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Analysis of Effects of Sponge City Projects Applying the Geodesign Framework

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Abstract: This study aims is to verify the effects of sponge city projects focusing on the aspect of water pollutant control and urban flood control, applying the geodesign framework as an integrated planning method that can evaluate alternatives against the impacts of the designs. The study analyzed the effects of sponge city projects in Harbin, Quzhou, and Sanya, China. Three LULC scenarios are proposed based on the geodesign framework, and the spatial distribution and quantitative values are simulated by the InVEST NDR model and urban flood model study. By comparing different scenarios, the study proved the current sponge project could improve the water pollutant control capability by 11–18% and the stormwater control capability by 0.4–6.3%. If the city-wide green infrastructure network is introduced with sponge projects, the water pollutant control capability can increase by 9–15% and the stormwater control capability can increase by 0.8–2.9%. These results show that the current sponge projects can improve the city's sustainability and be helpful strategies to fight climate change and global warming.

Keywords: geodesign; sponge city; water treatment; urban flood; InVEST model

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1. Introduction

1.1. Background and Goals

As the global economy grows and the population increases, urbanization accompanies adverse environmental impacts such as global warming, climate change, and heavy rainfall. Since the increase in rainfall intensity and the frequency of heavy rain have caused serious urban stormwater problems, various urban water cycle management solutions have been suggested internationally. For instance, the concept of low impact development (LID), developed in the United States, refers to systems to protect natural hydrologic features and associated aquatic habitat using or the mimicking natural process of the water cycle [1]. The concept of green infrastructure (GI) has emerged as an alternative approach to restoring good water circulation in urban areas by maintaining and expanding green spaces that can filter and absorb stormwater [2]. Other urban water management systems, including water sensitive urban design (WSUD) in Australia and sustainable urban drainage systems (SUDS) in the United Kingdom are widely explored in the literature [3,4].

After the reform and opening-up in 1978, China has experienced rapid urbanization. The urbanization rate of China was 20.16% in 1981, and reached 56.10% in 2015 [5]. The unprecedented speed of urbanization has seriously disturbed urban areas' natural water cycle system, causing severe flooding and water pollution problems. In response to the increased water management risk, the Chinese government presented a new integrated urban water management strategy called "sponge city" in 2013. Unlike the traditional rapid drainage approach, the concept focuses on improving the water absorption capability of a city through green infrastructure based on a natural water circulation system acting like a sponge [6]. It aims to control peak urban runoff and provide temporary storage, recycling, and purification of stormwater [7–9].

As sponge city received significant attention in academia and the planning practice, researchers have tried to prove its benefits more scientifically. However, it is necessary to consider that sponge city projects are not fully completed yet and are still ongoing. Most evaluation and simulation methods used in recent studies are optimized for evaluating the natural phenomena based on the current conditions, not the effects of unbuilt plans. In order to evaluate the ongoing planning process of sponge city, a new framework that can evaluate the projected effects of the planning and design alternatives is required. Based on these concerns, the objective of this study is to verify the effects of sponge city projects focusing on the capability of water pollutant and urban flood control applying the geodesign framework, an integrated planning and research method that can evaluate alternatives using a blend of science and value-based information. The study also aims to provide insights for future urban planning, looking for solutions to build a more sustainable environment that effectively faces water-related risks.

1.2. Concept of Sponge City

In 2014, the State Council of PRC announced the sponge city construction guideline. The guideline includes three main issues: (1) protecting the original ecological environment of a city; (2) remediating contaminated waters and damaged ecological systems with preserving a particular portion of the natural environment; and (3) applying LID to water management. It also suggests six strategic approaches for stormwater management: infiltration, stagnation, storage, purification, utilization, and discharge of stormwater [7,10]. According to the guideline, sponge city construction consists of three stages, the short-term plan from 2015 to 2018, the medium-term plan from 2018 to 2020, and the long-term plan from 2020 to 2030. In 2015, the Ministry of Housing and Urban-Rural Development (MOHURD), the Ministry of Finance (MOF), and the Ministry of Water Resource (MWR) selected 16 cities as pilot cities for the sponge city project. The same year, MOHURD announced the assessment methodology and system to evaluate the sponge city construction, consisting of water ecology, water environment, water security, and water resources utilization [11–13].

The sponge city solution is based on improving the natural water cycle system. It is implemented in three scales: the macro-scale, meso-scale, and micro-scale [14–16]. Sponge city is implemented through the "sponge project" on a micro-scale. Sponge projects are pilot programs to treat and manage stormwater at strategic points of the target area. Examples of sponge projects include waterfront renovations, constructed wetland parks, neighborhood green spaces, and local water collection units [15,17]. On a meso-scale, the sponge city solution focuses on combining micro-scale projects with larger river basins and catchment areas. The meso-scale solutions work in the city or township scale connecting individual projects as integrated water retention and purification [17]. On a macro-scale, the sponge city solution establishes the regional green infrastructure network to manage water systems on the regional scale, typically considering larger watersheds. The macro-scale solutions aim to maximize the water management capability of the region, integrating micro and meso-scale sponge projects into a holistic system [17,18].

The concept of sponge city has received widespread support from both the government and the academics, regarded as a breakthrough of the sustainable urban planning model in China and suggests practical guidelines and policies to manage the urban water system more sustainably [19]. Compared to similar international water management solutions, such as LID, WSUD, and SUDS, sponge city covers a greater scope and provides a more comprehensive system to develop innovative solutions, addressing urban water problems and enhancing ecological conditions that can mitigate climate risks [16].

1.3. Literature Reviews

It was found that most of the precedent researches evaluating sponge city projects focused on the built projects. The existing literature about the evaluation of sponge city projects mainly focuses on the environmental, economic, and social benefits of the implemented policies or built projects. Li et al. developed a comprehensive evaluation system using a stormwater management model and hierarchical analysis (AHP) to quantify a sponge city's economic, social, and environmental benefits [20]. Mei et al. studied the evaluation framework for sponge city projects based on the stormwater management model and life cycle cost analysis (LCCA) with suggestions on the decision-making process in sponge city construction [21]. There are also studies focused on evaluating the land suitability for sponge city projects. In the study of Luo et al., a radial basis function (RBF) network was used to assess environmental risk and flood resilience combined with demographic and economic indicators related to the land suitability of sponge city cases [22]. Wang et al. evaluated the sustainability of sponge city projects and analyzed the optimized layout of sponge projects considering the three factors of natural geography, socio-economics, and urban construction [23].

