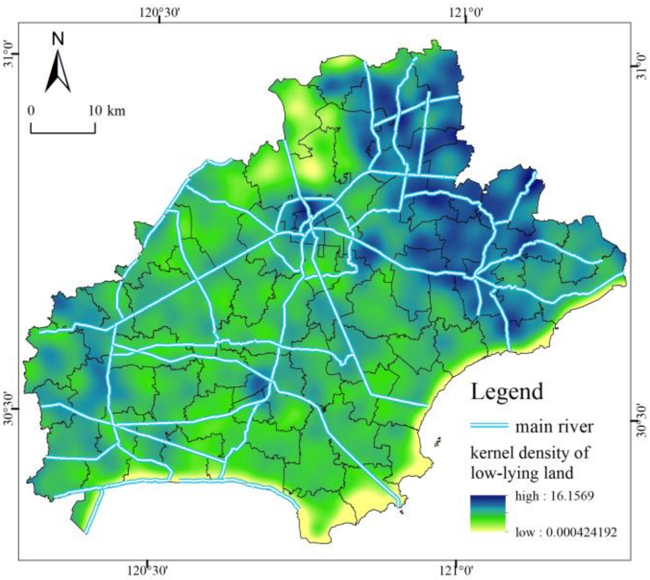
③ Inundation depth risk is highly positively correlated with the maximum kernel density of low-lying land. Low-lying land in Jiaxing plain are mainly distributed around the main water systems (Figure 5), indicating that the inundation depth risk of towns has a clustering effect in small and micro watersheds.

④ Risk of inundation area is positively correlated with the coverage rate of fire circle, which is different from the construction goal, indicating that the construction of rescue circle represented by fire circle is not synchronized with the road system. The road system that tends to be dense and higher than the surface causes more rainwater to converge into the living environment.

⑤ Risk of inundation depth is negatively correlated with GDP, and the risk of inundation area is negatively correlated with the transfer area from paddy fields to the built environment, that is, the towns with a large amount of paddy field transfer in recent five years have a smaller inundation area, indicating that the agricultural towns with low GDP are at higher risk at present. The survey results also show that paddy fields are the most widely inundated land type, so agricultural towns need adaptive regulation.

Table 4: Summary of regression analysis results.

Regression model	Model performance	Explanatory variables with statistical significance and robust probability	Coefficient
Regression of the whole urban area	85.95%	Max kernel density of low-lying land	0.068305
		Ineffectiveness of polder	0.057783
Regression of the whole urban inundation area	92.38%	Average cumulative precipitation in summer (June-September) over the years	0.000090
		Permanent resident population	0.000000
		5-minute fire circle coverage	0.066165
		3-minute police circle coverage	-0.075973
		Transfer area from paddy field to built environment	-0.008416
		Growth rate of built environment in towns	0.089708
		Ineffectiveness of polder	0.010831
Regression of the high-risk area	71.21%	Ineffectiveness of polder	0.047258
Regression of inundation depth in high-risk area	39.60%	Proportion of poorly drained soil	-1.303307
		GDP	-0.007343
		Max kernel density of low-lying land	0.315825
Regression of inundation area in high-risk area	92.70%	5-minute fire circle coverage	0.161287
		Transfer area from paddy field to built environment	-0.013923
		Ineffectiveness of polder	0.010987



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4. Construction Strategy of Human Settlements Based on Disaster Mechanism

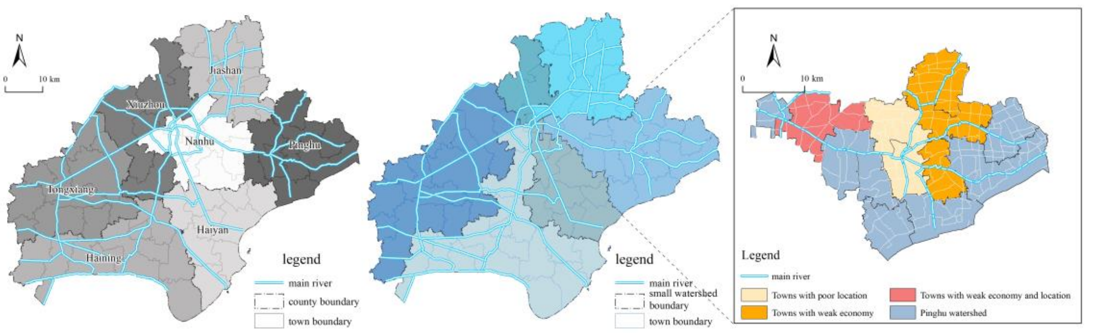
From the specific explanation of disaster mechanism, the risk of typhoon waterlogging in human settlements is determined by the natural geographical characteristics, the industrial nature of towns and the construction level of human settlement units. Therefore, combined with the characteristics of man-land relationship, from one aspect of planning and policy guidance and the other of architecture and facility support, this paper discusses the adaptive construction strategies of small and micro watersheds, town zoning and human settlement units.

