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Optimization of urban green space system planning in the context of rapid urban expansion

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SUMMARY: *The function of urban green spaces within the urban ecosystem should not be underestimated; therefore, optimizing the urban green space planning system is of great importance. In this research, City S was chosen as the representative study area; the urban green space network structure was developed according to the "four belts, three rings, seven wedges, and network linkages" model. By employing CFD simulation technology together with RS and GIS methods, the relationships and variation trends of wind speed, SO_2 concentration, and temperature were examined comprehensively, thereby confirming the effectiveness of the optimization scheme. Based on the analytical findings, numerical simulation errors for wind speed, SO_2 concentration and temperature are relatively small, satisfying the demands for simulation accuracy at the urban scale. The optimized urban ventilation environment is good, with the SO_2 concentration being in the range from 0–0.05169 mg/m³. Meanwhile, the urban heat island has been effectively controlled. Therefore, the proposed method in this paper can provide better optimization suggestions for urban green space system planning.*

KEYWORDS: *GIS; RS; CFD; numerical simulation; green space system planning*

1 Introduction

Urbanization can be defined as the transformation of the rural population into an urban one, involving all changes that accompany this phenomenon [1]. Given the fact that China is the largest populated country in Asia and the entire world, its rapid urbanization cannot be overlooked. It has been shown by the National Economic and Social Development Statistical Bulletin, issued by the National Bureau of Statistics, that the urbanization rate in China has increased dramatically from 10.64% at the establishment of the People's Republic to over 50% by the year 2011 [2]. According to Morgan Stanley's report "China Urbanization 2.0: Super Urban Agglomerations," China's urbanization rate is projected to reach 75% by 2030[3]. While urbanization meets market demands, creates substantial employment opportunities, significantly boosts national economic development, and elevates urban residents' living standards[4], rapid urban expansion essentially represents an extensive growth model characterized by outward sprawl. However, this happens often through environmental degradation that leads to rapid population growth, urban expansion, changes in land use, and reduction in the number of green spaces within urban settings [5-7]. The current scenario has led to the deterioration of urban environments caused by the effects of water and air pollution, increased urban heat island effect, accelerated land desertification, and more frequent occurrences of natural disasters like heat waves, drought, and downpour in urban areas [8-11].

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Such environmental problems that occur as the result of urbanization make it difficult for Chinese cities to develop sustainably both economically and socially, adversely affecting people's daily lives and even their physical and psychological well-being. In light of this, it is important to encourage urbanization and ecological development.

The presence of green spaces plays a critical role in urban ecosystems that can be applied in addressing the link between urbanization and ecological environments [12]. Early studies in the 20th century by Kang and Ruston found a positive relationship between sulfur content in the atmosphere and sulfur levels in plants, which stimulated the academic community to study the ecology of vegetation [13]. Many experts emphasized that green spaces help to control the balance of temperature and humidity, support the process of oxygen emission and carbon dioxide retention, and participate in purifying the air by means of plant evaporation, absorption, and adsorption of pollutants and reflection of sunlight [14-17]. Such ecological impacts help to reduce the environmental contamination of cities, reducing the urban heat island effect, and enhancing the living standards of residents [18].

In terms of green space system planning, the development of green spaces in China's urban areas has become increasingly functional and symbolic as a significant strategy for improving the environment and quality of life in urban settings. However, the common approach to green space system planning within contemporary cities in China is the "fill in the blank" approach [19-21]. In other words, it does not take into account the ecological impact and the benefits of green spaces. Apart from being inefficient in terms of making full use of the ecological role of green spaces, this approach cannot provide precise estimations of the optimal density of green spaces within urban districts [22]. Moreover, green space system planning is always subordinated to general planning, and the main aim of such planning is to fulfill quantitative requirements for green space coverages [23]. What planners care about is fulfilling quantitative goals, striving to increase the area of green space while neglecting real people's demands while addressing urban environmental problems [24].

Due to rapid urbanization, the development of these cities has caused the rise of various environmental challenges such as urban heat islands, air pollution, and water pollution. Among the problems, urban heat islands and air pollution stand out as the most evident examples of environmental concerns caused by imbalance in the urban ecosystems, making them two significant focal points for researchers nationally and internationally [25].

