A multi-objective spatial optimization of wetland for Sponge City in the plain, China

Abstract

Climate change exacerbates various environmental problems in cities, such as flooding, droughts, and water pollution. As a result of these urban environmental problems, China vigorously promotes the construction of Sponge City. Wetlands are an effective stormwater management facility of Sponge City which can regulate urban stormwater runoff and remove non-point source pollution from stormwater runoff. Wetlands, as sensitive ecosystems in cities, require additional consideration and rational planning in the construction of Sponge City. Wetlands constructed in suitable locations can improve constructed wetland potential, improve wetland benefits, and reduce cost. However, the multi-objective spatial optimization of wetlands in Sponge City is insufficient. To fulfill wetlands planning and construction for Sponge City, a multi-objective optimization method that maximizes constructed wetland potential and pollutant removal and minimizes input costs is proposed by genetic algorithm (NSGA-II, Non-dominated Sorting Genetic Algorithm-II). The wetland space was optimized for the study area, and the Pareto optimal solution of the wetland layout was obtained. The values of the three objectives of wetlands spatial optimization schemes (Pareto optimal solutions) identified is compared with the values of the three objectives of the planned wetlands, which verifies the effectiveness of the wetland spatial optimization method. On the basis of the Pareto optimal solutions, we propose four schemes with the highest economic benefit scheme for constructed wetland potential (constructed wetland potential/input costs), highest economic benefit scheme for pollutant removal efficiency (pollutant removal/input costs), the best compromise scheme between three objectives, and highest constructed wetland potential scheme. Compared with the planned wetlands scheme, these four schemes can increase the constructed wetland potential by 2.2% ~ 25.1%; increase the TN mass removal by -8.8% ~28.0%; reduce the input costs by 8.9% ~ 37.1%.

Keywords

Wetlands, Spatial Optimization, Multi-objective Optimization, Genetic Algorithm, Wetland Restoration Potential

1 Introduction

Due to the rapid expansion of cities, impervious surfaces such as buildings, parking lots, and pavements multiply, while the area of rivers, wetlands, and green spaces with purification functions in the city decrease. In addition, climate change has increased the frequency and intensity of extreme rainfall, further increasing urban stormwater runoff(Yao et al., 2022). These urban stormwater runoff and pollutants mix, which causes serious urban non-point source pollution and continued deterioration of the water quality in urban areas(Che et al., 2002; Deng et al., 2012; Dietz, 2007; Khan et al., 2006; She et al., 2021; Yao et al., 2022). This is a pressing issue in China, which has expanded rapidly as a developing country, where the urbanization rate reached 60% in 2019(Wang et al., 2021). In response to urban non-point source pollution, China has introduced Sponge City stormwater management policies. The concept of Sponge City is akin to low impact development design (LID), water sensitive urban design (WSUD), and sustainable development urban drainage system (SUDS), among others, which can also be called as the construction of low impact development rainwater system(Guan et al., 2021; Sun et al., 2020). A Sponge City comprises a sponge-like system with components such as wetlands, rain gardens, bioretention, green roof spaces, and permeable pavements(Guan et al., 2021). It follows the principles of "source reduction, process control, and system management" to enhance cities' resilience in adapting to climate change and resisting heavy rainfall(Yao et al., 2022).

Wetland as one of stormwater management facilities has proven to be effective in mitigating the pollution of urban non-point source pollution, and generally requires comparatively little input costs (construction, operation and maintenance), so it has become increasingly important in many practical applications of non-point source pollution treatment(Ravikumar et al., 2022). Wetland can remove total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), chemical oxygen demand (COD), and heavy metals through various processes such as filtration, adsorption, chemical precipitation, plant uptake, decomposition, and precipitation(Birch et al., 2004; Swarnakar et al., 2022; Walker & Hurl, 2002). The pollution removal effects of TN, TP, SS, and COD are as high as 73.2%, 89.0%, 80.4%, and 84.3% respectively, in wetlands with specific combination methods(Zhou et al., 2021). Wetlands are more complex ecosystems compared to other Sponge City facilities such as green spaces land, permeable pavement, green spaces roofs, and vegetative swales. Thus, when planning, additional environmental factors need to be taken into account. In fact, numerous wetlands fail or do not perform better due to poor planning or design(Rodrigo, 2021; Ryan, 2022; Van Lonkhuyzen et al., 2004). Therefore, in the wetland planning of Sponge City, it is essential to conduct quantitative analyses not only for wetland benefits and input costs, but also for wetland restoration potential (the object of this paper is the constructed wetland, so it refers to constructed wetland potential). However, in the existing research on wetland multi-objective optimization, no study has incorporated constructed wetland potential as a distinct objective that can be quantitatively analyzed within a multi-objective analysis system.

Constructed wetland potential often requires consideration of geological and hydrological factors such as elevation, slope, river network, soil type, land use, etc.(Ha & Lee, 2006; Horvath et al., 2017; Ma et al., 2016; Pal & Singha, 2022; White & Fennessy, 2005). These studies typically assign different weights to various geological and hydrological factors and obtain the constructed wetland potential value through the ArcGIS weighted analysis method. In addition, wetland benefit (pollutant removal, flood regulation, biodiversity, etc.)(Babbar-Sebens et al., 2013; Djodjic et al., 2020; Singh et al., 2019; Yang & Best, 2015) and input costs (construction cost)(Yang & Best, 2015; Singh et al., 2019) are usually considered in wetland multi-objective optimization studies. Yang and Best (2015) considered wetland benefit (TN removal) and input costs to optimize BMP (wetland and buffer strip) space using the NSGA-II method. Singh et al. (2019) optimized wetland space using the genetic algorithm method considering wetland benefit (P removal) and input costs. The wetlands optimization models presented in these studies are limited in assisting spatial planning decisions for larger urban areas because the suitable sites of wetlands are predefined in the optimization process, and quantitative analysis of the constructed wetland potential within the optimization process has not been included. These methods also fail to provide support when urban planning decision-makers consider the trade-off between constructed wetland potential and input costs. In addition, although constructed wetland potential, wetland benefits and input costs are critical considerations in wetland planning and design, in previous studies, we have not found a wetland spatial optimization model that simultaneously analyzes the trade-off relationship between the three objectives. Cities in the plains are flat and the elevation difference is tiny, so it is more difficult to subjectively compare the quality of wetland site selection in wetland planning and design(Wang et al., 2020). Wetlands in Plains cities require more detailed quantitative analysis to select more reasonable wetland locations. In this paper, we focus on cities in plain areas for multi-objective optimization of the Sponge City wetland.

In order to develop a spatial optimization model for decision-making support on selecting optimal wetland sites across urban areas, this paper aims to fill the research gap by including constructed wetland potential, wetland benefits (this paper mainly calculates TN mass removal) and input costs and verifying the effectiveness of the model's identified optimal wetlands against an actual plan in Shangqiu city, China. The research method is as follows: First, the spatial data of the study area is mapped, the function formula of the three objectives is decided, and Pareto optimal solutions (wetlands spatial optimization schemes) are obtained through the NSGA-II. Second, the three values (constructed wetland potential, TN mass removal, and input costs) of the planned wetlands are calculated through the function formula of this model, and the Pareto optimal solutions are compared to the planned wetlands in Shangqiu to verify the model's effectiveness. Finally, four wetland optimization schemes are proposed through the preferences of each objective and the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method.

2 Research method

2.1 Study area

The study area was selected based on the following conditions: 1. city in the plain and accessibility of relevant spatial information (elevation, land use map, soil type map, rainfall data), 2. significant urban non-point source pollution, 3. a wetland planning scheme has been created. Based on the above conditions, the downtown area of Shangqiu in the eastern part of Henan Province, China was selected as the study area. The area is drawn by Shangqiu Master Plan (2016–2035), with a total area of 382.5km² (Fig.1).