4.1. Structural Optimization of Small and Micro Watersheds Based on Flood Control and Drainage of "Towns Group"

In recent years, the spatial pattern of typhoon-waterlogging risk shows that there are both significant differences and agglomeration effects between towns. The flood control and drainage planning with the urban center as the core cannot meet the requirements of the surrounding wider plain human settlements. Therefore, in the future planning, it is necessary to take the "towns group" as the overall object. Take the high-risk Pinghu towns group as an example. Since the Yongle period of the Ming Dynasty (1403-1425), the river drainage has changed from entering the sea southward to entering the sea northward through the Huangpu River, and the waterlogging has intensified [25]. Although the Nanhetou drainage pump station in the expanded Hangjiahu drainage project was put into operation in 2020, typhoons 2004 and 2106 still caused large-area waterlogging in many towns. Therefore, it is necessary to deepen the adjustment of the overall structure of the small and micro watershed and strengthen the synergy with the existing drainage system, so as to optimize the water conservancy function of towns group to enhance the ability to resist typhoon-waterlogging (Figure 6(a)).

4.2. Establishment of Compensation Mechanism Based on Town Trade-offs

The group flood control and drainage planning based on small and micro watersheds not only makes all towns share the benefits, but also produces contradictions [26]. Some towns have short flood peaks, or usually need to bear more upstream floods, or have more tidal reaches, so it is more difficult to achieve a consistent goal of disaster prevention and reduction. Therefore, it is necessary to establish a compensation mechanism between towns. For example, in towns with weak location or economic weakness, appropriately adjust the rescue time limit, give priority to it as a pilot of new sponge facilities or materials. Make it have a higher proportion of sluice construction, appropriately relax the reconstruction policy of old houses, and provide more replacement homesteads for the existing reservation points with larger scale and better infrastructure (Figure 6(c)).



(a) Weak correlation between administrative and main water systems

(b) Town clusters based on small and micro watersheds

(c) Differences in disaster prevention strategies based on the nature of towns

Figure 6: Adaptive planning linking micro watersheds and towns.

4.3. Multifunctional Construction of Polders Based on Resilient Agriculture

Jiaxing plain is an important agricultural production base. Strengthening the risk response ability of agricultural towns and preventing their decline is of great significance to food supply and security. In recent years, the renovation of traditional polders has become an important construction content in the Yangtze River Delta. The construction of sluice gates and pump stations has been advancing, but the agricultural towns are still fragile in the face of repeated waterlogging, and farmers suffer heavy losses. This means polder construction has become a complex problem of environment, economy and society, and there is an urgent need for the composite oriented maintenance methods and technical strategies:

① Operation and maintenance method: break the administrative boundary, re-examine the advantages and disadvantages of the traditional spatial pattern, revitalize the existing resources and grasp the key needs to update the polders. Emphasize the mobility of the rescue circle and improve the awareness of farmers' spontaneous management, so as to make up for the single infrastructure strengthening plan. Gradually transition from "point and line" to the "place and sequence" of human settlements unit, so as to improve the efficiency of financial expenditure and resource sharing.

② Technical strategy: on the premise of ensuring agricultural safety, agriculture and tourism can be integrated with the help of ecological methods. For example, flexible materials such as local soil and aquatic plants and porous blocks can be used in the dike consolidation design [27], and leisure agricultural land can be added to the land use planning to provide a way for the people in polders to increase their income (Figure 7).