Numerous foreign and local studies have revealed that when cities grow in size, there is also a shift in the characteristics of surface cover in cities. Moreover, population growth causes a marked rise in the emissions of carbon as well as energy consumption. This creates a domino effect and leads to an increase in the urban heat island phenomenon [26, 27]. In their research on spatial and temporal patterns, as well as the correlation between daily mean temperature variations and changes in land use and population numbers, over a period of ten years, Mohan and Kandya [28] investigated the city of New Delhi, India. They found that the changes in land use, especially in terms of dominance in urban development (above 50% in land), as well as the quick rate of population increase, have negatively affected the thermal environment of the city. Zhao et al. [29] studied the relationship between urban growth and urban heat islands in Shanghai, China, during the period from 1984 to 2014. According to their research, rapid urban growth intensified the heat island effect; however, a compact urban structure (a compact city with a compactness ratio of less than 0.15) could contribute to decreasing the heat island effect. In their research, Al-Marzooqi et al. [30] explored the relationship between urban growth and urban heat islands in Doha, Qatar. According to their research, there was a strong relationship between the strength of the urban heat island effect and urban growth intensity. Additionally, the researchers offered some strategies for mitigating the effects of the discussed phenomena.

In their research, Qiao et al. [31] examined the relationship between Beijing's urban growth and urban heat islands during the period from 1989 to 2010. Their findings indicated that urban growth patterns like compactness and green space areas could have a significant impact on urban heat islands, meaning that efficient urban planning could reduce negative effects of the phenomena under investigation. In the research carried out by Li et al. [32], a study of the urban heat island effect intensity in Zhengzhou, China, in the past 39 years was performed. It was found that the warming in Zhengzhou is twice as high as the mean warming around the globe, and there is a high level of positive correlation between indicators of urbanization and heat island effect intensity. The relationship between the morphology of urban areas and the heat island effect in China was studied in Kong [33].

Apart from the heat island effect, fast urbanization is often associated with considerable issues related to air pollution. Research into urban expansion and air pollution conducted by domestic and international scholars is usually concentrated on analyzing the influence of urban shape and form, land use pattern, urban population, and urban transport on air pollution [34]. According to Acharya [35]], the need for economic development has led to the occurrence of haphazard urban expansion, thereby contributing greatly to the degradation of air quality. At the same time, fast urban growth has become responsible for environmental degradation, higher risk of natural disasters, and social inequalities due to inadequate regulations and lack of urban green areas. Zhou et al. [36] analyzed the influence of urban form on air pollution in China's five fastest-growing megacities, namely Beijing, Tianjin, Guangzhou, Chongqing, and Shanghai during the period between 2000 and 2012. The results obtained demonstrated that urban expansion contributed to the reduction of air pollution, whereas previous academic research proved the opposite. Spatial implications of urban growth on air pollution and ecological efficiency in Chinese cities (2008-2018) were assessed by Zhang et al. [37]. The authors revealed a complex impact of urbanization on the selected parameters. They found that moderate urbanization positively impacts air pollution and ecological efficiency, while excessive urbanization worsens the environmental situation in the area. Tao et al. examined the influence of urban expansion on local air quality conditions. [38], who discovered that rapid urbanization in eastern China has made irreversible damage to local air quality and could further affect pollution unless emissions would be effectively controlled. Larkin et al. [39] investigated the connection between urban characteristics and levels of air pollution in East Asia (2000-2010).

Along with growing national attention towards environmental issues, studies on urban green spaces have made remarkable progress. The theoretical basis of research in this area has been further enriched, with abundant and profound theoretical applications, especially in ecology. This offers ample support and scientific guidance for the urban green space system plan. For example, Zhu et al. [40] applied the theory of landscape ecology to construct an optimization scheme for landscape ecological planning in urban green space systems, attempting to resolve environmental problems brought about by rapid urbanization in China. Additionally, Hwang et al. [41] have developed a multi-objective decision support model for optimizing urban green space planning systems. The model takes into account multiple constraints, including carbon fixation, ecological linkage, and cost constraints. Through reasonable compromise of different objectives, it helps to ensure sustainable development of urban environment. Li et al. [42] developed an approach for spatial optimization in urban green space planning considering spatial equity and conversion costs. The proposed approach reduces the total conversion cost while satisfying both per capita needs for urban green spaces as well as the needs of spatial equity, providing extensive applicability prospects. The authors Pribadi and Xu [43] established a mathematical optimization model of urban green space planning system for identifying optimal spatial configuration maximizing the possibility of provisioning multiple types of

ecosystem services. This ensures the capability of the proposed green infrastructure to satisfy the need for a better quality life by the residents of urban areas. The authors Dhote, M and Khurana [44] proposed a mathematical model considering six major parameters such as fragmentation, biodiversity, natural condition, pollution, air quality, hydrology, and noise levels.

