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Study on Suburban Land Use Optimization from the Perspective of Flood Mitigation—A Case Study of Pujiang Country Park in Shanghai

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Abstract: The integration of nature-based solutions into land use optimization has become a central focus of current research, primarily due to its effectiveness in mitigating flooding impacts and promoting sustainable development in both urban and rural areas. Taking Shanghai's Pujiang Country Park as a case study, this paper conducts a simulation analysis to assess the flood mitigation effectiveness of three distinct land use patterns (Natural scenario, Scenario N; Complete urbanization scenario, Scenario U; Country Park Planning scenario, Scenario P) under five stormwater scenarios with return periods of 2, 5, 10, 20, and 50 years. The findings reveal that Scenario P exhibits superior flood mitigation performance, particularly under stormwater scenarios with a return period of less than 50 years. Building upon these results, the paper proposes recommendations for optimizing land use to mitigate the impact of flooding. This study is crucial for understanding the mechanisms involved in urban stormwater logging mitigation through land use methods and holds significance for decision-making in land use and planning at the micro level.

Keywords: flood regulation service; land use optimization; urban-rural fringe area; Pujiang Country Park

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1. Introduction

Under the background of climate change and rapid urbanization, urban population and scales continue to expand, leading to a large number of wetlands and farmland being replaced by impervious ground. This shift exacerbates pressing issues such as flood disasters, water shortage, water quality deterioration, and ecosystem degradation. In particular, flood disasters have become increasingly costly worldwide [1]. In China, frequent floods have also caused serious loss of life and property [2]. Therefore, reducing urban-rural flood disaster risks, enhancing urban resilience, and improving adaptative capacity have currently become pivotal topics. In this context, research on Nature-based Solutions (NbS) for mitigating flood risk through land use adjustments has attracted academic attention [3–8]. Currently, a large number of studies have delved into the assessment of flood risk under multiple land use scenarios and the examination of the influence of land use changes on flooding processes [3–6]. For example, Peng et al. (2018) explored the relationship between the land use change and the storm flood hazard risk in the Maozhou River Basin of Shenzhen and concluded that, at the same level as the storm hazard, the increased construction land led to the increase of the storm flood hazard risk [9]. Jiang et al. (2022) found that upstream and downstream land use changes have different effects on the flooding process in the Piedmont Plain area based on multi-scenario numerical simulation [10]. Building on such research, scholars have advocated for adjusting the land use structures and layouts to mitigate flood risks, often through incorporating ecological space bottom-line control and local natural geographic patterns [4,7,11–13]. However, existing studies predominantly focus on large and medium scales such as watersheds, neglecting the localized spatial scale and the varied responses of land use changes to flood risks. As a result, implementing precise spatial control policies in land use planning remains challenging [14].

In recent years, China has also explored the practical implementation of sponge cities. In Shanghai, country parks emerged as important ecological spaces for urban-rural development as a result of land remediation and village development strategies [15,16]. These parks play an important role in mitigating flood risks and improving resilience in both urban and rural areas [17,18]. However, despite their designation as pivotal nodes within the Basic Ecological Net-work Plan for Shanghai's rural areas, country parks often face the threat of conversion into construction land due to their integration of ecological, production, and living functions. Accordingly, this study endeavors to examine the impact of land use changes on flood regulation at a localized spatial scale, aiming to offer insights into precise spatial control policies for reducing flood risk. The study area selected for this analysis is Pujiang Country Park, situated closest to the urban built-up area. Utilizing scenario-based methodologies, the study evaluates the effects of various land use scenarios on flood regulation across five 1-h stormwater scenarios, each with return periods of 2 years, 5 years, 10 years, 20 years, and 50 years. These land use scenarios include the natural state, full urbanization, and country park planning. The findings of this research have the potential to inform decision-making processes aimed at stabilizing urban ecological spaces, establishing reasonable urban growth boundaries, and enhancing flood risk resilience in suburban areas.