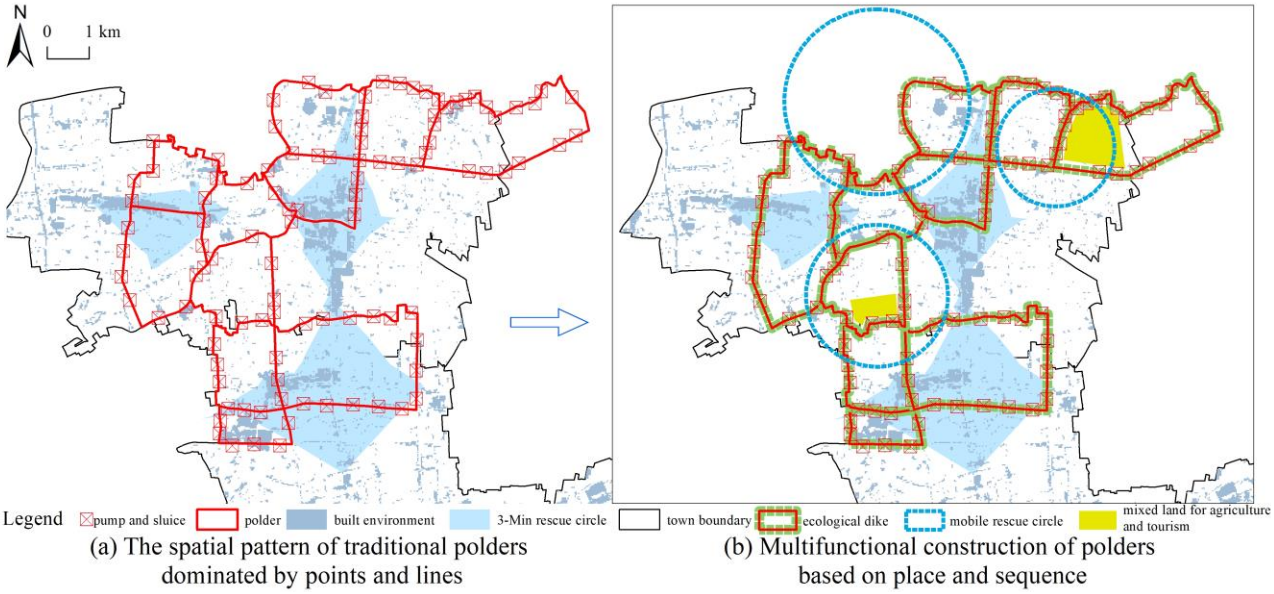


Figure 7: Multifunctional construction method of polders.

4.4. Division of Waterlogging-control Unit

With the deepening of spatial agglomeration, a large number of new residential areas have been separated from the protection of traditional polders, or are located in areas lacking polders. It is urgent to establish a new concept of "water conservancy - human settlement" unit. In addition to the existing polder areas, reservoirs and lakes, the prevention and control levels of other catchments can be divided according to the close relationship between man and land, so as to turn these catchments into flood preventable and risk controllable human settlements by setting flexible intervention methods. For example, in the primary waterlogging-control unit with high urbanization rate, it is necessary to add pump stations and restore the internal small and micro storage water surface to compensate for the regulation and storage effect of the water system [28]. In the secondary and tertiary waterlogging-control units with high proportion of farmland, a more robust single way can be adopted (Figure 8).

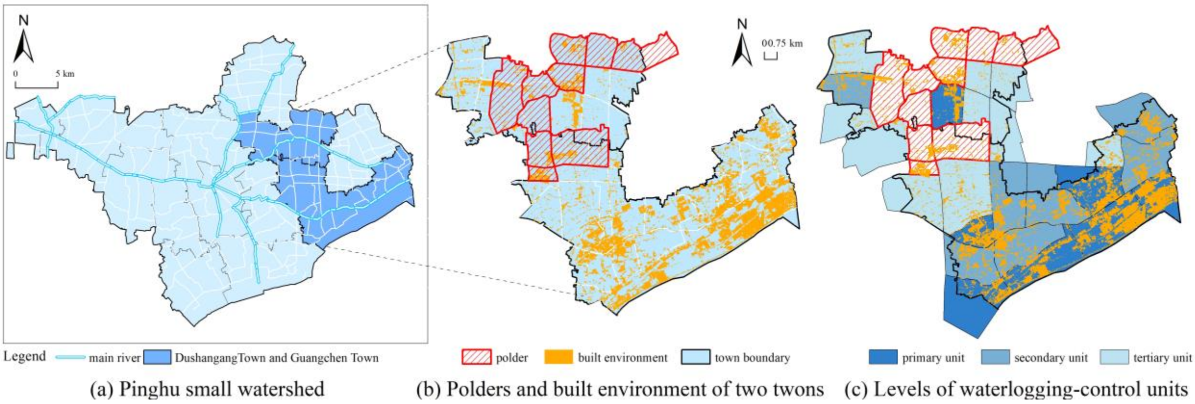


Figure 8: Division method of waterlogging-control unit.

5. Conclusion

According to the real waterlogging spatial data caused by typhoons that affected and landed in Jiaxing, Zhejiang, GIS was used to realize the visualization of the risk level of typhoon-waterlogging in human settlements. Behind the risk, through regression analysis, it is clear that " ineffectiveness of polders" is the most critical factor. The risk clustering effect of small and micro watersheds, the high stagnancy of urban impervious surface and drainage system, the significant vulnerability of agricultural towns, and the poor construction of rescue circles are closely related to the risk. It is revealed that coordination and adaptation to natural geography, rational allocation of township resources, and resilience governance of human settlement units are important to reduce the systemic risk in coastal plain area. On this basis, the optimization of the structure of small and micro watersheds, the establishment of disaster prevention and mitigation compensation mechanism according to the nature of towns, the innovation of the maintenance and technical methods of traditional polders, and the "waterlogging-control unit" are the cold thinking under the high-speed urbanization wave. It is an exploratory work to carry out the adaptive construction of human settlements in coastal plain area, which can make the construction strategy more explanatory and valuable.

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