To better understand the optimization process for urban green space planning in the context of rapid urbanization, this study analyzes the properties of the urban green space green space system in S City from the perspective of diversity, dominance, evenness, isolation, and fragmentation using remote sensing and GIS in central urban areas. Through the analysis, an optimal "four belt, three ring, seven wedge, and network connection" plan is generated for urban green space planning with both centralized and decentralized methods. CFD simulation technique is employed to numerically simulate urban wind speeds, pollution concentration, and temperature under optimized urban green space planning.

2 Theoretical Foundations of Urban Green Space System Planning

The planning scheme of the city's green space system will basically fall into place following the initiative of the city's overall master plan. Through the identification of the places and areas of the various green spaces, a scientific and systematic green space system is generated which suits the developmental objectives of the city and offers functional green spaces to meet its ecological and recreational needs. Generally, the urban green space system can be divided into two broad types – specialized planning and thematic planning. Alongside the emergence of the modern territorial spatial planning system, it is important to have an active response to the requirements of the system, position correctly and transform effectively the function of green space planning. From a systematic standpoint, the scope of "specialized planning" must be broadened to cover the planning of ancient and famous trees, road greening, and disaster-proofing green spaces. This would be very important in coming up with green space planning that is "feasible and functional."

In recent times, rapid urban development and urban expansion in China have brought about a sudden change in urban land use and natural resources, thus causing significant effects on the ecological environment of the city. An urban green space can be described as a form of urban space that encompasses vegetation. These spaces have historically fulfilled important ecological, recreational, landscaping, and protective roles. With the rapid urbanization process taking place, urban green spaces are encroached upon by construction lands and passively adapted to the development pressure, which contradicts the natural law and brings harm to the regional ecological pattern. Green space ecological network can be seen as a unified spatial network established based on the natural law connecting scattered green space. Through such a unified spatial structure, the flow of energy and species is increased, thus making it possible to stabilize the spatial structure of ecosystems and reduce the danger imposed by green spaces to biodiversity and ecosystems. Green ecological networks are important in stabilizing urban ecological structures.

3 Research Methods

3.1 CFD-Based Simulation Method for Urban Atmospheric Environmental Effects

Urban green spaces play a very critical role in ensuring improvements within the urban

environment. Well-planned urban green spaces can help in combating the urban heat island effect. In addition, urban green spaces absorb pollutants and help in cooling and moisturizing the atmosphere while cleansing it as well. With increased urbanization and the resulting construction of huge buildings as well as an increase in urban population levels, the levels of natural environments and urban green spaces have continuously decreased. Studies on the atmospheric environmental effects of urban green space patterns have both academic and practical significance. The latter includes regional air quality problems and urban green space planning quantification. In terms of the planning approach, numerical simulations study the atmospheric environmental effects of various urban green space planning patterns. In this respect, the spatial configuration and functional design of the green space will be determined. Currently, a number of researchers across the globe have made use of computational fluid dynamics (CFD) technology in the numerical simulation of the impact of urban atmospheric environment on urban planning. However, the research literature on the use of CFD technology in the numerical simulation of the impact of green landscape pattern on urban atmosphere environment is quite scanty. The paper employs the use of the CFD numerical simulation technology to construct the spatial diffusion models of urban wind speed, SO_2 mass concentration, and surface temperature under various green landscape spatial configurations. It also analyzes the existing problems in the current green spaces and evaluates some green spaces optimization designs.

Computational fluid dynamics (CFD) is one of the branches of fluid mechanics which involves the use of the computer to conduct numerical experiments and simulations on fluid mechanics problems. That is say, the fundamental idea of CFD technique is to solve practical problems through numerical solution of the equation that governs fluid motion in order to obtain discrete distribution of fluid field. In urban thermal environment research, establishing a three-dimensional mathematical model of a specific area and employing CFD technology to numerically calculate its airflow organization enables the intuitive visualization of temperature and velocity fields formed by regional airflow. Based on provided reasonable boundary conditions and parameter settings, the feasibility and rationality of the results can be analyzed and studied, continuously optimizing design solutions. However, CFD technology faces challenges in urban-scale research, including difficulty in parameter setting and verification. This study employs parameters and results from remote sensing technology to refine the parameter settings of CFD models [45].