2. Materials and Methods

2.1. Study Area

Pujiang Country Park is an important ecological node at the intersection of the Shanghai Municipal Ecological Spacing Belt, Suburban Green Ring, Dazhi River Ecological Corridor, and Jinhui Port Ecological Corridor. As a spacing green belt, it connects the central city with the peripheral green spaces and acts as a buffer, curtailing the unchecked expansion of the main urban area. The park is located in the southeastern part of Minhang District and the western part of Pujiang Town (Figure 1), with the central area of Pujin Street to the north, the Luhui community and large residential communities to the south, Huangpu River to the west, and the old community of Tanjiagang to the east. The area is about 15.2 km^2, with a registered population of 25,400, a foreign population of 10,700, and an agricultural population of 0.56 million [19]. Characterized by low and flat terrain, with elevations ranging from 2.4 to 3.0 meters, the park features five land use/cover types: farmland, water bodies, construction land, green spaces, and bare land. The region is susceptible to waterlogging during periods of extreme precipitation and inadequate drainage, particularly in summer. With the urbanization of the suburbs, the risk of flooding in the area continues to escalate.

2.2. Data

Research data comprises multiple types, including land use data, soil data, elevation data, precipitation, and building data. First, land use data were derived from Shanghai Minhang District Planning and Natural Resources Bureau, including land use vector data in 2013 (Figure 2a) and Pujiang Country Park planning data (Figure 2b). The spatial resolution of land use data is set at 10 m by 10 m. Importantly, the utilization of land use data from 2013 is selected based on the fact that the project of Pujiang Country Park was approved but has not yet been constructed this year, which aligns with the design parameters for scenario N.

Second, soil data were obtained from the Nanjing Soil Institute of the Chinese Academy of Sciences. In conjunction with the research conducted by Hou et al. (1992) titled '*Shanghai Soil*' [20], the soil types in Pujiang Country Park were classified into four distinct categories (labeled as A, B, C, and D). This categorization was based on the criteria outlined by the Soil Conservation Service (SCS) model. In this classification, 'tidal sandy mud' falls under category A, 'dredged ash tidal soil' is assigned to category B, 'yellow mud' is designated as category C, and 'inland lakes' are classified under category D. These categories were determined based on the unique properties and minimum infiltration rates of each soil type, facilitating effective land management and environmental planning.

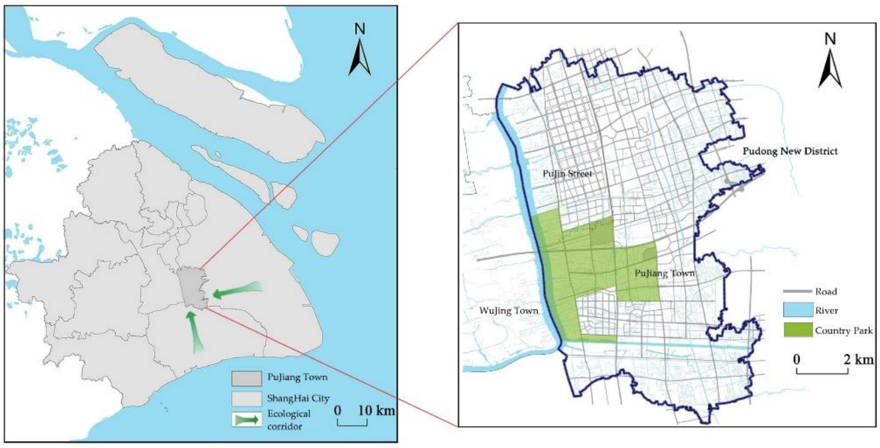

Figure 1. Location of Pujiang Country Park in Shanghai, China.

Figure 2. Land use and digital elevation model of Pujiang Country Park.

Third, elevation data utilized in this study, comprising the 1:10,000 topographic map (2010) and lidar data (2010), were obtained from the Shanghai Institute of Surveying and Mapping [21]. Initially, the original lidar data underwent pre-processing to eliminate non-topographic features, ensuring the accuracy and reliability of the dataset. Subsequently, the 1:10,000 topographic map was utilized to validate the calibration of the acquired data. To fulfill the specific requirements of this study, the nearest neighbor resampling method was applied to acquire elevation data with a spatial resolution of 1 m (Figure 2c).