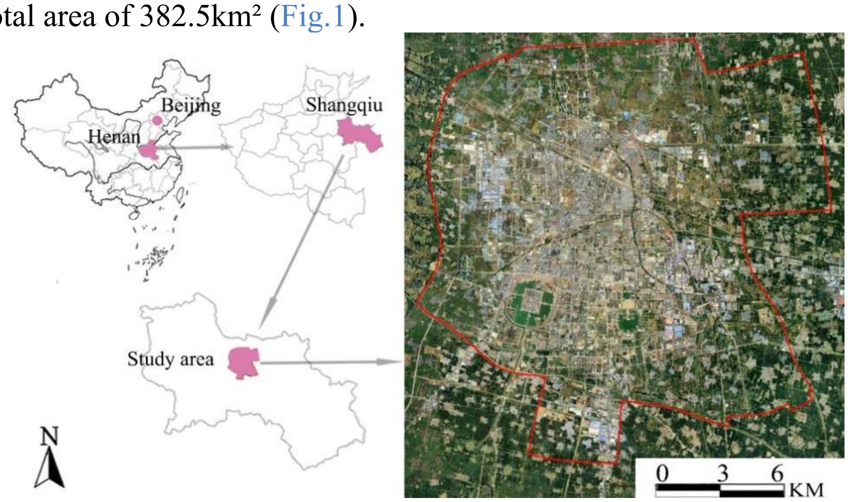

Fig. 1. Map showing the location and outline of the study area.

Shangqiu is mainly located in the Yellow River alluvial plain, with simple topography and good geological environment (no geological hazards, groundwater and soil pollution, flat overall slope etc.), which provides good prerequisites for wetland construction(Wang et al., 2020; Wang & Guo, 2022). In addition, Shangqiu is high in the northwest and low in the southeast, and is flat, with an average slope of 1:5000–1:7000 (Xu et al., 2020). However, there are many small-scale topographic variations such as sand dunes, beach land, ponds, pothole, and lake depressions intersecting each other. The average annual precipitation in Shangqiu is 741 mm, and the average annual temperature is 14.7°C(Shangqiu Municipal Government, 2023). Due to the serious nitrogen pollution in surface water, 82% of surface water system was black and odorous with NH3-N levels of greater than 8.0mg/L(Housing and Urban-Rural Development, 2015; Xu et al., 2020). The municipal government of Shangqiu city has released the black and odorous water treatment planning (2016-2035), aiming to achieve the objective of attaining surface water quality of IV standard (NH3-N≤1.5mg/L, TN≤1.5mg/L, etc.) in the surface water system by 2035(State bureau of environment protection & quarantine, 2002; Xu et al., 2020). The plan focuses on enhancing water quality through various means, including the use of sewage treatment plants, overflow pollution facilities, riverside green space, and the construction of 13 wetlands covering a total area of 84 ha (accounting for 0.2% of the study area). The site selection of planned wetlands is mainly in large parks near river, green spaces land near river, farmland near river, and water supply places of reclaimed water. The wetlands located near the reclaimed water supply site can not only purify the urban non-point source pollution, but also purify the recycled water. After the water quality reaches the IV standard, it will be discharged into the river to supplement the ecological water (Xu et al., 2020). For the specific location of planned wetlands, please refer to Shangqiu Sponge City planning (2016-2035)(Shangqiu Municipal Administration, 2019b).

2.2 Construction of a multi-objective model

Due to the serious nitrogen pollution in the rivers of the study site, TN removal was taken as a objective of wetland space optimization, which is also consistent with the purpose of the planned wetlands (Xu et al., 2020). Constructed wetland potential and input costs are also important factors to be considered by decision-makers. Therefore, maximizing restoration constructed wetland potential and minimizing input costs are two other objectives of wetland space optimization.

The study area was divided into 38,141 land units, each measuring 1 ha (100m×100m), which is the smallest wetland area considered. Compared to the planned wetlands, wetlands with the same area (see to 2.1) were selected for the study. The values of the three objectives were computed for each land unit. Thus, the spatial optimization problem involves selecting the optimal combination of 84 land units from the total of 38,141 units. If multiple adjacent land units are selected, they are aggregated and treated as a larger wetland, with its area constrained by the catchment area (refer to Section 2.2.2). This paper used NSGA-II and ArcGIS (10.8) to build a multi-objective spatial optimization model. As one of the most famous multi-objective optimization algorithms, the NSGA-II algorithm has been widely used in many research fields(Galvani et al., 2022), and can find a better uniform distribution of solutions and better convergence near the true Pareto optimal front(Deb et al., 2002). In recent years this method has also been widely used in low impact development-best management practices (LID-BMPs) construction(Ghodsi et al., 2020; Raei et al., 2019), and has been applied to spatial optimization of wetlands as well(Singh et al., 2019; Yang & Best, 2015). The NSGA-II algorithm is implemented through a python library for genetic algorithms (http://geatpy.com/).

2.2.1 *Data and function of constructed wetland potential*

Wetland construction or restoration generally considers economics, geological, hydrological, and environmental factors, and the scoring systems for each factor varies depending on the objectives of construction or restoration (Moreno-Mateos et al., 2010; Pal & Singha, 2022; Palmeri & Trepel, 2002). In this paper, we adopt the scoring system for each factor developed by Palmeri and Trepel (2002), because it shares a common objective with our research (improving water quality). Furthermore, this system incorporates more comprehensive impact elements and employs a more detailed scoring systems. Palmeri and Trepel (2002) analyzed three different scoring systems according to the emphasis on economics and geology, or geology and hydrology, or economics and environment. As this study focuses on the analysis of constructed wetland potential, we refer to the scoring system dominated by geology and hydrology. The data used for scoring system for geology and hydrology involves elevation, slope, river network, soil type, land use, and presence of wetland areas in the past (Palmeri & Trepel, 2002; White & Fennessy, 2005). We determined the scoring system by combining the characteristics of the study area, referring to Palmeri and Trepel (2002) and related studies of wetland scoring systems (Table 1). The land unit scores we calculated using Table 1 ranged from 40.5 to 137. Fig. 2 shows the spatial distribution map of each evaluation element score.

The elevation and slope play a crucial role in hydrological processes and the spatial distribution of water. For instance, they directly influence surface water flow and soil moisture(Phillips, 1990; White & Fennessy, 2005). Low elevation areas or depressions suitable for constructing wetlands can effectively capture and retain more stormwater runoff, reducing the need for pump installations(McCauley & Jenkins, 2005; Moreno-Mateos et al., 2010). Thus, low elevations are assigned higher scores. The elevation scoring needs to be adjusted to the actual conditions of the study area, in order to be able to better select the low elevation or depressions suitable for the construction of wetlands(Palmeri & Trepel, 2002; White & Fennessy, 2005). Therefore, we adjusted the elevation scoring criteria to match the actual conditions of the study area (adjusting the range of each scoring level from 10m to 5m). To reduce the vertical error of the elevation data, we selected the elevation of TanDEM-X DEMs(TanDEM-X 12 m, TanDEM-X 30 m, TanDEM-X 90m), which is a new elevation dataset produced by the German Aerospace Center (DLR), and is currently the best global elevation data available (Grohmann, 2018; Hawker et al., 2019). Among the TanDEM-X data options, we chose the TanDEM-X 90m data, which is freely available and has a mean error of 1.06m and a bare error of 0.03m (Hawker et al., 2019). We downloaded this dataset measured in winter (January 2023) from this link: https://download.geoservice.dlr.de/TDM90/. During winter, after the leaves fall off the trees, non-urban areas such as green spaces and farmlands become more like bare ground, reducing the error to a level close to the bare ground error (0.03). Although the presence of buildings can increase the vertical error, it does not significantly affect the results because the model does not select areas unsuitable for wetland construction. In the scoring system, altitudes (orthometric heights) are generally used, so we converted the ellipsoidal height of the TanDEM-X 90m to altitudes through ArcGIS (10.8) and replaced the extreme values with the maxima and minimum values after removing the extreme values.