The air movement in the natural world is mostly characterized by turbulence. The kinetic energy in turbulent pulsation consists of two forms of energy; one form of energy is due to turbulence, while the other is attributed to shear stress. The governing equations for the compressible turbulent mean flow are as follows (for convenience, except for the time-averaged values of pulsations, the overbar "—" denoting time-averaging is omitted in the following equations, e.g., $\overline{\varphi}$ is represented as φ):

Continuity equation:

$$\frac{\partial \rho}{\partial t} + div(\rho U) = 0 \tag{1}$$

Momentum Equation:

$$\frac{\partial(\rho u)}{\partial t} + div(\rho u U) = div(\mu \, grad u) - \frac{\partial p}{\partial x} + [-\frac{\partial(\rho u'^2)}{\partial x} - \frac{\partial(\rho u' v')}{\partial y} - \frac{\partial(\rho u' w')}{\partial z}] + S_u \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+div(\rho vU)=div(\mu gradv)-\frac{\partial p}{\partial y}+[-\frac{\partial(\rho\overline{u'v'})}{\partial x}-\frac{\partial(\rho\overline{v^2})}{\partial y}-\frac{\partial(\rho\overline{v'w'})}{\partial z}]+S_v \quad (3)$$

$$\frac{\partial(\rho w)}{\partial t}+div(\rho wU)=div(\mu gradw)-\frac{\partial p}{\partial z}+[-\frac{\partial(\rho\overline{u'\varphi'})}{\partial x}-\frac{\partial(\rho\overline{v'\varphi'})}{\partial y}-\frac{\partial(\rho\overline{w'\varphi'})}{\partial z}]+S_w \quad (4)$$

Other transport equations for variables:

$$\frac{\partial(\rho\varphi)}{\partial t}+div(\rho U\varphi)=div(\Gamma grad\varphi)+[-\frac{\partial(\rho\overline{u'\varphi'})}{\partial x}-\frac{\partial(\rho\overline{v'\varphi'})}{\partial y}-\frac{\partial(\rho\overline{w'\varphi'})}{\partial z}]+S \quad (5)$$

In the equation, ρ represents the density of the atmosphere. t denotes time. U is the velocity vector. u,v,w is the component of U in the direction of x,y,z. P represents the pressure on the atmospheric element. S_u, S_v and S_w are the volumetric forces acting on the element. φ' is a universal variable. Γ is the generalized diffusion coefficient. S is the generalized source term.

The standard k-ε model is:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \quad (6)$$

$$\frac{\partial}{\partial x_j}[\rho u_j k-(\mu+\frac{\mu_t}{\delta_k})\frac{\partial k}{\partial x_j}]=\rho(P_k-\varepsilon) \quad (7)$$

$$\frac{\partial}{\partial x_j}[pu_j\varepsilon-(\mu+\frac{\mu_t}{\delta_\varepsilon})\frac{\partial\varepsilon}{\partial x_j}]=\rho\frac{\varepsilon}{k}(C_1P_k-C_2\varepsilon) \quad (8)$$

$$P_k=\frac{\mu_t}{\rho}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i})\frac{\partial u_i}{\partial x_j} \quad (9)$$

In the equation, μ_t represents the eddy viscosity coefficient; P_k denotes the turbulent kinetic energy production term. $C_\mu=0.09$. $\delta_k=1-0$. $C_1=1-44$. $\delta_s=1-3$. $C_2=1-92$.

3.2 Image Interpretation and Data Extraction

Extracting green space systems can be achieved through various methods, but for high-resolution GeoEye imagery, an object-oriented classification approach proves highly efficient. With Erdas software support, preprocessing steps for GeoEye imagery include orthorectification, data fusion, mosaicking, and color balancing. The preprocessed imagery was then subjected to object-oriented classification using eCognition software. This involved multi-scale image segmentation and segmentation-based classification, combined with fuzzy classification employing membership degrees. This approach fully leveraged spectral and spatial information for automated image classification, enabling rapid computer-aided extraction of urban green space data.