Fourth, the precipitation for different return periods was calculated using the Shanghai storm intensity formula, designed by the Shanghai Engineering Design Institute. This formula was selected due to its ability to account for the uniformity of precipitation in both spatial and temporal distributions within the smaller study area.

Lastly, the building data utilized in this study was sourced from Google Satellite Maps and employed to develop three distinct land use scenarios. To maintain consistency in the building data, the study adheres to the principle of proximity. Specifically, the shape and distribution of buildings are derived from the surrounding communities adjacent to Pujiang Country Park. The spatial resolution of the building data is set at 1.2 m by 1.2 m, ensuring detailed representation and accuracy in the analysis.

2.3. Methodology

2.3.1. Terrain Correction

Terrain correction involves adjusting exposed surface elevations to accommodate the influence of surface buildings, thereby producing surface elevation data that closely reflects reality. The process entails several steps. First, elevation data with a spatial resolution of 10 m is resampled to 1 m resolution using the nearest neighbor method. Second, the attribute "building floors" within the building data table is transformed into "ground clearance height." This adjustment accurately represents the vertical clearance from the ground to the base of the building. Third, by utilizing the attribute "ground clearance height", the building data is rasterized to generate grid data depicting building ground clearance height. The spatial resolution of this grid data is set to 1 m. Last, using the Raster Calculator, the grid data depicting building height above ground is superimposed onto the Digital Elevation Model (DEM) data of the study area [22]. This process effectively corrects elevation data by accounting for the above-ground level of buildings, resulting in a more accurate representation of terrain elevation. This corrected elevation data is employed for simulating flood risk.

2.3.2. Stormwater Scenarios and Land Use Scenarios Design

Due to the limited size of the study area, this study simplifies the analysis by disregarding the spatial and temporal variability of rainfall distribution. Instead, it assumes uniform rainfall distribution across the study area. Building upon this assumption and considering the condensed timeframe of urban stormwater events, which typically last 1–2 h, as well as the widespread adoption of 1-h precipitation calculations in meteorological and municipal engineering standards [4,22], the Shanghai stormwater intensity formula is employed in this study. This formula, proposed by the Shanghai Engineering Design Institute, is utilized to calculate 1-h precipitation values corresponding to return periods of 2, 5, 10, 20, and 50 years (Table 1):

$$q = \frac{1995.84\left(p^{0.3} - 0.42\right)}{(t + 10 + 7lgp)^{0.82+0.07lgp}} \tag{1}$$

Table 1. One-hour precipitation at different return periods.

Return Period (Year)	2	5	10	20	50
1-h precipitation (mm)	44.3	56.3	65.8	75.8	89.7

Here, q represents the stormwater intensity (mm/h), t denotes the precipitation calendar time (min), p stands for the stormwater return period (year), and lg indicates the logarithm with a base of 10.

Addressing the research requirements, the acquired building data were utilized, taking into account the building density standards for multi-story and high-rise residential buildings in typical towns outside the outer ring road of Shanghai, where the density is stipulated to be less than 30% [23]. Additionally, referencing the spatial arrangement of the neighborhoods around Pujiang Country Park, the initial building data underwent adjustments to generate data reflective of different land use scenarios. Three distinct land use scenarios were established based on these adjusted building data (Table 2).

Table 2. The design of land use scenarios.

Land Use Scenario	Scenario Explanation
Natural scenario (scenario N)	It refers to the natural state, where land use is not affected by excessive human interference and related planning. In this paper, we utilize the 2013 land use data, predating the construction of country parks, to represent the land use status in this scenario.

Table 2. *Cont.*

Land Use Scenario	Scenario Explanation
Complete urbanization scenario (scenario U)	It represents the condition of maximum urbanization of Pujiang Country Park. Constructed based on 2013 land use data, this scenario designates farmland as urban residential land, taking into consideration the current status of surrounding land use.
Country park planning scenario (scenario P)	It pertains to the land use state guided by scientific planning. In this paper, we adopt the land use settings outlined in the planning of Shanghai Pujiang Country Park as the representation of the land use status in this scenario.