Flatter areas are favorable for wetland construction, while steeper areas are less suitable for creating wetlands(Moorhead, 1991). Higher slopes can also increase the cost of constructed wetlands(Moreno-Mateos et al., 2010). Additionally, vegetation growing at the water's edge tends to grow faster when the slope is below about 5% and develops more slowly when the slope is above 10%(Lim & Kim, 2009). Therefore, areas with slopes of 10% or more are assigned lower grade scores. The study area has a maximum slope of 8%, and majority of the area has slopes within 1%, with only a small portion having slopes greater than 5% (Fig. 2(b)). The slope data were generated using TanDEM-X 90m data via ArcGIS (10.8).

Land use type reflects the level of human disturbance and cost-effectiveness (Moreno-Mateos et al., 2010; Qu et al., 2018) and influences the migration of species, material and energy exchange(Ou et al., 2011). Therefore, it significantly impacts the success of wetland construction(Qu et al., 2018). The existing land use map of Shangqiu is no longer highly applicable due to rapid development and substantial changes in land use. Therefore, we made a detailed land use map through ArcGIS (10.8) based on the Shangqiu planning scheme (2015-2035)(Shangqiu Municipal Government, 2018) and combined with the 2018 Shangqiu Land Use (http://data.ess.tsinghua.edu.cn).

Soil type is a representative factor for wetland restoration or construction(Qu et al., 2018) and reflects the water storage capacity of the soil(Moreno-Mateos et al., 2010; Whitis, 2007). The soils with high water holding capacity are more conducive to sustaining wetlands, thus receiving higher grade scores (Tang et al., 2012). In this study, the soil types ranked in descending order of moisture content were solonetz, fluvo-aquic soil (loamy), and fluvo-aquic soil (silty) (Zhang et al., 2019), which differ from the soil types in the reference paper(Palmeri & Trepel, 2002), necessitating adjustments to the scoring criteria for soil types. The higher the water content, more suitable the soil for constructed wetlands (Palmeri & Trepel, 2002; Van Lonkhuyzen et al., 2004), and since the water content of solonetz is greater than glacial till, we can assign a score for solonetz based on Palmeri and Trepel (2002). Additionally, fluvo-aquic soil (loamy) and fluvo-aquic soil (silty) have higher water content and are more suitable soils for constructed wetlands(Ma et al., 2016), therefore we can determine their scores based on Palmeri and Trepel (2002).

Wetland systems are particularly fragile, especially in terms of water availability, and even small changes in water availability (in quality or quantity) can lead to significant changes in plant communities and animal habitats(Acreman et al., 2007). Since the river plays a vital role in ensuring a stable water source for wetlands and significantly influences the total cost of wetland construction(Moreno-Mateos et al., 2010), it carries the greatest weighting in the scoring system. The area within 150 m from river is considered to be the area where the increase in energy and cost required to construct wetlands is not significant(Moreno-Mateos et al., 2010), As a result, the area within 150 m is assigned a high grade score. We obtained the Shangqiu river network data from OpenStreetMap (https://www.openstreetmap.org/#map=11/34.3930/115.6572).

Due to insufficient winter rainfall in the study area, wetland water supply is ensured by utilizing recycled water as a supplementary source in the planned wetlands. Therefore, the "Recycled Water Pipelines distance" is included in the scoring system. Since it serves the same purpose (providing a water source) as the river, we assign it the same weight as the river. We obtained the network planning map of Shangqiu Recycled Water Pipelines (2016-2035) from the Shangqiu Municipal Administration website(Shangqiu Municipal Administration, 2019a). Since historical wetland data is unavailable, past wetland areas are not considered.

Table 1. Constructed wetland potential evaluation metrics and weight.

Indicator type	Weight	Sub-indicators	Criterion score	Data source	Reference papers
Elevation	1.5	< 40m	10	TanDEM-X 90m (https://download.geoservice.dlr.de/TDM90/)	Lim and Kim (2009); Palmeri and Trepel (2002)
		40-45m	8		
		45-50m	6		
		50-55m	4		
		> 55m	2		
Slope	2.5	0-1%	10	It made by ArcGIS using TanDEM-X 90m data	Lim and Kim (2009); Palmeri and Trepel (2002)
		1%-2%	9		
		2%-5%	6		
		5%-10%	3		
		> 10%	1		
Land Use	2.0	Water, mire, swamp	10	Shangqiu Municipal Government, 2018; http://data.ess.tsinghua.edu.cn	Ou et al. (2011); Schleupner and Schneider (2013); Palmeri and Trepel (2002)
		grassland	8		
		Farmland/ forest	5		
		urban/industry	2		
Soil type	2.0	water	10	Zhang et al. (2019)	Tang et al. (2012); Ma et al. (2016); Palmeri and Trepel (2002); Van Lonkhuyzen et al. (2004)
		fluvo-aquic soil(silty)	8		
		fluvo-aquic soil(loamy)	7		
		solonetz	6		
River distance	3.0	0-50m	10	OpenStreetMap: https://www.openstreetmap.org/# map=11/34.3930/115.6572	Lin and Kleiss (2007); Palmeri and Trepel (2002)
		50-150m	9		
		150-300m	6		
		300-600m	3		
		> 600m	1		
Recycled water pipelines distance	3.0	0-50m	10	Shangqiu Municipal Administration, 2019a: https://csglj.shangqiu.gov.cn/zwdt/tzgg/content_45705	Palmeri and Trepel (2002)
		50-150m	9		
		150-300m	6		
		300-600m	3		
		> 600m	1		