The amount of academic literature about geodesign increased significantly after Landscape and Urban Planning published the special issue on geodesign in 2016. The early academic literature on geodesign mainly focused on theoretical analysis and conceptualizing; however, many types of planning projects have been recently published about geodesign application. Newman et al. developed a resilient master plan using the resilience scorecard to assess flood vulnerability applying a geodesign process [24]. Pettit et al. used the geodesign framework to create an integrated strategic plan, breaking down the barriers between several agencies [25]. Reynolds, Murphy, and Paplanus applied the geodesign framework to decide a watershed restoration project [26]. Gottwald et al. studied the alternative planning options with nature-based solutions (NBS) through the geodesign process [27]. The geodesign framework was used in the study to find the best options for infrastructure facilities such as high-voltage transmission lines and fuel stations [28,29]. Recent research has proven that the geodesign framework is helpful in ecological planning and broader planning issues such as the optimization planning of infrastructure or community planning.

2. Methodology

2.1. Study Area

Among three scales of sponge city solutions, the study focuses on the micro-scale approach of the individual project level, since most of the municipalities in China have started to apply the sponge city policy at the micro-scale level. However, the effect of the sponge city was assessed in the meso-scale. In order to analyze the water management system, the watershed coverage area should be decided first. As the watershed delineation does not match the municipal boundary, the study area for assessment is decided by the result of watershed analysis, not following a city or township boundary. The watershed scale is decided by hydrology analysis in the ArcGIS spatial analyst model. According to the Strahler stream order [30], the watershed stream is divided into seven levels. Level 1 is the smallest, and Level 7 is the largest. The study area scale for the effect assessment accords with the level 2 scale watershed.

Qunli National City Wetland Park (群力国家城市湿地公园) in Harbin, Mangrove Eco-Park (红树林生态公园) in Sanya, and Luming Park (衢州鹿鸣公园) in Quzhou are selected as study areas among sponge city projects built in the last decades (Table 1). The criteria for the selection were as follows. First, the area of projects should be similar for the comparison. Second, the projects should be located in the urbanized area to evaluate sponge city projects' effect on urban water management. Third, the projects should be located at different climate zones to verify if the climate affects the sponge city projects. Even though Harbin, Sanya, and Quzhou are not pilot cities, the sponge city projects in these cities are internationally recognized. Three projects are designed by Prof. Kongjian Yu of Turenscape, one of the pioneers of sponge city. Figure 1 shows the geographical location of the study areas.

Table 1. Basic information about the study area.

Project	Location	Coordinate	Area	Year	Climate Class
Qunli Park	Harbin, China	45.7296, 126.5563	34 ha	2011	Dwa
Luming Park	Quzhou, China	28.9695, 118.8367	32 ha	2016	Cfa
Mangrove Park	Sanya, China	18.2715, 109.5246	28 ha	2015	Aw

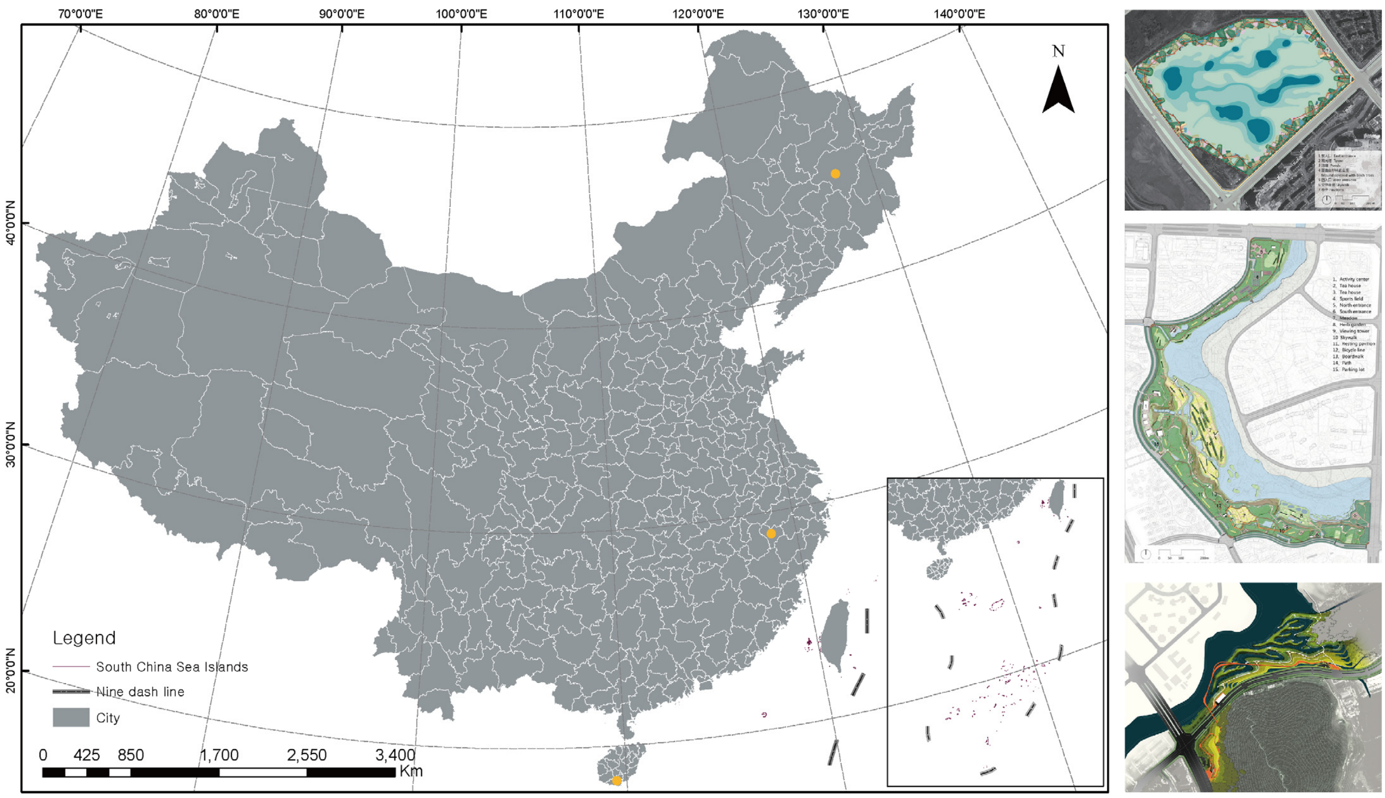

Figure 1. Study area. The order of the three study areas from top to bottom is Qunli Park, Luminous Park, and Mangrove Park. Source of pictures of the study area: https://www.turenscape.com (accessed on 24 January 2022).

Qunli Park is located in Harbin, Heilongjiang Province, in the northeast region of China. The climate of Harbin is characterized by a continental climate with cold, dry winters and hot summers. The annual average temperature is 4.6 °C, and precipitation is mainly concentrated in the summer months, with an average annual precipitation of 529.08 mm. Harbin has numerous wetlands with rich biodiversity, such as the Songhua River basin that flows through the city. Qunli Park is located at the Qunli New Town district on the Eastern outskirts of the city. The site that used to be a marsh threatened to disappear was constructed into a new wetland park.