2.3.3. Stormwater Flood Simulation

1. SCS Model

The SCS model is an empirical hydrological model developed by the U.S. Department of Agriculture's Soil Conservation Service in the 1950s. It is characterized by high accuracy, few parameters, and simplicity in computation, making it widely applicable across different regions and scales [24–27]. It can be used to calculate the spatial distribution of runoff in a study area [24,28]. Some studies have utilized this model to analyze flood risk at different scales in Shanghai [1,22,29,30]. The runoff formula of the SCS model is as follows:

$$Q = \begin{cases} \frac{(P-Ia)^2}{P+S-Ia} \; P \geq Ia \\ 0 \; P < Ia \end{cases} \tag{2}$$

where Q represents the runoff depth (mm), P is the total amount of precipitation for a single rainfall event (mm), Ia is the initial abstraction (mm), and S is the maximum potential soil−water capacity (mm).

$$Ia = 0.2S \tag{3}$$

$$S = \frac{25400}{CN} - 254 \tag{4}$$

where CN is a comprehensive parameter in the SCS model that reflects the characteristics of the study area before rainfall, which is associated with factors such as soil type, land use/cover type, Antecedent Moisture Condition (AMC) of the soil in the study area before the precipitation event, and slope. In the SCS model, AMC is classified into three types: dry (AMCI), normal (AMCII), and wet (AMCIII). Based on the study area's conditions and previous research, in this paper, the AMC was assumed at the AMCII level during the calculation process [1,31]. The CN values were determined by referring to the *CN* value parameter table of the SCS model (Table 3).

Table 3. *CN* value of SCS model in the Pujiang Country Park (AMCII).

Land Use/Cover	Soil Permeability			
	A	**B**	**C**	**D**
Construction land	77	85	90	92
Bare land	72	82	88	90
Farmland	67	76	83	86
Green land	34	60	74	80
Water	98	98	98	98

2. GIS-based flood simulation

The area outside the outer ring road in Shanghai is self-draining [22] and the drainage engineering plan of Pujiang Country Park has not been released to the public [32], so drainage is not considered in this study. Based on the SCS model, the total accumulated water in the study area can be determined with the following formula:

$$W = Q \times S \tag{5}$$

where W is the total waterlogging volume (m^3), Q is the runoff volume (mm), and S is the catchment area (m^2).

On this basis, utilizing the adjusted elevation data and the equal-volume method [1,4,22,31], the inundation depth and inundation extent of Pujiang Country Park were simulated in ArcGIS.

3. Results

3.1. Flood Regulation Functions Assessment

The flooded areas for the three land use scenarios were presented according to the model calculations for stormwater scenarios with return periods of 2, 5, 10, 20, and 50 years (Table 4). It can be observed that, with an increase in the return period of heavy rainfall, the inundation areas for all three land use scenarios consistently increase (Figure 3). However, under the same stormwater conditions, the flooded area for scenario P is the smallest. It is noteworthy that, for stormwater scenarios with return periods of 2 years, 5 years, 10 years, 20 years, and 50 years, the inundation area of scenario P is reduced by approximately 0.16 km^2, 0.17 km^2, 0.16 km^2, 0.16 km^2, and 0.10 km^2 compared to scenario N. It also decreases by approximately 0.42 km^2, 0.40 km^2, 0.40 km^2, 0.41 km^2, and 0.34 km^2 more than scenario U. This suggests that, although scenario P exhibits good flood regulation functions, its effectiveness diminishes compared to the other two scenarios as the stormwater return period increases to 50 years. Additionally, the analysis reveals that, across the five stormwater scenarios, the inundated areas for all three land use scenarios are mainly concentrated in the northwest and southwest parts of the study area. The inundation depth is less than 36 cm, with the majority of the inundation depths concentrated in the range of 0 to 12 cm.

Table 4. Inundation range of the three land use scenarios.