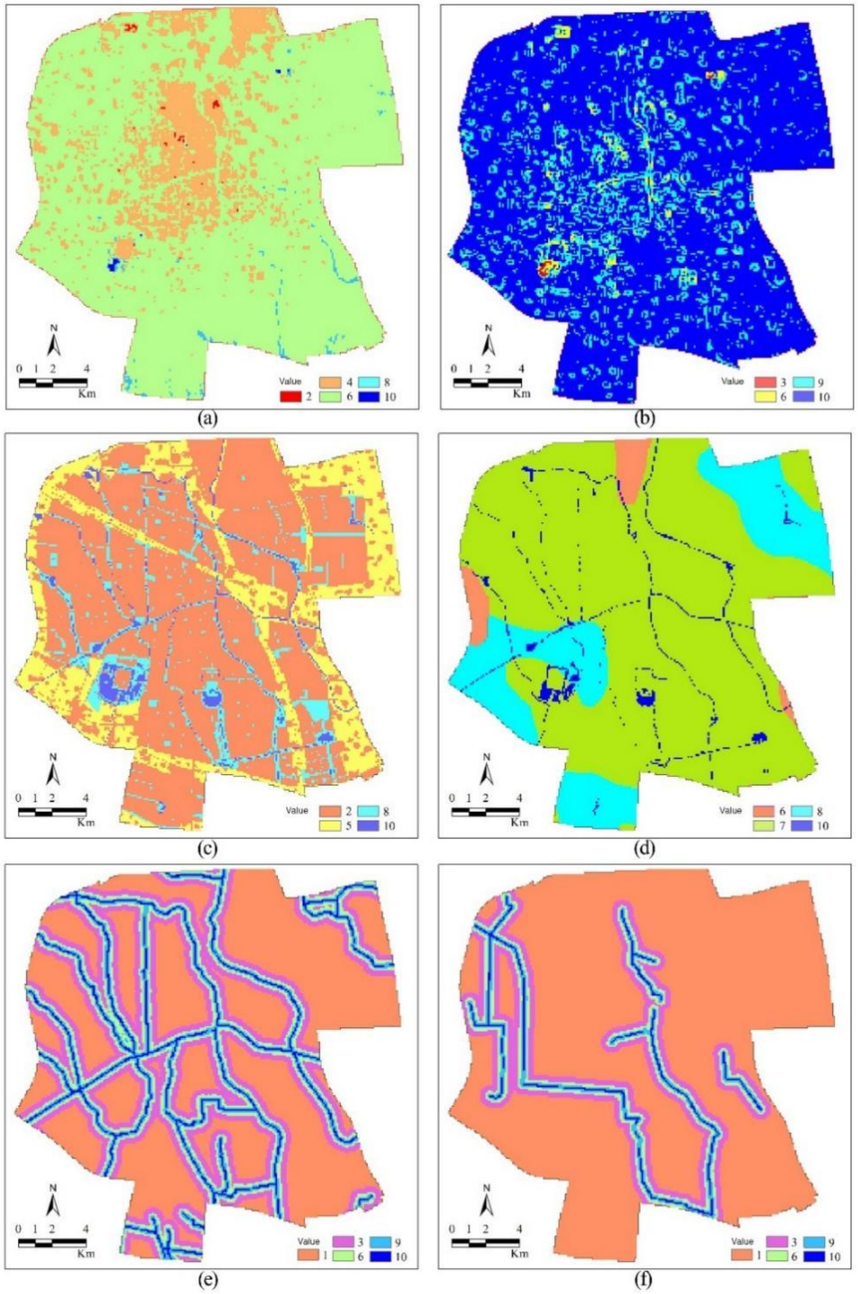

Fig. 2. Spatial distribution map of criterion score of (a) elevation, (b) slope, (c) land use, (d) soil type, (e) river distance, (f) Recycled water pipelines distance.

Constructed wetland potential is calculated using to the scoring system in Table 1 by Equation 1.

$$fit_{max} = \sum_{i=1}^{84}(C_1 * A_{1i} + C_2 * A_{2i} + C_3 * A_{3i} + C_4 * A_{4i} + C_5 * A_{5i} + C_6 * A_{6i}) \quad (1)$$

where i is the index of land units selected as wetland; $C_1 \sim C_6$ is the weighted value of elevation, slope, land use, soil type, river distance, and Recycled Water Pipelines distance; $A_{1i} \sim A_{6i}$ is the criterion score of elevation, slope, land use, soil type, river distance and Recycled Water Pipelines distance of ith land unit selected as a wetland.

2.2.2 Data and function of TN removal

Because the newly constructed wetland ecosystem is still unstable and cannot reflect the TN removal capacity of wetlands, this study calculates the TN removal quality of the wetland with a relatively stable ecosystem. Jordan et al. (2011) analyzed many wetland studies on TN removal to evaluate the factors affecting TN removal rates. Regardless of changes in wetland type and other factors, the results showed that there was a positive near-linear relationship between TN loading and TN removal (Equation 2) and about 82% of the variation is determined by the regression model ($R^2 = 0.82$). Yang and Best (2015) applied Equation 2 to calculate the TN removal of wetlands. Including all the influencing variables in a regression model is almost impossible in practical applications (Yang & Best, 2015). Therefore, in this paper, the TN removal function (Equation 3) of wetland was determined according to Equation 2. Through this calculation formula, the model can select the catchment with high TN load, and further select the pixels with high TN load in the catchment. In addition, the model can calculate the TN mass flowing into the wetland based on the total exported TN mass in each catchment, and finally calculate the TN removed mass of the wetland.

$$log_{10}(y) = 0.99 \times log_{10}(x) - 0.46, \quad R^2 = 0.82 \tag{2}$$

$$TN_{max} = \sum_{i=1}^{84} (c \times 10^{\,0.99 \times log_{10}(x) - 0.46} + x_i \times c) \tag{3}$$

$$TN_{export\_new} = TN_{export} - \sum_{i=1}^{n} (x_i \times c) \tag{3a}$$

$$x_{into_{mass}} = TN_{export_{new}} \times ((A_{flush} + A_{wetland}) / A) \tag{3b}$$

$$A_{flush} = A_{wetland} / 3\% \leq A - A_{wetland} \tag{3c}$$

$$x = x_{into\_mass} / A_{wetland} \tag{3d}$$

where y is the TN mass removed per area per time (g/m²/year); x is the TN loading loaded into a wetland (g/m²/year); i is the index of land units selected as wetland; c is the area of land units (m²); x_i is the TN load of land unit (i) (g/m²/year); TN_{export_new} is the total exported TN mass of the catchments after wetland sites selection is determined (g/year); TN_{export} is the total exported TN mass of the catchment before wetland site selection is determined (g/year); n is the number of land units selected as wetlands in the catchment; x_{into_mass} is the total TN mass loaded into a wetland (g/year); A_{flush} is the first flush area (only this portion of the first flush stormwater flows into the wetland). The first flush typically originates from upstream areas within this small catchment, referring to the initial runoff from early stages of rainfall(Maniquiz-Redillas et al., 2022). A is the catchment area; $A_{wetland}$ is the wetlands area. We specify that the sum of the wetland and first flush areas are no larger than the catchment area (Fig.3).

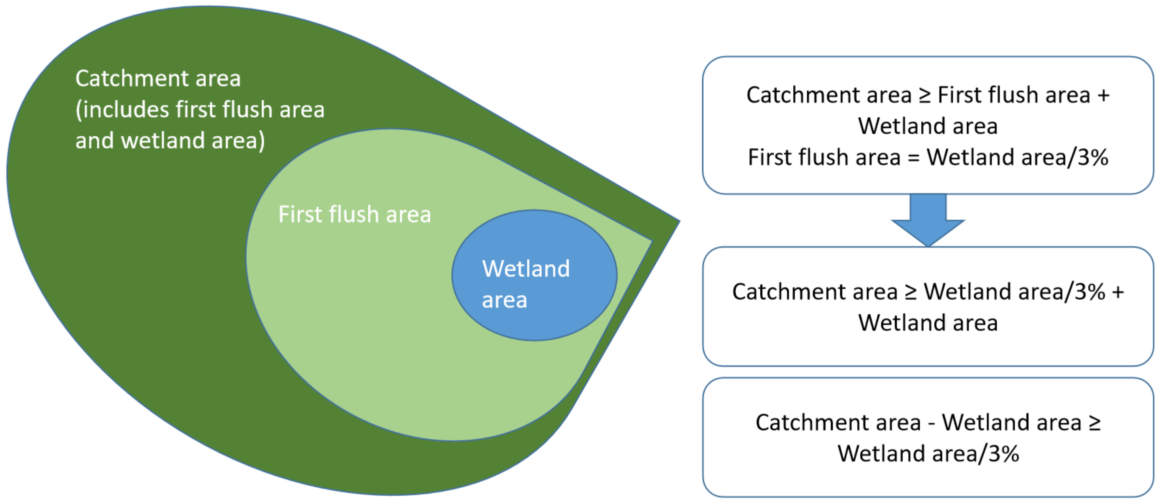

Fig. 3. Wetlands, first flush and catchment relationships.

The total exported TN mass of the catchment is constantly changing with the selected location of the wetland. When a land unit (i) is selected as a wetland, the TN load of this land unit becomes 0, and the total exported TN mass of the catchment will be recalculated. Wetlands can collect TN mass from surrounding land or upstream of the catchment, and the total TN mass loaded into a wetland (x_{into_mass}) is determined by the TN mass of the first flush area. Since the mass of TN loaded into a wetland cannot be precisely calculated and the terrain of the study area is flat, so x_{into_mass} is simplified as TN_{export_new} times the first flush and wetland area fraction of a catchment (Equation 3b)(Yang & Best, 2015). In general, the wetland area is typically 1%-5% of the first flush area(Xiao et al., 2013). In this study, we use the average value of 3% to calculate the first flush area.