Luming Park is located in Quzhou City, Zhejiang Province, with a subtropical monsoon climate. The average annual temperature is 17.4 °C, and the annual rainfall is 2300 mm. Quzhou is in the western part of the Jinqu Basin, surrounded by mountains to the south, west, and north, with a predominantly mountainous and hilly landscape. Luming Park covers an area of about 32 hectares, surrounded by high-density development, with the Xiliang River to the west and the city's major traffic routes to the east.

Mangrove Park is a wetland park restored by the sponge city project. It is located in Sanya, Hainan Province, the southernmost island of China. Hainan has a tropical marine monsoon climate with an average annual temperature of 25.4 °C and annual precipitation of 1347.5 mm. Sanya is one of the few tropical cities in China. Mangrove Park is a part of the sponge system of the city connecting Linchun River and the Lin Chunling Forest Park.

Most of the waterways in Sanya are straightened with a concrete structure, having lost their original ecological functions and leisure services. The hardened edge of the streams caused severe damage to the shore vegetation, especially to mangrove reserves, which have been reduced by 92% since 1995.

2.2. Method of Geodesign Framework

The study applies the geodesign framework to verify the effect of sponge city projects. Unlike the present research, the study analyzes the current condition of the project and compares the project with different planning scenarios. In the planning practice, although the post-evaluation of the finished project may help to fix the problems of former planning results, it may not be helpful in the actual decision-making process for choosing planning alternatives. Planners usually compare various schemes before implementation; however, the quantitative evaluation of alternatives rarely happens at the planning stage. The geodesign framework provides an effective instrument to fill the planning and evaluation stage gap.

The idea of geodesign was developed in the 1970s, but there was no consensus on methods or practices of geodesign until Steinitz established the geodesign framework in 2012 [31]. The geodesign framework starts with data organizing, transforming it into information, and uses knowledge to change the study area by evaluating its actual impact. The framework goes through three iterations, and each of them is composed of six stages that work as models (Figure 2). Three processes of iterations have different roles of "understand study area," "specify methods," and "perform a study." According to Steinitz, each iteration consists of six models, namely: a representation model, a process model, an evaluation model, a change model, an impact model, and a decision model. In this way, each process proceeds sequentially three times through six models.

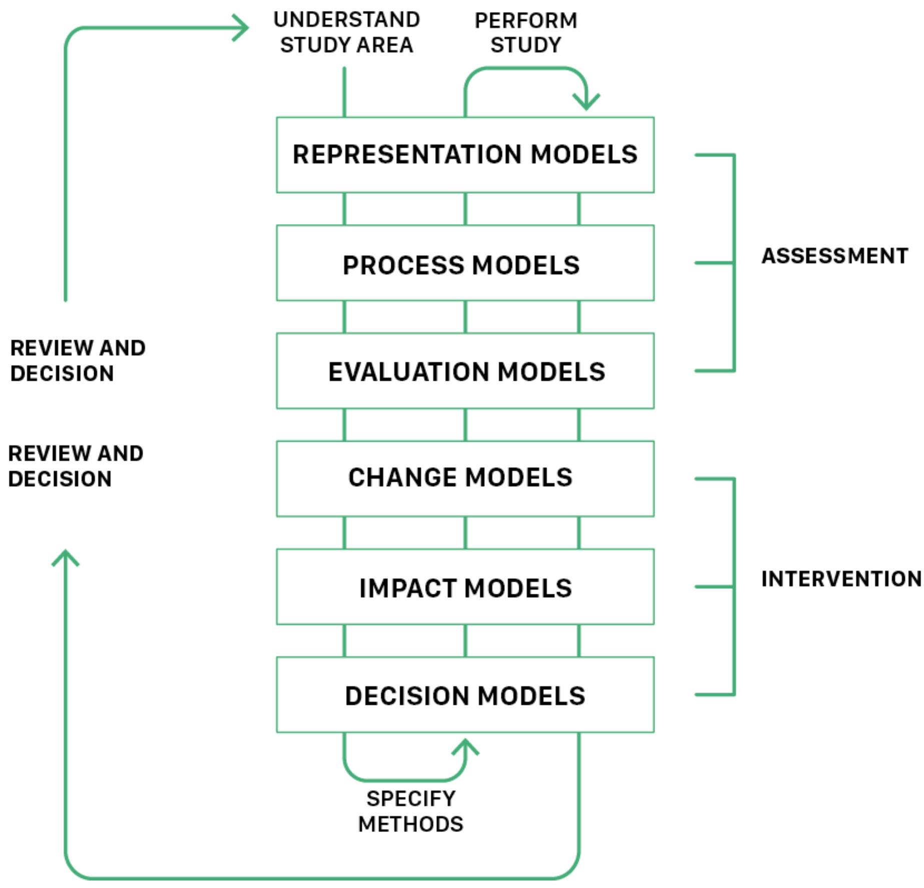

Figure 2. Geodesign framework.

Among these six models, planning or design alternatives to change the target site are proposed in the change model. The change model is regarded as the most crucial stage in the physical planning process because spatial schemes are proposed at this stage. Effects of the change model are predicted and evaluated based on the analysis methods decided in the process model using a data set from the represented model. The impact model is closely linked to the change model, verifying the predicted impacts of the design alternatives made through the change model [32].

2.3. Scenario Design

Applying the geodesign framework, the study does not go through three iterations but focuses more on the linear process of six models. The study focused on the change model and the impact model among the six models. In the impact model, in addition to the existing sponge city project, two other scenarios are proposed to compare the impact of the current condition. Therefore, three scenarios, including the existing project, are evaluated in the impact model.

1. **Scenario 1 (Existing project):** Scenario 1 represents the current sponge project. It is equivalent to the current condition of the study area following the original plan.
2. **Scenario 2 (Maximization of development):** Scenario 2 assumes the maximum development condition replacing the current sponge project, of which land use is designated to park or green space, and to other land use more suitable for urban development, for instance, residential or commercial areas.
3. **Scenario 3 (Maximization of sponge city):** Scenario 3 assumes maximizing sponge projects in the urban area replacing selected developments to wetlands or parks located at proper sites to enhance sponge city performance. Scenario 3 adds more sponge projects in addition to the existing project.

Tables 2–4 show the changes in land use and land cover (LULC) according to different scenarios. The original LULC data were achieved from the USGS database, and ArcGIS calculated the area and the area of each LULC type. LULC types of three sites are differentiated by the current land use classification [33]. In general, the wetland and water area are decreased, whereas the urban area and built-up area are increased in scenario 2 compared to scenario 1. On the contrary, the wetland and water area increase, whereas the urban area and built-up area decrease in scenario 3 compared to scenario 1. The spatial changes of LULC in different scenarios are presented in Figure 3. In Figure 3, the solid red outline represents the existing sponge project, and the red dashed outline represents the additional sponge project area decided by the change model of the geodesign framework.