Following computer-automated classification, thematic information on the green space system was obtained. The further classification of the green areas within the city was done by looking at planning papers, basic geography data, and information from the landscaping bureau. Categorization of the data was done using the green space system criteria. This study classified green spaces in the study area as parks, production green spaces, protective green spaces, etc., based on urban green space classification standards and the actual characteristics of the study area [46]. The technical workflow for extracting urban green space coverage information is illustrated in Figure 1.

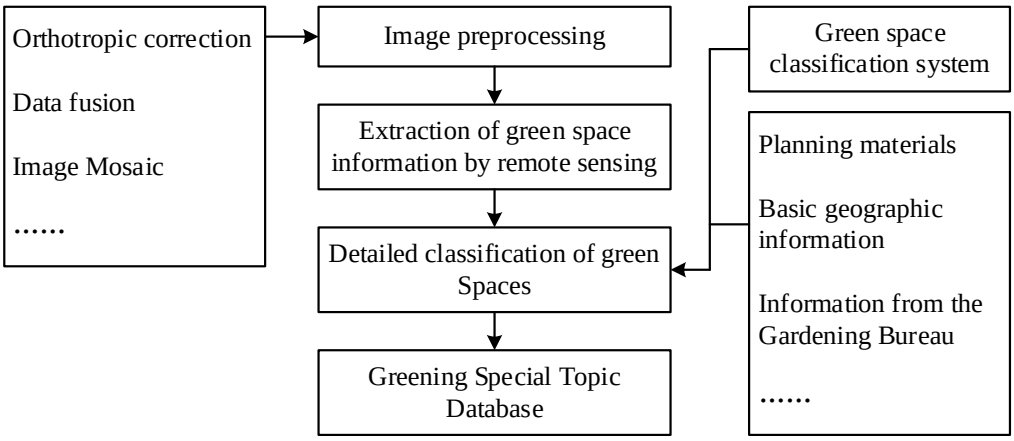


Figure 1: Flowchart of green space coverage information extraction technology

3.3 Methodology for Analyzing Green Space Landscape Patterns

This study, grounded in landscape ecology theory, addresses the characteristics of green space landscapes within urban built-up areas and the requirements for ecological planning and construction of such landscapes. The following indicators were selected to analyze the green space system within the built-up area:

1) Green space landscape composition analysis. Landscape composition examines the constituent elements of a landscape, including the number of landscape types, the quantity of patches, landscape area, and proportion.

2) Diversity Index. This index reflects the number of landscape types and their respective proportions. A higher diversity index indicates greater green space landscape diversity. Its calculation formula is as follows:

$$H = -\sum_{i=1}^{n} P_i \log_2 P_i \tag{10}$$

H is the diversity index. P_i indicates the ratio between the number of occurrences for the i-th type of green landscape and the total number of green landscapes. n is the total number of green landscape types.

3) Dominance Index. The dominance index reflects the dominating feature(s) of landscape. Its calculation formula is as follows:

$$D = H_{\max} + \sum_{i=1}^{n} P_i \log_2 P_i \tag{11}$$

$$H_{\max} = \log_2 n \tag{12}$$

where D is the dominance coefficient, P_i is the percentage of the i-th green landscape type to the sum of all landscape types, n is the total amount of green landscape types, $H_{\max}$ is the maximum value of the diversity index. The higher value of D shows that only one or several landscape types dominate the whole landscape system. A lower value suggests greater landscape homogeneity. A D value of 0 indicates complete landscape homogeneity.

4) Evenness Index. Evenness describes the uniformity of distribution among landscape types within a landscape. A higher value indicates more balanced distribution of landscape components:

$$E = (H / H_{\max}) \times 100\%, H = -\log_2 \sum_{i=1}^{n} P_i^2 \tag{13}$$

$$H_{\max} = \log_2 n \tag{14}$$

where E is the uniformity coefficient, H is the modified diversity index, $H_{\max}$ is the maximum value of the diversity index. The closer E is to 1, the closer the uniformity of the landscape patches distribution to its maximum.