Using the elevation and river network of the study area, the study area is divided into 109 catchments by ArcSWAT. The total exported TN mass of the catchment and the TN load map was created by the Nutrient Delivery Ratio (NDR) of the InVEST model (https://naturalcapitalproject.stanford.edu/software/invest-models/sediment-retention). Because the InVEST model is simple to operate, fast to calculate, and powerful in spatial representation capabilities, it is the most widely used model in the world(Yang et al., 2019). The NDR module is specifically designed for TN and TP exports and has been used in many parts of the world (Yang et al., 2019). The data needed for this model are elevation (elevation), land use/land cover, precipitation, catchment, and others (Table 2).

Table 2. Input of the data for the InVEST model.

Input data	Data source	Remarks
Elevation	TanDEM-X 90m	Refer to Table1
Land use/land cover	Shangqiu Government Network Shangqiu Master Planning scheme (2015-2035)	Refer to Table1

Nutrient runoff proxy	Made by China Meteorological Data Center (Average annual precipitation from 1990-2019)	http://data.cma.cn/
Watersheds	Made by ArcSWAT	Need elevation and Stream Network data
Biophysical Table	Wang (2019)	-
Threshold flow accumulation	InVEST documentation	https://naturalcapitalproject.stanford.edu/software/invest-models/sediment-retention
Borselli k parameter	InVEST documentation	
Subsurface Critical Length	InVEST documentation	
Subsurface Maximum Retention Efficiency	InVEST documentation	

The resolution of Land use/land cover is 90m.
Nutrient runoff proxy: the nutrient runoff proxy is a map of runoff potential, the capacity to transport nutrients downstream, this can be a quickflow index or annual precipitation.

2.2.3 *Data and function of input costs*

In this paper, input costs include land prices, construction cost, and operation and maintenance (O&M) cost. The land prices range from 108 CNY / m² for farmland to 4000 CNY /m2 for commercial land(Shangqiu Municipal Government, 2020a, 2020b). According to the research(She et al., 2021; Xu et al., 2022; Yang & Best, 2015), in the space optimization or site selection of LID-BMP-BC facilities, a specific value is generally used to calculate the construction cost. The wetland construction cost of Sponge City in Beijing is 500-700 CNY / m² (Housing & Development, 2014). Differences in material cost, labor cost, and design parameters in different cities can affect the construction cost of Sponge City facilities(She et al., 2021). The material cost and labor cost of Shangqiu are lower than that of Beijing, so the lower 500 CNY / m² is chosen as the wetland construction cost. To emphasize the difference in input costs due to the location of the wetland, reduced the O&M cost impact on construction cost. Therefore only 1-year the annual average O&M cost is calculated as part of the input costs. According to research(Houle et al., 2013), the O&M is set at 4.3 CNY / m² / year (the average of wet pond and gravel wetland). The final function (Equation 4) of input costs is as follows:

$$cost_{min} = \sum_{i=1}^{84} c(a_i + B + B') \tag{4}$$

where i is the index of land units selected as wetland; c is the area of land (m²); a_i is the cost of ith land unit selected as wetland (CNY / m²); B is the cost of constructing wetlands (500CNY / m²); B' is the cost of the O&M (4.3CNY / m²).

2.2.4 *Optimization process*

The process of the spatial optimization model based on NSGA-II is as follows (Fig.4). First, the data of each objective was processed by ArcGIS, and the function of each objective was decided. Second, the chromosome encoding, input parameters, and the initial population were designed according to the type, purpose, and scale of the research question. Third, through the non-dominated sorting, suitable individuals were selected from the initial population and used for crossover and mutation operations. Later, the population consisting of parents and offspring were obtained. Finally, better individuals in the population were selected through calculating non-dominated sorting and crowding distance, and a new parent population was secured. This process was repeated until the set termination condition was reached, and finally, the Pareto optimal solutions were obtained.

The number of land units in the research area is large (38,141), which makes it difficult in the search for the optimal solution. To improve the effectiveness and accuracy of the search, the initial population was selected in the field where the best solution can be found (sites within 300 meters of the river). Based on prior studies, the crossover rate and mutation rate were set at 0.9 and 0.001, respectively (Babbar-Sebens et al., 2013; Yang & Best, 2015). Due to the large search range, the population multiple was set to 2000, which increased the amount of computation but reduced the risk of falling into a local optimum. Every 100 generations of calculation, the coordinates of the optimal solutions (the locations of the wetland) were imported into the ArcGIS and spatial distribution of the wetlands was generated. When the spatial distribution was no longer altered for every generation, the computation was terminated.

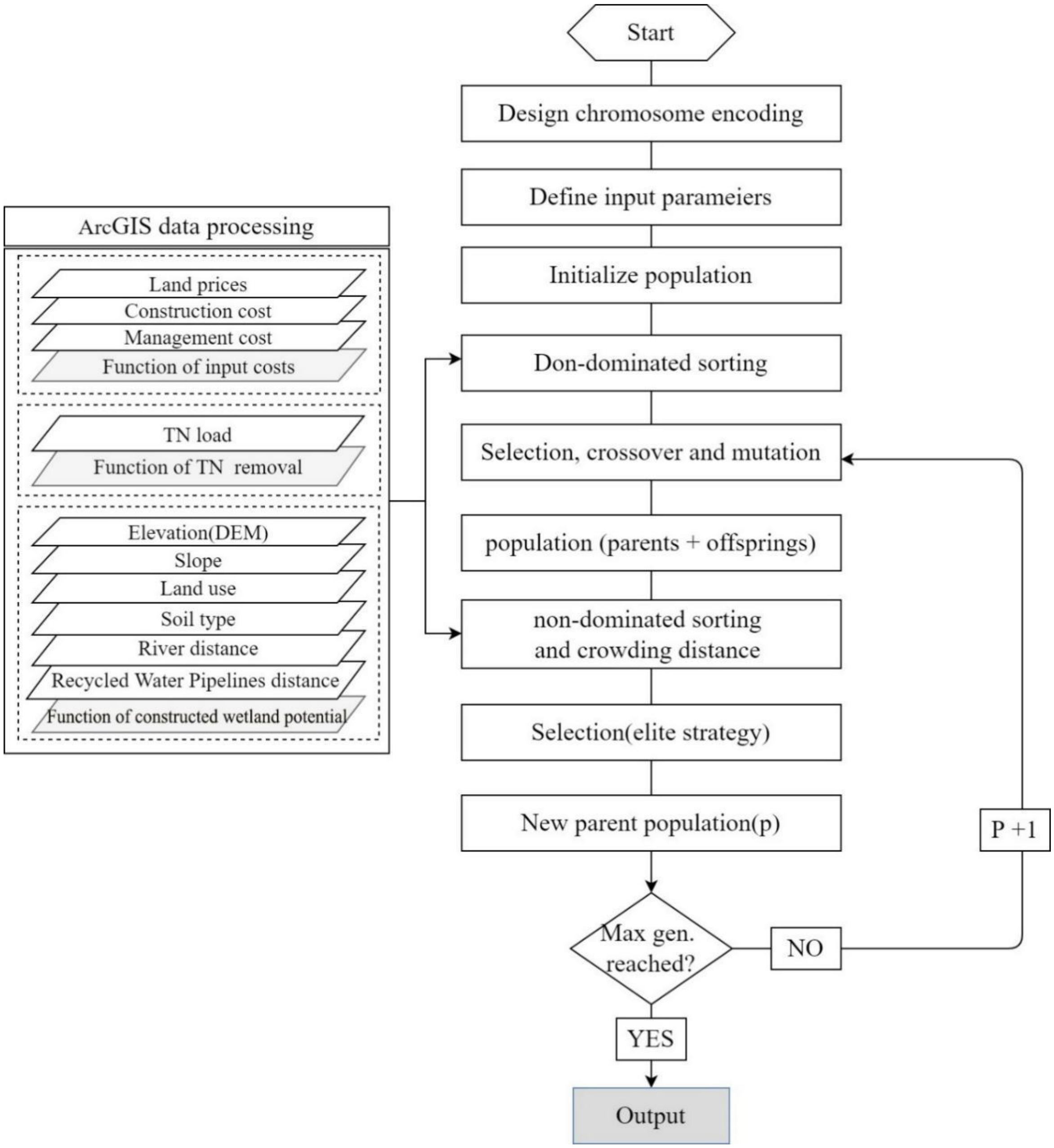

Fig. 4. Optimization process of the optimization model for Wetland site selection.