2.4. InVEST Model Analysis

2.4.1. Nutrient Delivery Ratio Model

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model was jointly developed by Stanford University in the United States, Natural Conservancy, and the World Wildlife Fund (WWF) to support policy decisions based on ecosystem services. The spatio-temporal structure allowing the analysis of territorial units, and the spatially-explicit input and outputs based on land cover maps are seen as an advantage of the model [34]. In terms of the accuracy of the model, several studies have performed a sensitivity analysis of the model and validated it by comparing field observations with the results of the model. Cong et al. adjusted Borselli's K parameter to 1.9, and the relative errors of N, and P export were 0.02% and 0.79%, which was consistent with the observed data [35]. Yan et al. showed that the difference between nitrogen results of the model simulation and empirical observations was 2.98% [36]. The present study's results indicate that the accuracy of the model is reliable compared with field observation data, which can confirm that the model can simulate the study results well and effectively [37–39].

Table 2. The percentage of Qunli Park about LULC data in the three scenarios.

LULC Type	Scenario 1		Scenario 2		Scenario 3	
	Area (ha)	**Percent**	**Area (ha)**	**Percent**	**Area (ha)**	**Percent**
Wetland	218.41	8.90	201.69	8.22	244.54	9.97
Paved road	174.91	7.13	173.66	7.08	174.91	7.13
Agriculture	163.40	6.66	163.40	6.66	163.40	6.66
Build up	399.85	16.30	399.85	16.30	358.05	14.60
Urban	792.11	32.29	822.03	33.52	773.61	31.54
Greenland	499.28	20.36	499.27	20.36	521.32	21.25
Forest	3.60	0.15	0.00	0.00	3.60	0.15
Water	201.16	8.20	192.80	7.86	213.47	8.70
Total	2452.7	100.0	2452.7	100.0	2452.9	100.0

Table 3. The percentage of Luming Park about LULC data in the three scenarios.

LULC Type	Scenario 1		Scenario 2		Scenario 3	
	Area (ha)	**Percent**	**Area (ha)**	**Percent**	**Area (ha)**	**Percent**
Wetland	0	0	0	0	12.61	0.69
Paved road	79.89	4.41	79.89	4.41	79.90	4.40
Agriculture	754.01	41.63	754.01	41.63	717.10	39.48
Urban	228.16	12.60	264.30	14.59	217.65	11.98
Greenland	160.58	8.86	145.18	8.01	202.60	11.15
Forest	285.68	15.77	270.74	14.95	285.68	15.73
Water	93.09	5.14	91.21	5.04	102.49	5.64
Unpaved road	17.11	0.94	17.11	0.94	17.11	0.94
Village	179.20	9.89	179.20	9.89	167.47	9.22
Meadow	3.92	0.22	0	0	3.92	0.22
Vacancy	9.76	0.54	9.76	0.54	9.76	0.54
Total	1811.41	100	1811.41	100	1816.29	100

Table 4. The percentage of Mangrove Park about LULC data in the three scenarios.

LULC Type	Scenario 1		Scenario 2		Scenario 3	
	Area (ha)	**Percent**	**Area (ha)**	**Percent**	**Area (ha)**	**Percent**
Wetland	51.85	2.904	38.35	2.156	125.80	7.048
Paved road	49.56	2.776	49.56	2.787	49.56	2.777
Agriculture	223.10	12.495	223.10	12.544	193.08	10.817
Urban	486.51	27.246	500.97	28.166	486.51	27.256
Greenland	51.29	2.873	51.29	2.884	51.29	2.874
Forest	633.34	35.469	633.34	35.608	633.34	35.482
Water	39.10	2.190	38.15	2.145	50.06	2.805
Build up	234.75	13.147	234.75	12.806	179.23	10.041
Vacancy	16.09	0.901	16.09	0.904	16.09	0.901
Total	1785.60	100	1785.60	100	1785.60	100

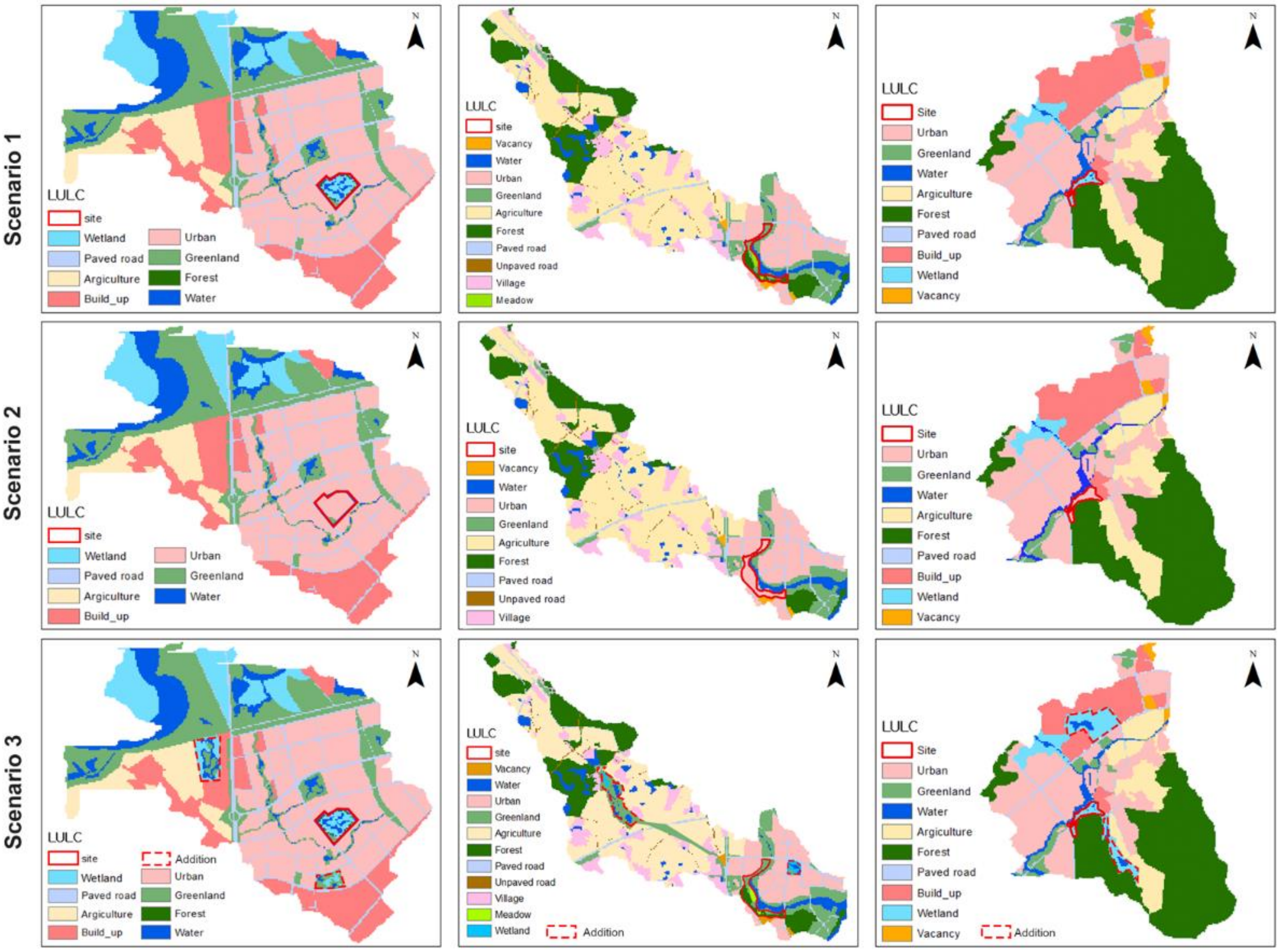

Figure 3. LULC of study area in three scenarios. From left to right in the picture shows the watershed area of Qunli Park, Luming Park and Mangrove Park.