Rp / Land Use	2-Year		5-Year		10-Year		20-Year		50-Year	
	Inundation Area (km^2)	**Ratio (%)**	**Inundation Area (km^2)**	**Ratio (%)**	**Inundation Area (km^2)**	**Ratio (%)**	**Inundation Area (km^2)**	**Ratio (%)**	**Inundation Area (km^2)**	**Ratio (%)**
Scenario P	1.89	12.41	2.66	17.52	3.21	21.11	3.76	24.75	4.52	29.69
Scenario N	2.05	13.48	2.83	18.61	3.37	22.15	3.92	25.75	4.62	30.37
Scenario U	2.31	15.21	3.06	20.10	3.61	23.71	4.17	27.44	4.86	31.93

In the context of the identical stormwater scenario, scenario N exhibits minimal inundation extent and average inundation depth. The exception is a few rural houses located in the southwestern part of the study area, where the maximum inundation depth is relatively significant. Notably, the northwestern and northern portions of the study area, characterized by predominantly green land, experience marginal impacts from waterlogging. Consequently, scenario N demonstrates a discernible flood regulation capability, as illustrated in Figure 4a.

Scenario U exhibits a notable increase in both inundation extent and maximum inundation depth. The average inundation depth is sufficiently impactful to disrupt normal travel patterns, indicating a weakened flood regulation function compared to other scenarios. The presence of impervious surfaces significantly hampers the ground's capacity to absorb standing water, leading to a larger total volume of inundated water. Particularly affected are structures in the southwestern region, predominantly designated for construction purposes, and the northwestern area, primarily consisting of green land with supplementary construction areas. Consequently, these factors contribute to larger losses, as depicted in Figure 4b.

Scenario P demonstrates comparatively minimal inundation extent and average depth, with only a few rural houses and structures in the northwestern part of the study area experiencing inundation and incurring minor damage. The remainder of the area is relatively unaffected by standing water, as depicted in Figure 4c. Consequently, scenario P exhibits a more pronounced flood regulation function. This superiority becomes evident when compared to scenarios N and U under the same stormwater conditions. Notably, scenario P’s effectiveness stems from a higher proportion of green land and farmland, coupled with reduced construction land areas and a relatively rational spatial layout of land use. For instance, under a stormwater scenario with a 50-year return period, the total volume of waterlogging in scenario P is 521,475.9 m^3, significantly less than scenario N (542,646.6 m^3) and scenario U (601,544.6 m^3). Furthermore, the average inundation depth in scenario P is 3.4 cm, marking a 15% reduction compared to scenario U.