2.3 Comparison of planned wetlands and Pareto optimal solutions

First, a spatial map(100m×100m) of the planned wetlands was created. Second, according to the spatial data of the three objectives of the planned wetlands, the input costs, TN mass removal, and constructed wetland potential values from each function were obtained. Finally, the value of each objective function of the planned wetlands and the value of each objective function by the Pareto optimal solutions was compared and analyzed to test the effect of the model.

2.4 Wetland optimization schemes selection

From the Pareto optimal solutions, four wetland optimization schemes with the highest economic benefit scheme for constructed wetland potential, highest economic benefit scheme for pollutant removal efficiency, the best compromise scheme between three objectives, and highest constructed wetland potential scheme were selected to provide reference for urban decision-makers. The highest economic benefit scheme for constructed wetland potential is one with the largest ratio of constructed wetland potential to input costs among the Pareto optimal solutions. The highest economic benefit scheme for pollutant removal efficiency is one with the largest ratio of pollutant removal to input costs among the Pareto optimal solutions. The best compromise scheme between three objectives is calculated by the TOPSIS method using the Pareto optimal solutions. This method is commonly used when choosing the final solution in a multi-objective optimization scheme (Behzadian et al., 2012; Locatelli & Mancini, 2012; Souier et al., 2019; Zheng et al., 2017). For example, Zheng et al. (2017) selected the best compromise of the three objectives from the Pareto optimal solutions by the TOPSIS method. The principle and calculation process of the TOPSIS method refer to the previous research paper(Behzadian et al., 2012).

3 Results and Discussion

3.1 Pareto optimal solutions

Fig. 5 shows the change in the value of each objective throughout generations. It can be found that after 500 generations, the function values of all objectives have reached a balanced state. In addition, the spatial distribution of wetlands did not change after 500 generations (Fig. 6a). Thus, after 500 generations of evolution, the Pareto front or the approximate Pareto front is obtained. Simultaneously, 1,708 Pareto optimal solutions satisfying the three objectives were obtained, which can serve as a foundation for decision-makers to select the most suitable option based on planning requirements, preferences, available funds, and other considerations.

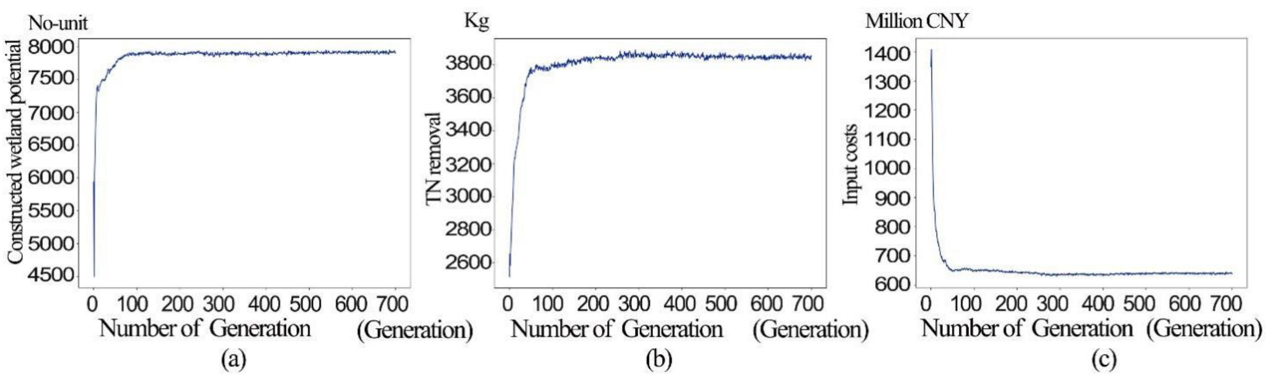

Fig. 5. (a) Constructed wetland potential varies with the number of generations; (b) TN mass removal varies with the number of generations; (c) Input costs vary with number of generations.

Fig. 6(a) shows the location of wetlands corresponding to the Pareto optimal solutions. This is the spatial distribution of 1,708 Pareto optimal solutions (Each Pareto optimal solution represents 84ha wetlands), where most of the Pareto optimal solutions correspond to most wetland locations that are similar or overlapped. More than 70% of the wetlands are in farmland areas near rivers, while others are in grassland near rivers. There are many wetlands located near the recycled water pipelines, which satisfies the purpose that some of the wetlands in the planned wetlands will be used to treat recycled water that does not reach water of IV standard. The wetlands in the Fig. 6(a) (1-3) area can avert the polluted stormwater runoff passing through farmland areas, preventing it from flowing into urban rivers. The wetlands in the Fig. 6(a) (4-7) area can treat the polluted stormwater runoff before it flows out of the city.