The Nutrient Delivery Ratio (NDR) of the InVEST model is designed to map the nutrients' source and transport process within a watershed. The spatial information in the NDR model can be used to assess the retention of nutrients by natural vegetation, which is related to biological water treatment. When it rains or snows, water flows over the landscape, carrying pollutants from these surfaces into streams, rivers, lakes, and the ocean, resulting in water pollution [38,40,41]. Based on the NDR model, this study selected nitrogen and phosphorus as indicators for water quality analysis to verify the impact of sponge city projects on water purification. The study assumes that less export in the watershed of nitrogen and phosphorus (the non-point source pollutants) will improve water quality.

Input data for each scenario was collected in land cover maps and processed into GIS data. The following summarizes the specific requirements of the NDR model used in the analysis.

1. DEM data downloaded from Geospatial Data Cloud (http://www.gscloud.cn/ (accessed on 3 November 2020)). were transformed into the raster data with a spatial resolution of 30 × 30 m, using ArcGIS.
2. LULC data of 2019 was collected from the database of the USGS. Using the high-resolution remote sensing ground survey results, the input data required to analyze scenarios were made in the resolution of 30 × 30 m using ArcGIS.

3. The nutrient runoff proxy data were made from the precipitation data of 2019, collected from the Greenhouse database (http://data.sheshiyuanyi.com (accessed on 15 November 2020)), and obtained by processing the inverse distance weighted (IDW).
4. The watershed was extracted through the hydrological analyst tool provided in ArcGIS using DEM as the primary data for the sub-basin including the study area.
5. The maximum retention efficiency (EFF) data indicates the retention efficiency of vegetation for pollutants. Since there is no fixed value for the retention efficiency in the InVEST model, the study defined the values from reviewing the related literature [42]. The value of retention efficiency varied between 0 and 1, and the higher value yielded the greater retention efficiency of the pollutant.
6. The critical length (critlen) indicates the retention distance of LULC against contaminants at maximum capacity [43].

The subsurface proportion data was used to analyze the level of pollutants flowing underground. A value of 0 was set in the study, indicating that the pollutants only flow out through the surface. The NDR model calculation is done by the following Equations (1) and (2):

$$x_{exptot} = \sum_i x_{expi} \tag{1}$$

$$x_{expi} = load_{surf,i} \times NDR_{surf,i} + load_{subs,i} \times NDR_{subs,i} \tag{2}$$

In the formula, x_{exptot} is the total nutrient export from all pixels within that watershed. x_{expi} means the nutrient export from each pixel i, which is decided by nitrogen and phosphorus. $load_{surf,i}$ means that nutrients are transported by surface for a pixel, and $load_{subs,i}$ represents nutrients transported by groundwater. NDR of Equation (2) is based on the nutrient delivery ratio. $NDR_{surf,i}$ is the amount of the nutrient transported by the surface flow, and $NDR_{subs,i}$ is the nutrients from the subsurface flow. NDR is calculated by Equation (3):

$$NDR_i = NDR_{0,i}\left(1 + exp\left(\frac{IC_0 - IC_i}{k}\right)\right)^{-1} \tag{3}$$

$NDR_{0,i}$ is the proportion of nutrients that is not retained by downstream pixels. IC_0 and k are calibration parameters, and IC_i is a topographic index.

2.4.2. Urban Flood Risk Mitigation Model

The risk of urban flood is decided by various factors, including adjacency from coast or river, precipitation, and the sewer system. Green infrastructure can significantly control urban flooding by reducing runoff and ground flow. According to rainfall, the urban flood risk mitigation model calculates how much green infrastructure can withhold the runoff. The outflow is estimated according to the types of land cover and soil characteristics.

$$Q_{p,i} = \begin{cases} \frac{(P-\lambda S_{maxi})^2}{P+(1-\lambda)S_{msx,i}} & if \quad P > \lambda \cdot S_{max,i} \\ 0 & otherwise \end{cases} \tag{4}$$

P is the design storm depth in mm. $Smax, i$ is the potential retention in mm, $\lambda \cdot Smax$ is the rainfall depth needed to initiate runoff, also called the initial abstraction ($\lambda = 0.2$ for simplification). LULC and the watershed area used in the NDR model can be used in the urban flood risk mitigation model. Additional parameters required in the model are summarized below.

1. The soil hydrologic group in a raster data is downloaded from the ORNL (https://daac.ornl.gov/SOILS/guides/Global_Hydrologic_Soil_Group.html (accessed on 7 December 2020)).
2. The curve number (CN) data are recommended in the literature review to analyze values specific to the study area.

3. Results

3.1. Pollutant Export Using the NDR Model

Figures 4 and 5 are the InVEST model results of non-point source pollutant loadings represented in the form of spatial maps at the sub-watershed scale. The three scenarios show how the nitrogen and phosphorus export loadings change spatially. The darker colors in the figure represent higher pollutant loads, meaning higher levels of pollutants flowing into the watershed. As seen in the analysis maps, there is variation in the nitrogen and phosphorus export loading according to the different scenarios.