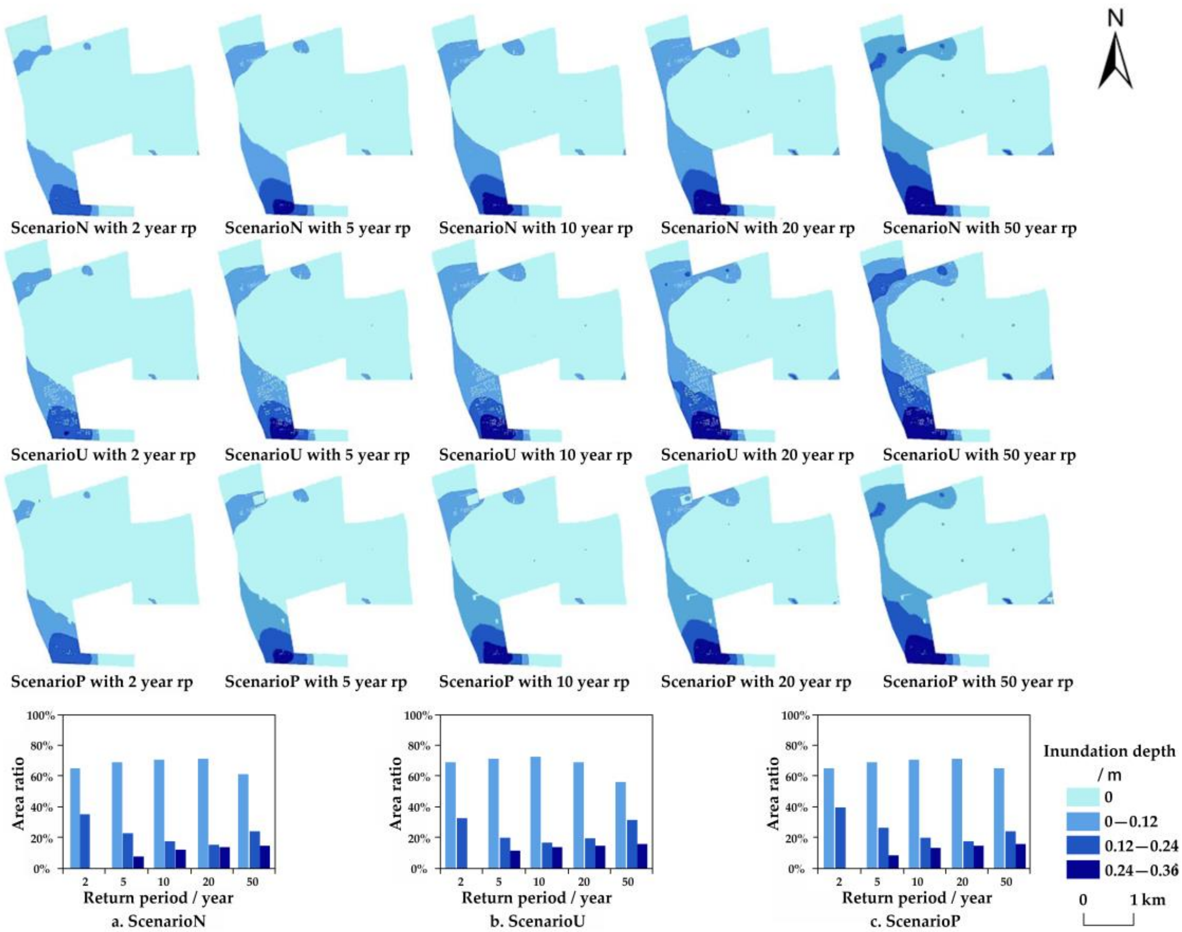

Figure 3. Water accumulation in Pujiang Country Park and inundation area ratio of each water depth interval.

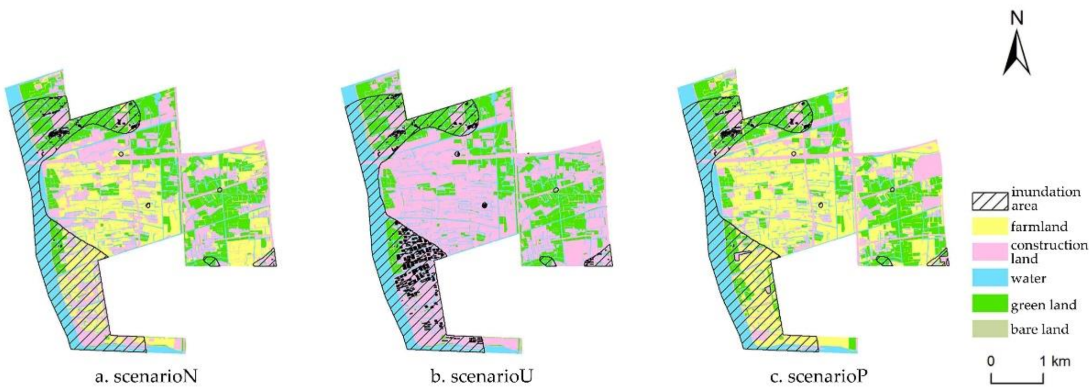

Figure 4. Land use layout and inundation area under the stormwater scenario with return period of 50 years.

3.2. Suggestions for Land Use Optimization from the Perspective of Flood Mitigation

3.2.1. Adjustment of Land Use Structure

Upon scrutinizing the land use structure in three distinct scenarios, as depicted in Figure 5, and integrating the assessment outcomes regarding flood regulation functions, the following recommendations for adjusting the land use structure are proposed:

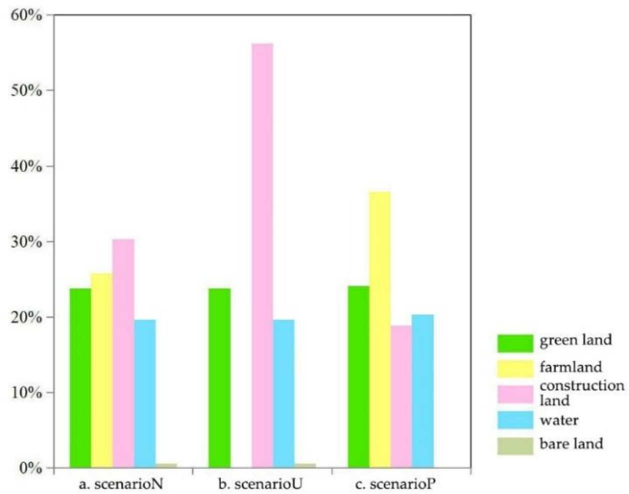

Figure 5. Land use structure in different land use scenarios.

To enhance resilience against stormwater and waterlogging disasters, it is recommended to optimize the stock of construction land and exercise moderate control over the expansion of newly added construction land. The research findings consistently indicate that, under identical stormwater scenarios, indicators such as inundation extent and depth follow the order: scenario U > scenario N > scenario P. A critical factor influencing these outcomes is the proportion of construction land, where the distribution is also observed as scenario U > scenario N > scenario P. Given this correlation, it becomes evident that an increase in the area of construction land exacerbates the risk of stormwater and waterlogging disasters. To mitigate this risk, it is suggested that Pujiang Country Park leverage the Beautiful Countryside Construction Project as an opportunity to reduce the footprint of construction land. This can be achieved through policies such as village merging and demolition. Simultaneously, inefficient factories and warehouses should be subject to renovation and redesign, transforming them into essential public service facility land. These measures aim to foster a more resilient and sustainable land use structure in the face of potential environmental challenges.

To foster ecological and livable communities, it is advisable to prioritize the construction of homes with a strong ecological focus while judiciously increasing the area dedicated to farmland and green spaces. A comparative analysis between scenario P and scenario N reveals that, under scenario P, both the inundation extent and depth are smaller than those observed in scenario N. The key disparity between the two scenarios lies in the sum of farmland and green spaces, constituting 60.7% of the study area in scenario P, a notable increase from the 48.6% recorded in scenario N. This discrepancy underscores the significance of farmland and green spaces in mitigating stormwater and waterlogging risks. Consequently, a strategic recommendation involves gradually transforming reduced construction land, highly fragmented farmland, and bare land into contiguous farmland and green spaces. This approach aims to enhance the overall resilience of the area while concurrently promoting a more sustainable and harmonious living environment.

To alleviate the impact of low-frequency heavy rainfall events, it is recommended to implement a moderate increase in the area of concave green land. Additionally, undertaking timely dredging of river and lake systems and establishing interconnections between water bodies can serve as effective measures for water storage and flood prevention.

3.2.2. Optimization of Land Use Layout

Upon comparing the land use layouts depicted in Figure 6 across three distinct scenarios and synthesizing the evaluation results of flood regulation functions, the following recommendations for adjusting the land use layout are proposed:

Figure 6. Optimization scheme of land use layout.

To enhance the flood regulation function of the farmland ecosystem within Pujiang Country Park, it is recommended to adopt a concentrated and continuous layout of farmland in the central area which entails reducing the fragmentation of farmland. Given the relatively serious inundation situation in the northwest and southwest regions of Pujiang Country Park, further suggestions include optimizing the planting structure or reinforcing infrastructure in these vulnerable areas. These adjustments aim to promote a more cohesive and resilient agricultural landscape and improve the overall flood resilience of the park.

To minimize the impact of stormwater and waterlogging disasters, it is recommended to optimize the layout of construction land within Pujiang Country Park. Concentrated distribution of construction land in the northern and eastern regions is suggested, while in the central area, a thoughtful allocation of construction land based on the requirements of public service facilities can enhance the rural living environment. In areas where inundation is relatively severe, particularly in the northwest and southwest of Pujiang Country Park, precautionary measures should be implemented. During the architectural design process for villages in these areas, considerations such as raising the height of buildings off the ground through the use of thresholds or steps should be employed for renovation. These measures collectively contribute to minimizing the vulnerability of structures to flooding events.