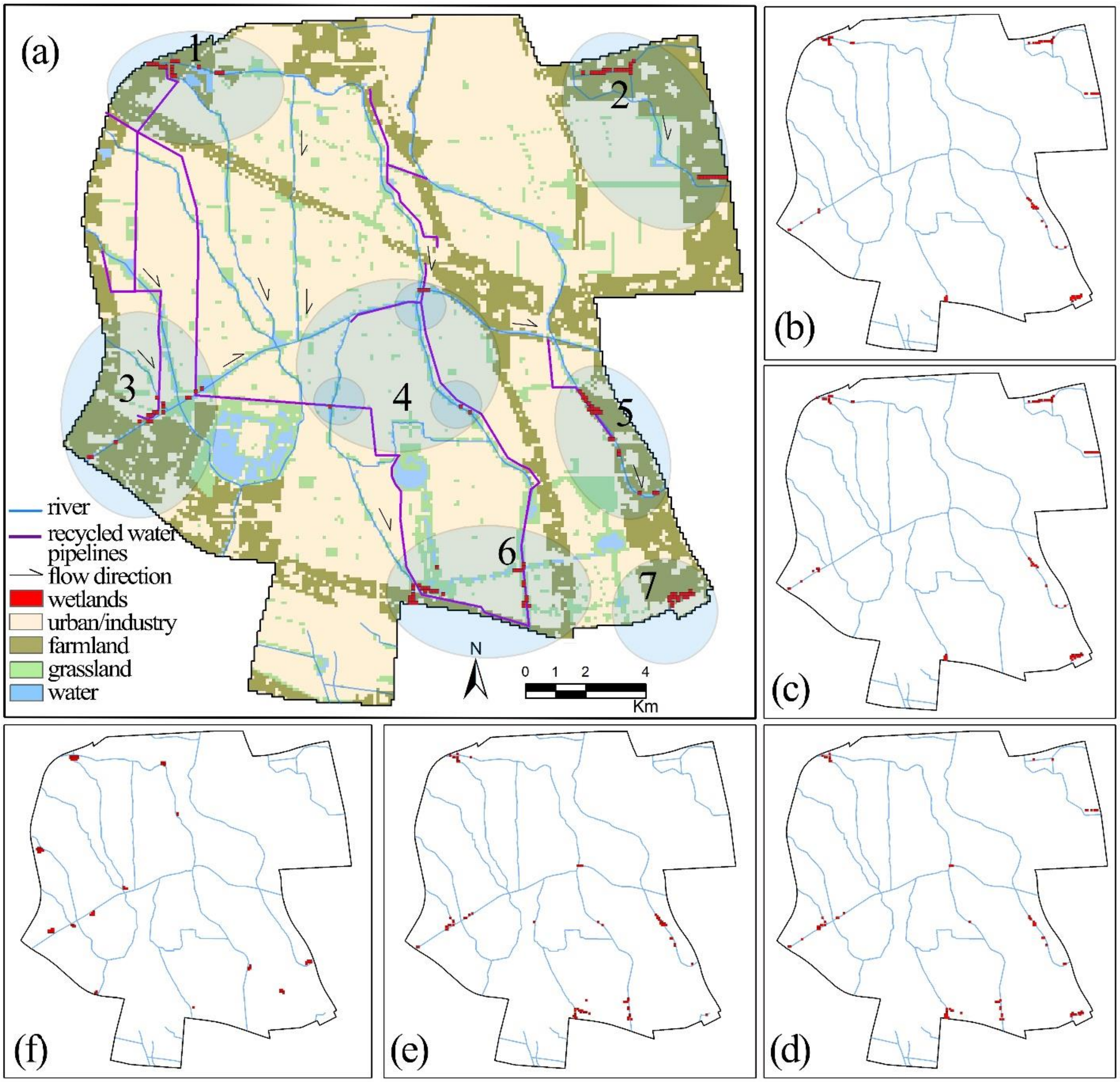

Fig. 6. (a) Wetland's location corresponding to the Pareto front; (b) Highest economic benefit scheme for constructed wetland potential (Constructed wetland potential / input costs); (c) Highest economic benefit scheme for pollutant removal (TN mass removal / input costs); (d) Best compromise of the three objectives; (e) Highest constructed wetland potential scheme; (f) Scheme of planned wetlands.

Fig. 7 shows the correlations between the two objectives. Fig. 7(a) shows the correlation between increased constructed wetland potential and increased input costs. If the input costs are high, this model will select the expensive grassland near the river with a higher constructed wetland potential as the wetland location. Fig. 7(b) reveals the connection between decreased TN mass removal and increasing input costs. If input costs fall, this model will choose less expensive farmland areas as wetland locations. However, as the TN load of this area is high, the TN mass removal will also be higher. Fig. 7(c) shows the trade-off between constructed wetland potential and TN removal. If the constructed wetland potential is higher, this model will choose the grassland with a low TN load near the river as wetlands.

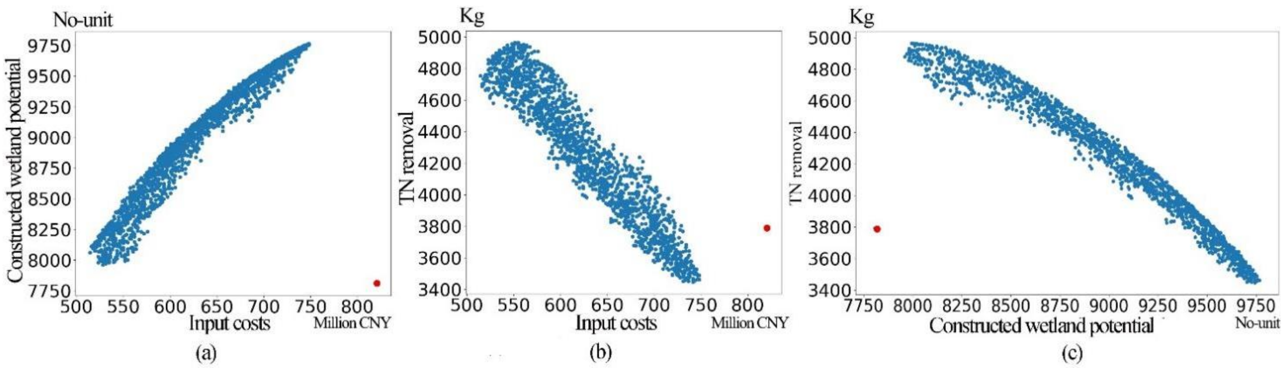

Fig. 7. Relations between (a) input costs and constructed wetland potential; (b) input costs and TN removal; (c) constructed wetland potential and TN removal. The red point represents the value of the planned wetlands scheme.

In this paper, the input costs were calculated by the cost of land prices, construction cost, and O&M cost. These calculations show more accuracy than calculating only the cost of land purchase(Singh et al., 2019), or construction cost and O&M cost (She et al., 2021; Yang & Best, 2015). The construction cost refers to the wetland construction cost of Sponge City in Beijing, which may lead to overestimation of the construction cost, as the material cost and labor cost in Shangqiu are lower than that in Beijing. The TN mass removal (4.1-5.9g/m²/year) is a little higher than the average Nr (reactive nitrogen) mass removal (4.4g/m²/year) of palustrine emergent (including constructed wetlands) in the United States (Jordan et al., 2011). This is because the TN removal in this study (before wetland construction) added the TN load (0.1-1.1g/m²/year) of the original land use (before the wetlands was set up) at the site of the wetlands. The wetlands after construction will collect more of the first flush through the pipeline, which may remove more TN mass. The wetlands selected by this model have a high constructed wetland potential, and all wetland locations are within 300m of water.

3.2 *Comparison of Pareto optimal solutions and planned wetlands*

Table 3 reveals the comparison of Pareto optimal solutions and planned wetlands. Compared with the planned wetlands, the Pareto optimal solutions have better benefits in the constructed wetland potential, which can increase to 1.9% ~ 25.1%; 82% of the Pareto optimal solutions, have high results in TN removal, and they can be increased to 30.8%; the input costs of the Pareto optimal solutions have superior benefits, and the input costs can be reduced by 8.9%-37.4%.

Table 3. Comparison of Pareto optimal solutions and planned wetlands.

Three objectives	Minimum	Maximum	Average	Planned wetlands	Increase rate

Constructed wetland potential	7,960	9,766	8,962	7,808	1.9% ~ 25.1%
TN mass removal (kg/ year)	3,447	4,964	4,248	3,794	-9.1% ~ 30.8%
Input costs (million CNY)	514	748	629	821	-37.4% ~ -8.9%

Fig. 7 and Fig. 8 shows relationship between the Pareto Front and the planned wetlands scheme. In comparison with the Pareto Front, the constructed wetland potential is lower than the minimum value of the Pareto Front, the TN mass removal is in the low-value area, and the input costs of the planned wetlands is much higher. Each scheme of the Pareto Front has a minimum of two objectives, better than the planned wetlands.

The TN mass removal of the 84ha wetlands were in the range of 3,447 to 4,964 kg/year, which falls short of meeting the surface water of IV standard. This deficiency arises because when only wetlands are employed to treat the majority of stormwater runoff (90%) from urban, the wetlands area must constitute at least 1-2% of the entire watershed (NRCS, 2001), whereas the wetlands area in this study accounted for merely 0.2% of the study area. Consequently, to a larger volume of stormwater runoff to be treated, the wetlands area or other stormwater management facilities needs to be expanded, such as rain garden, sunken green space, green roof, grass swale, detention pond, etc.(Yin et al., 2021).