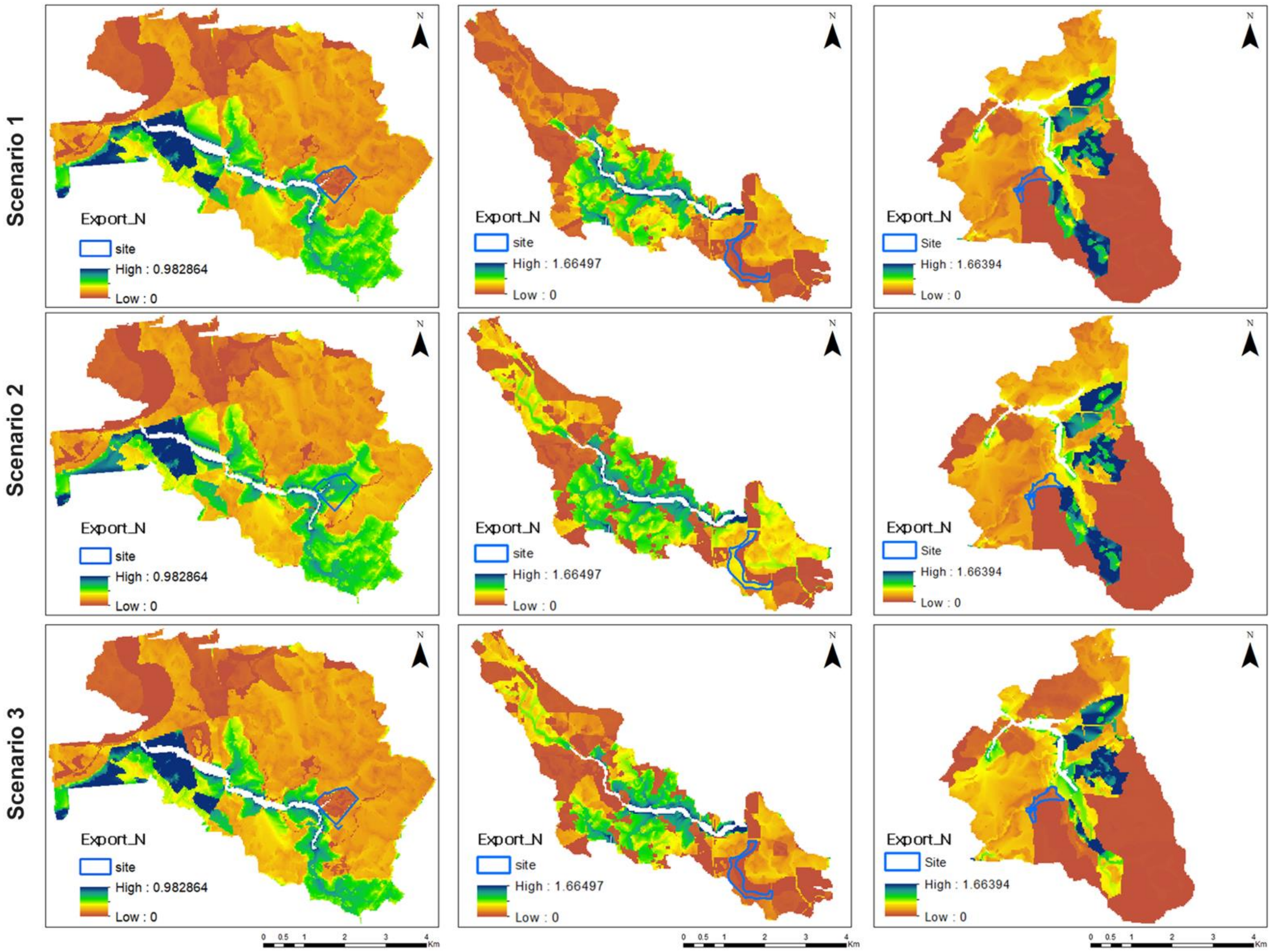

Figure 4. Spatial distribution of the nitrogen load of each study area.

According to different scenarios, Table 5 shows the increase and decrease of the nutrient export from the watershed. The table shows that the annual nitrogen export from the Harbin watershed in scenario 1 is 3198.09 kg, with 90.11 kg export for phosphorus. If the Qunli Park is fully developed in scenario 2, the annual nitrogen and phosphorus export are expected to increase to 3566.13 kg and 95.99 kg, an 11% and 6% increase, respectively, compared to scenario 1. If additional sponge projects are built in the urban area, establishing a more extensive sponge city network connected to the Qunli Park according to scenario 3, the annual nitrogen export and phosphorous export are expected to be reduced to 2901.05 kg/year and 83.3 kg/year in scenario 3. These results are 18% and 15% less than the exports of scenario 2, and 9% and 7% less than scenario 1. It is shown that the nitrogen export of the Quzhou watershed in scenario 1 is 1641.74 kg/year, while scenario 2 is 1725.24 kg/year, a total increase of 4%. The export of scenario 3 is 1382.89 kg/year, 15%

less than scenario 1. The annual phosphorus export of the Quzhou watershed in scenario 1 is 46.91 kg/year and 52.82 kg/year in scenario 2, a 12% increase. The export of scenario 3 is 44.33 kg/year, which is 5% export less than scenario 1. The nitrogen export of the Sanya watershed is 4326.74 kg/year in scenario 1 and 4420.96 kg/year in scenario 2; a 2.2% increase is observed in scenario 2 compared to scenario 1. The export of scenario 3 is 3710.14 kg/year, 14% less than for scenario 1. The phosphorus export of the watershed is 343.74 kg/year in scenario 1 and 348.35 kg/year in scenario 2, a 1% increase from scenario 1. The export of scenario 3 is 240.15 kg/year, 45% less than scenario 2. Regarding both nitrogen and phosphorus, scenario 2 yields the highest export, and scenario 3 yields the least, which means that scenario 3 has the most positive impact on water quality.