To enhance water management and flood resilience, we propose building an "ecological, open, and parallel" river network system within Pujiang Country Park, with a focus on improving the canal system water conservancy project in the central region. In the northwest and southwest areas, enhancing water system connectivity by constructing drainage networks and pumping stations and adopting strategies such as returning farmland to lakes or creating artificial lakes in low-lying zones are recommended. These measures aim to boost flood storage and prevention capabilities effectively. Simultaneously, constructing green belts on both sides of the river corridor to serve as natural ecological buffers for barges is recommended. The creation of green belts along main roads, branch roads, and rivers, and the utilization of line-of-sight analysis and infrastructure construction, coupled with the development of activity venues to enhance the precision of micro-terrain design, is recommended [33].

4. Conclusions and Discussion

4.1. Conclusions

In this study, Pujiang Country Park in Shanghai is used as a case study and the scenario analysis method is employed to assess the flood regulation function of three land use patterns under five stormwater scenarios. The findings are summarized as follows:

Scenario P consistently outperforms scenarios N and U in flood regulation function under equivalent stormwater scenarios. Across return periods of 2, 5, 10, 20, and 50 years, scenario P exhibits the smallest inundation area. While the reduction in the inundation area of scenario P becomes less pronounced with an increase in the return period to 50 years, its average inundation depth is noteworthy, showing a 15% decrease compared to scenario U.

Through stormwater inundation simulation and a comparative analysis of the land use structure and layout of the three scenarios, it is observed that the inundation range in all three scenarios is predominantly concentrated in the northwest and southwest regions of the study area. Recommendations are made to enhance flood risk adaptation by optimizing land use structure and layout.

It is crucial to note that none of the three scenarios demonstrates a substantial degree of mitigation against flooding risk under the 50-year return period storm. Therefore, a combination of measures, with a focus on ecological mitigation, is deemed necessary to mitigate the impact of stormwater and waterlogging during extreme precipitation events.

4.2. Discussion

The analysis reveals that none of the examined scenarios exhibit substantial mitigation capabilities in flood risk reduction during the occurrence of a 50-year return period storm. Notably, even within scenario P, the observed reduction in inundation area remains modest. Consequently, although ecological spaces such as country parks may bolster adaptability to flood-related hazards [34–36], their efficacy in impact mitigation of infrequent yet intense rainfall events remains constrained [37,38]. These research findings corroborate previous studies within the field.

While Scenario P demonstrates superior performance in flood regulation functions compared to scenarios N and U across equivalent stormwater scenarios, its effectiveness could be further optimized through the integration of green infrastructure with grey infrastructure. This combined approach has the potential to mitigate the adverse impacts of infrequent yet intense rainfall events more effectively [39–42]. However, it is pertinent to note that this study primarily focused on self-draining in simulation analysis due to the lack of available drainage data, thereby omitting consideration of the grey infrastructure component of drainage facilities. In future analyses and research endeavors focused on evaluating the mitigation effects of ecological spaces on rainstorms and waterlogging at a broader spatial scale, municipal drainage pipe network data should be integrated. This incorporation is crucial for enhancing the precision and reliability of simulation outcomes, thereby facilitating a more comprehensive understanding of the role of ecological spaces in mitigating the impacts of rainstorms and waterlogging.

Suggestions for optimizing land use planning projects to reduce flood risk were derived from scenario simulation analysis. The forthcoming research will focus on developing a novel land use planning project that adopts a future-oriented perspective to evaluate the effectiveness of flood regulation functions. This endeavor aims to enhance land use management decisions by providing valuable insights into the design and implementation of strategies for mitigating flood risks.

Author Contributions: H.X. conceived the research's framework, developed research objectives, and revised the manuscript; J.G. conducted the data analysis and wrote and revised the manuscript; X.Y. and C.W. collected the data and wrote the manuscript; Y.L. and J.W. made suggestions for revising and improving the research; Q.Q. revised the manuscript and edited and refined the English language. All authors have read and agreed to the published version of the manuscript.

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