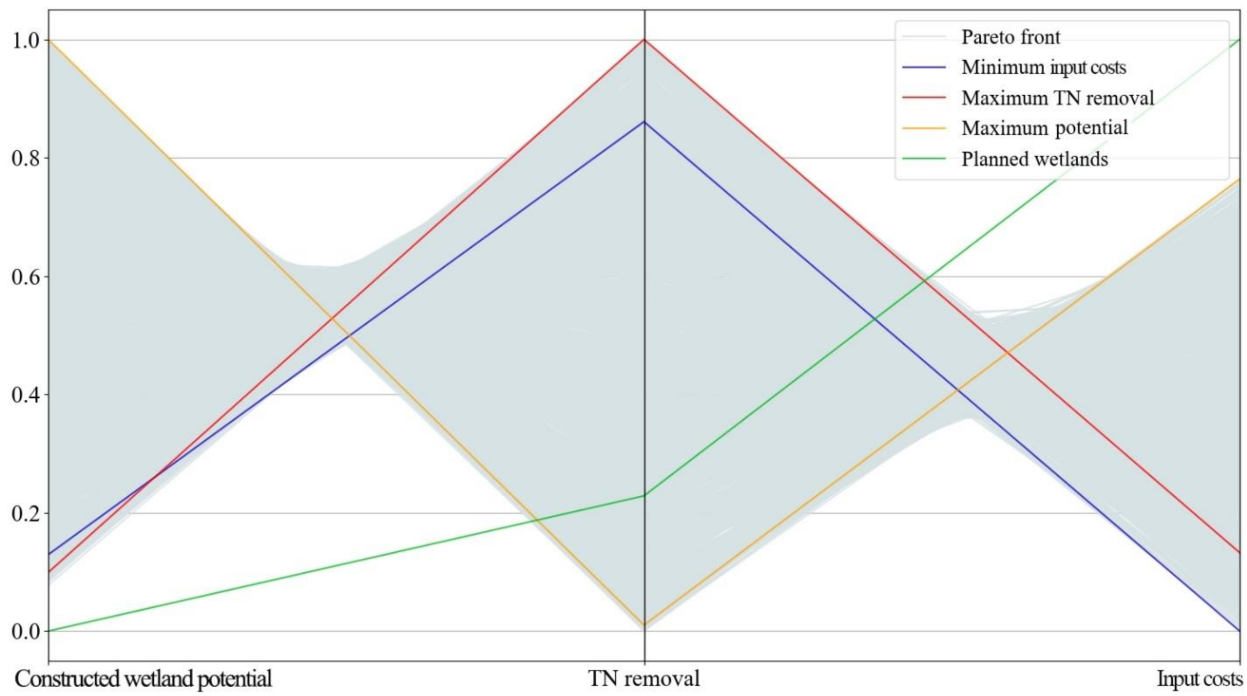

Fig. 8. Parallel coordinates of various wetland location schemes on the three targets. Pareto front: All Pareto optimal solutions; Minimum input costs: wetland site selection scheme of minimum input costs; Maximum TN removal: wetland site selection scheme of maximum TN removal; Maximum potential: wetland site selection scheme of maximum constructed wetland potential.

3.3 *Proposed wetlands optimization schemes*

Fig. 6(b-e) shows our four proposed wetland schemes. Fig. 6(b) shows the highest economic benefit scheme for constructed wetland potential, which allows for the highest constructed wetland potential with the minimum input costs. Fig. 6(c) shows highest economic benefit scheme for pollutant removal, which allows for maximum pollutant removal with minimum input cost. Fig.

6(d) shows the scheme that is the best compromise of the three objectives at a statistical level. Fig. 6(e) shows the scheme with the highest constructed wetland potential, which is also the closest one to the planned wetland. Most of the schemes with higher economic benefits are situated in agricultural fields. The scheme with best compromise between three objectives and the scheme with highest constructed wetland potential are more evenly distributed spatially and has more wetlands in the riverside greenbelt.

Table 4 shows the values of the proposed wetlands optimization schemes and the comparison of the proposed and the planned wetlands scheme. The four proposed wetlands optimization schemes are superior to the planned wetlands scheme. While the highest constructed wetland potential scheme has a smaller TN mass removal than the planned wetland, the other two objectives were better than the planned wetland. Compared to the planned wetland, the constructed wetland potential can be improved by 2.2% ~ 25.1%; TN mass removal can be improved by -8.8% ~28.0%; input costs can be reduced by 8.9% ~ 37.1%.

Table 4. Proposed wetland optimization schemes

Wetland location scheme	Constructed wetland potential(unitless)	TN mass removal (kg/ year)	input costs (million CNY)
Highest economic benefit scheme for constructed wetland potential	8,114	4,688	516
Highest economic benefit scheme for pollutant removal	7,979	4,855	523
Best compromise of the three objectives	9,139	4,237	684
Highest constructed wetland potential scheme	9,766	3,462	748
Planned wetlands scheme	7,808	3,794	821
Compare with the planned wetlands scheme	2.2% ~ 25.1%	-8.8% ~28.0%	-37.1% ~ -8.9%

Many wetland locations in the proposed schemes are comparable to the planned wetlands (Fig. 6(b-f)), providing evidence of the reliability of our model. Moreover, these schemes are further optimized at three objectives (constructed wetland potential, TN mass removal and input costs) compared to planned wetlands (Table 4). In the proposed wetlands optimization schemes, the nearby but disconnected wetlands can be combined with the surrounding planned green spaces to build urban wetland parks for leisure, entertainment, and purification functions.

The Pareto optimal solutions represent an optimal solution set, offering various options to meet the diverse needs of decision-makers. When facing budget constraints, we recommend decision-makers to prioritize schemes with higher economic efficiency (Fig. 6(b-c)). In cases where decision-makers have no specific preferences, the most appropriate scheme (Fig. 6(d)) can be selected through quantitative analysis methods (Taboada & Coit, 2007; Zheng et al., 2017). If wetlands are required to simultaneously perform purification functions, provide recreational spaces, and support educational functions, we suggest decision-makers choose the scheme with the highest constructed wetland potential (Fig. 6(e)). This is because a higher constructed wetland potential enables wetlands to better withstand disturbances from human activities. Additionally, some of the wetlands in the scheme with the highest constructed wetland potential are situated in riverside green spaces in urban centers, providing easy access for public activities. Apart from these four proposed schemes, decision-makers can also consider other schemes based on specific circumstances, such as schemes with the lowest input costs or the highest TN mass removal, among others. If decision-makers want to assign different weighted values to each objective or adjust the weighted value, they can also use the Pareto optimal solution set to obtain the optimal scheme through the weighted calculation of each objective. In a word, these Pareto optimal solutions can provide a theoretical basis for decision-makers, intuitively display the characteristics of each scheme, provide a variety of results for decision-makers, and meet the requirements of those who choose one, or parts, of the solution from the Pareto front according to their preferences or different situations(Ma et al., 2010; Wang & Tong, 2009).

4 Conclusions

In this paper, a multi-objective optimization model was developed for spatial optimization of wetlands and was applied to a case study in Shangqiu City. The model's aim was to effectively search for optimal wetland areas within the boundaries of the entire city by optimizing three objectives at the same time (maximizing constructed wetland potential, maximizing the TN mass removal and minimizing input costs). The results of this study verified that, even if there is no pre-selected potential wetland in the city, the model can also select an effective wetland site (Pareto optimal solutions). With the four proposed wetland schemes, the constructed wetland potential and TN removal can be greatly improved (2% ~ 25%; − 9% ~ 28%, respectively) and the cost can be greatly reduced (9% ~ 37%) compared to the planned wetlands. Furthermore, this model can provide decision-makers with a variety of optimal alternatives for wetland planning even when considering multiple objectives with trade-offs. By analyzing the correlations between the objectives, this model can provide decision-makers with an objective, quantitative, and visual basis for wetland site selection.

By applying a heuristic multi-objective optimization algorithm, NSGA-II, the model developed in this study, optimizes the multiple benefits of wetlands simultaneously as well as improving the efficiency of urban land use by evaluating the suitability of wetland restoration. This model can be expanded to be used for different cities of all spatial scales, given the data availability, while the objective setting (total wetlands area to be selected), constraints and objectives (maximizing flood reduction, improvement of urban thermal environment and urban ecological axis connection) can be adjusted according to various planning regulations and decision-maker preferences.

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