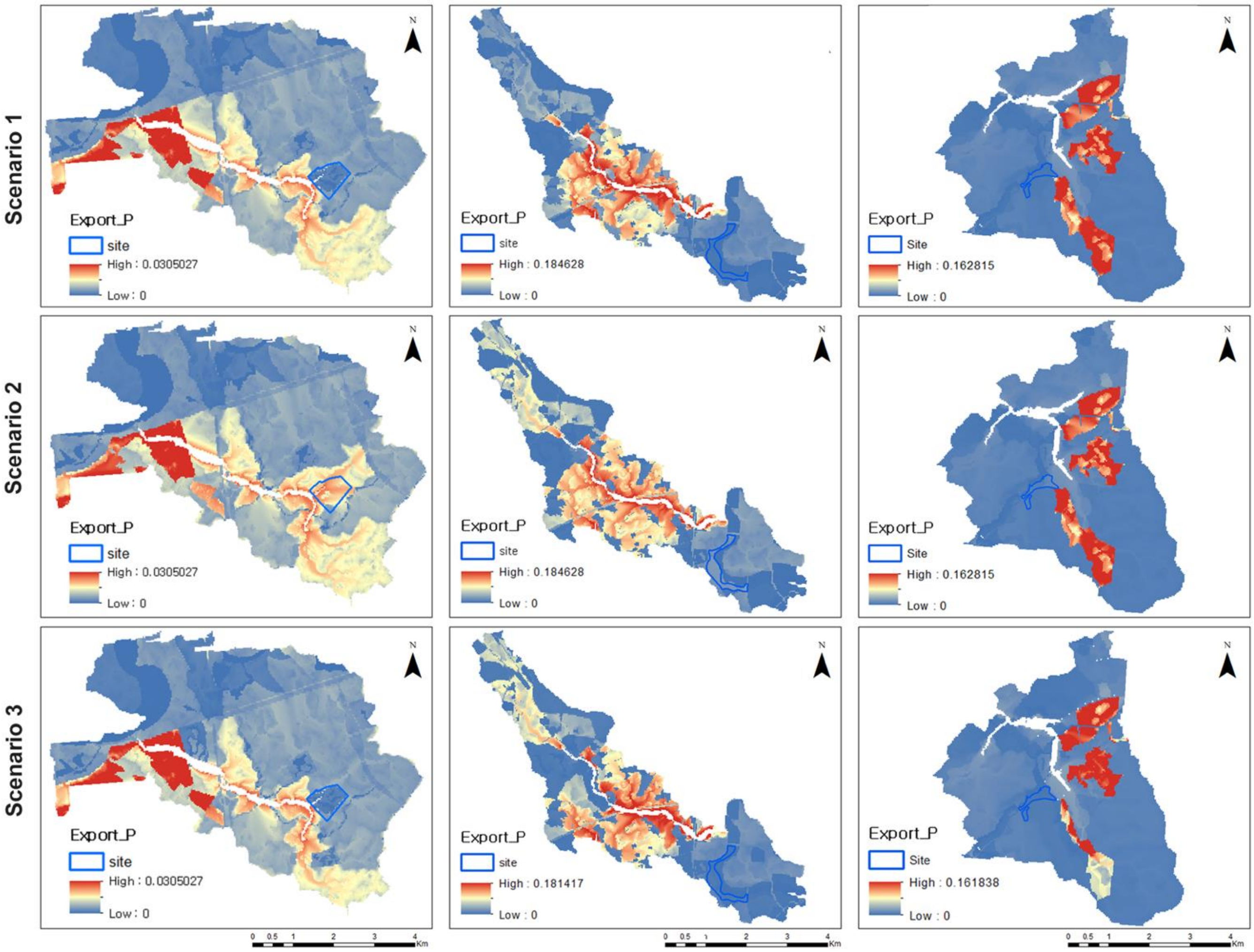

Figure 5. Spatial distribution of the phosphorus load of each study area.

Table 5. Runoff NDR model of nutrient (N and P) export (Unit: kg/year).

Study Area	Scenario 1		Scenario 2		Scenario 3	
	N	P	N	P	N	P
Qunli Park	3198.09	90.11	3566.13	95.99	2901.05	83.30
Luming park	1641.74	46.91	1725.24	52.82	1382.89	44.33
Mangrove Park	4326.74	343.74	4420.96	348.35	3710.14	240.15

3.2. Urban Flood Export

The flood mitigation effect of the urban parks and green spaces is quantified in terms of expected runoff retention. According to three scenarios, Figure 6 shows the spatial distribution of urban stormwater runoff retained by each pixel within the watersheds. Darker colors represent higher runoff retention values, which better mitigate urban runoff. As shown in the figure, there is a significant difference in the amount of runoff in the three scenarios. This result is inextricably related to LULC and HCG. The road infrastructure and water bodies have the lightest color. If the dry season is assumed, the water bodies in wetland parks can be turned into the darkest color, increasing the overall run-off retention capacity.

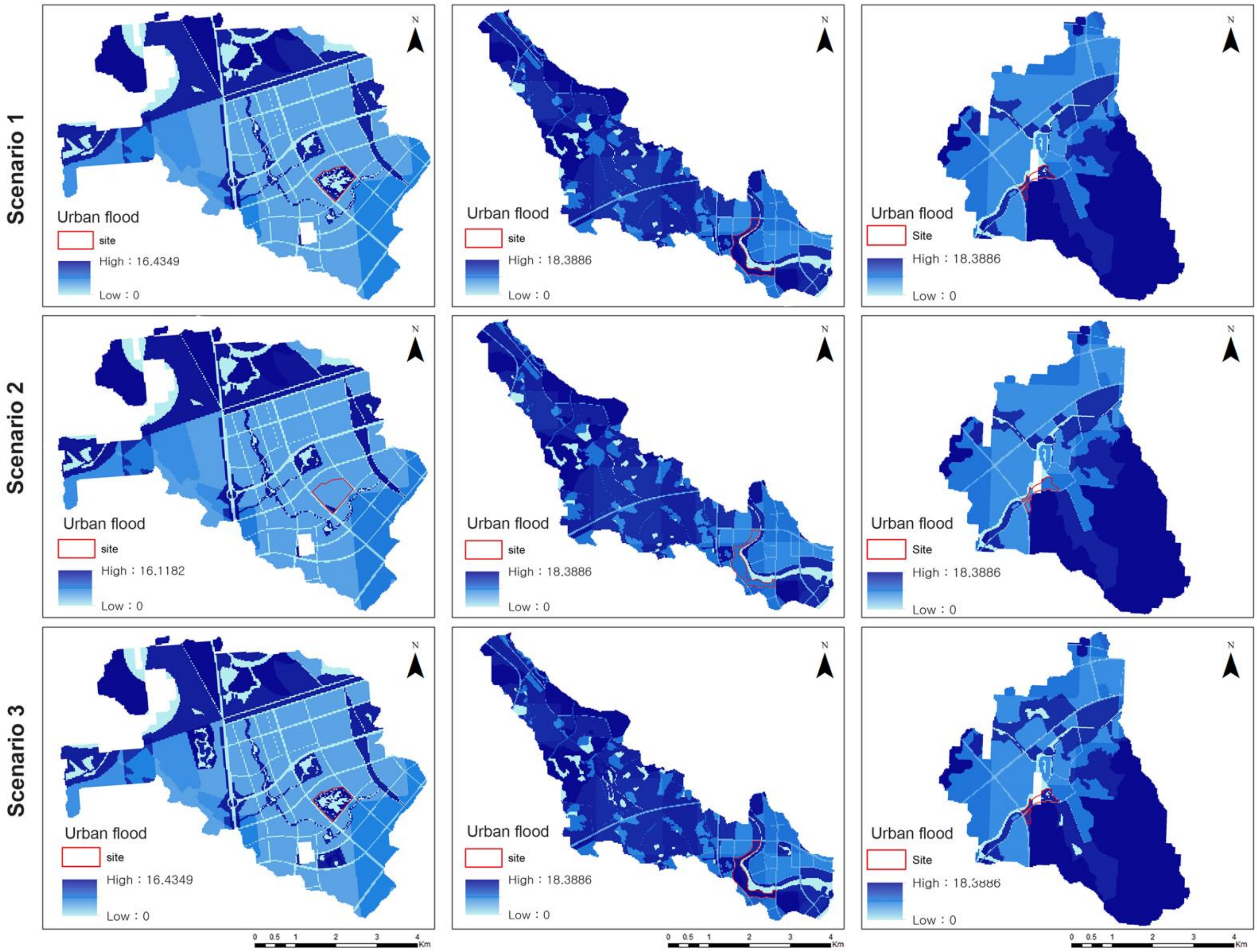

Figure 6. Spatial distribution of the urban flood retention.

Table 6 shows the total runoff volume generated in the study area. In the case of Qunli park in Harbin, the total runoff volume of scenario 1 is 173,431.54 m^3, and that of scenario 2 is 174,188.18 m^3. The runoff is increased by 0.4% in scenario 2 compared to scenario 1. The runoff of scenario 3 is 170,444.17 m^3, which is decreased by 1.7% compared to scenario 1. In the case of Luming Park in Quzhou, the runoff of scenario 1 is 1,496,780.37 m^3, and that of scenario 2 is 1,590,450.76 m^3. The runoff is increased by 6.3% in scenario 2. The runoff of scenario 3 is 1,484,466.62m^3, which decreased 0.8% compared to scenario 1. In the case of Mangrove Park in Sanya, scenario 1 is 76,588.91 m^3, and scenario 2 is 77,448.94 m^3. The runoff is increased by 1.1% in scenario 2. The runoff of scenario 3 is 74,339.53 m^3, which is decreased by 2.93% compared to scenario 1.

Table 6. Runoff model of urban flood export (Unit: m^3).

Watershed of Study Area	Scenario 1	Scenario 2	Scenario 3
Qunli Park	173,431.54	174,188.18	170,444.17
Luming park	1,496,780.37	1,590,450.76	1,484,466.62
Mangrove Park	76,588.91	77,448.94	74,339.53

4. Discussion

4.1. Pollutant Load Conrorl

The results confirmed that the InVEST NDR model could accurately simulate the loading and output of nitrogen in the watershed, which is consistent with previous studies [38,44]. Non-point nitrogen and phosphorus pollutants are mainly derived from agricultural fields and domestic wastewater from urban or rural areas. The urban development and the expansion of paved areas have led to the reduction of natural vegetation and the deterioration of soils, which consequently increase outputs of nitrogen and phosphorus in the watershed.

In this study, the simulation results of the pollutant load under three different scenarios showed that changes in LULC affected the nitrogen and phosphorus output. The results also implied that sponge city projects could reduce water pollution from the surface flow. Changes in land use and adding more sponge projects could significantly affect water quality. Theoretically, wetlands can remove pollutants by slowing the timing of water flow and allowing pollutants to be absorbed by vegetation. Removal of pollutants is further promoted when wetlands and buffer zones are considered an integrated system [45,46]. Therefore, preserving existing wetlands and forests, and introducing more constructed wetland parks similar to sponge projects to build an integrated green infrastructure network can be an effective planning method to improve the water quality of developed urban areas.

Regarding the sponge city planning, the study results imply that the larger-scale approach is more effective in improving water quality than the micro-scale approach, mainly focusing on independent projects. Most municipalities not selected as the pilot cities implicate the sponge city solutions in the micro-scale. According to the study results, it is encouraged to expand the sponge city solutions to larger scales. However, increasing parks and green spaces inevitably reduces developable areas and may have adverse external effects, such as urban sprawl and an increase in traffic infrastructure. The cost of expropriating land to build the sponge city network's integration should also be considered. Since wetlands are not as effective as purification plants, they cannot replace chemical and mechanical water treatment systems. Therefore, the balance between the sponge city solutions and engineered solutions needs to be considered in sustainable urban planning.

4.2. Urban Flood Reduction

The simulation results of the three scenarios showed that the study areas with the sponge project have a high stormwater retention capability. This is consistent with the results of previous studies [47–49]. Improving stormwater runoff through increasing sponge projects was not as effective as the pollutant load control with sponge projects. For instance, scenario 3 for Harbin, proposing an integrated green infrastructure with a series of sponge projects, reduced 9% of pollutants compared to scenario 1. Meanwhile, scenario 3 for Harbin only decreased the stormwater runoff by 0.8%. The analysis of other sites showed similar results. However, the analysis target was the overall watershed, including surrounding rural areas. The result may differ if the analysis area is only limited to the urbanized area. The temporal condition of the analysis also needs to be considered. The analysis assumed the rainy season in which wetlands and streams' water bodies reached the total retention capacity. If the dry season was assumed, the positive impact of sponge projects could be more significant.

Even though the impact of urban flood reduction by sponge projects is not as significant as the pollutant control's impact, a 1–3% improvement of the stormwater runoff can significantly contribute to regional-scale flood control. Therefore, reducing impervious pavement of the urban area by introducing sponge city projects can be an effective way to mitigate urban flooding problems. In addition to increasing constructed wetlands and parks proposed in the change model of this research, smaller-scale solutions, such as introducing rain gardens, water cisterns, green roofs, permeable pavements, and more sustainable green architecture are needed to be considered in sponge city projects. In terms of the sponge city planning, similar to the interpretation of the pollutant load control analysis, it can be said that expanding the scale of the sponge city solutions can improve the overall urban flood capability of the city. However, the urban flood control improvement that resulted from the building a large-scale sponge city network was not significant compared to the pollutant load control.

4.3. Limitations of the Model

Every model has strengths and limitations, and the InVEST model is no exception. Both the NDR model and the urban flood model operate on a watershed scale, so the model results include outflows from the entire watershed, which is much larger than the study area itself. Therefore, this study used the LULC that only changed a part of the study area to verify the effect of the sponge city. One of the more critical limitations of the model was that it had relatively few parameters, and the output results are sensitive to the input data values and the choice of parameters. The precedent studies needed to decide the pollutant output coefficients in the NDR model for LULC and the values of plant retention efficiency for pollutants. Therefore, sensitivity analyses may also be needed to address the accuracy of the model.

Another limitation of the study is that sponge city effects were verified in only two categories: pollutant control and urban flood control. Since the city's planning should consider a variety of indicators considering social and economic aspects, the strong environment emphasis of the sponge city should be balanced with other essential considerations required for the city. More factors deciding the pollutant control effect and urban flood control effect should be analyzed in future research. This study analyzed the pollutant control effect by the amount of nitrogen export; however, the source of urban water pollution is not limited to nitrogen. In terms of urban flood control, analyzing the amount of stormwater runoff, the recharge rate to groundwater, the retention capacity of different vegetation types, and the water recycling rate should also be considered to find more accurate effects.

5. Conclusions

The study analyzed the effects of the sponge city projects with scenario-based models following the geodesign framework. The simulation with the InVEST model verified how sponge city projects could contribute to pollutant control and urban flood control by analyzing the output of pollutants in the watershed and the volume of stormwater runoff in the watershed. By comparing different scenarios, the study proved that the current sponge project can improve the water pollutant control capability by 11–18% and the stormwater control capability by 0.4–6.3%. If the city-wide green infrastructure network is introduced with sponge projects, the water pollutant control capability can increase by 9–16%, and the stormwater control capability can increase by 0.8–2.9%. These results show that the current sponge projects can improve the city's sustainability and can be helpful in strategies to fight climate change and global warming. The study also examined the methods to fill the gap between the traditional design process with the scientific evaluation process applying the geodesign framework. It is proven in this research that the theory and the framework of geodesign have great potential to develop a new integrated method in planning and design, bridging practice and academic research. The limitation of this study is that the results are based on scenarios and model simulations without empirical on-site observations. In future studies, more empirical data-based research is needed to prove the more accurate effects of sponge city projects.

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