5) Separation coefficient. The separation of landscapes means the isolation of their individual components inside the landscape type. A higher separation index indicates greater spatial dispersion of the landscape. Its calculation formula is:

$$F_i = D_i / S_i, S_i = A_i / A, D_i = 0.5\sqrt{n / A} \tag{15}$$

In the formula, F_i represents the separation degree of landscape type i. n denotes the number of elements within landscape type i. A_i indicates the total area of landscape i. A signifies the total landscape area of the study region.

6) Fragmentation Index. The fragmentation index represents how much fragmentation occurs in the landscape, thus representing the extent of human interference. Higher fragmentation indicates greater disturbance. The more fragmented the landscape and the smaller the green patch units, the more limited the functional capacity of these green landscape units. Its calculation formula is:

$$C_i = n_i / A_i \tag{16}$$

In the formula, C_i represents the fragmentation index of landscape type i; n_i denotes the number of patches in landscape i; A_i indicates the total area of landscape i [47].

4 Overview of the Study Area and Data Processing

City S lies in the southwestern part of the Sichuan Basin, between 102°55′08″ and 104°14′52″ east longitude and 28°24′57″ and 29°56′14″ north latitude. The map of City S is shown in Figure 2. This study utilizes the S City central urban planning map and the GlobeLand30 global land cover data sourced from the National Geographic Information Resource Catalog Service

Platform as foundational datasets. In accordance with the Ministry of Construction's "Urban Green Space Classification Standards," a spatial geographic database for S City's park green spaces was established. Spatial statistical analysis functions of RS and GIS were employed to calculate and compute various indicators of the green space system, performing image processing and data statistics to generate a thematic map depicting the distribution of green spaces in the central urban district of City S. Subsequently, corresponding pattern indices were calculated. According to the latest Urban Green Space Classification Standards promulgated by the Ministry of Construction, urban green spaces are functionally grouped into five major categories: park green space, protective green space, square land, supporting green space, and regional green space. In this study, the main concern is the landscape configuration of urban green space. Accordingly, the zoning analysis is conducted at the macro scale, without addressing how different categories of urban green space affect spatial pattern formation. For classification of urban green space in the main city area, land use classification standards of S City master plan have been considered.

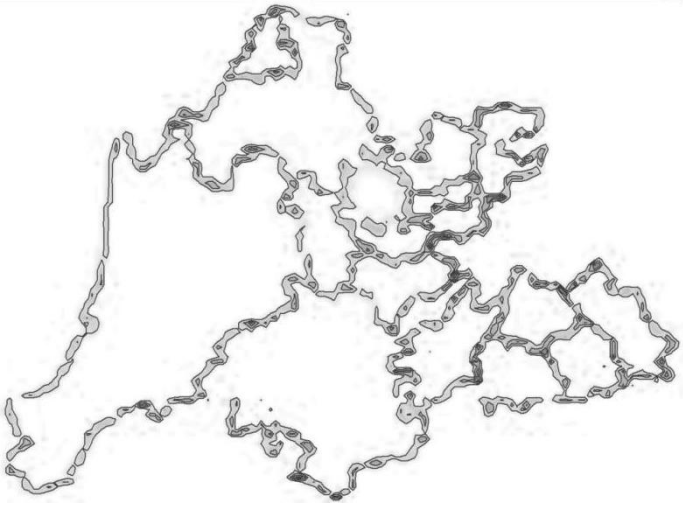


Figure 2: Map of S city

From the calculation and analysis of the central urban planning map of S City, the data on the spatial distribution of green patches in the study region were acquired. From Table 1, it can be observed that the total green patch coverage in City S amounts to 11,096.75 hectares. Ecological green patches make up the largest portion, accounting for 84.55%, while all other types of patches are lower in numbers. This is attributed to the fact that at present, the overall framework for urban planning not only consists of urban ecological green patches but also encompasses urban-related green patches and vast forests. The green spaces of parks rank second on the scale of landscape types (13.81%), coinciding with planning aims. The least amount of land is taken up by the protective green spaces (1.64%). As regards patch numbers, park green spaces show the highest number of patches but not necessarily the greatest area. This is explained by the fact that while city parks have large planned areas, other park green spaces have many patches scattered throughout without any coherence and thus do not represent an integral whole. Additionally, the 36 hm^2 Jiazhou Green Heart (park) in the central urban district was included within the ecological green space category during planning. Although ecological green spaces have the largest area, they have relatively fewer patches. This is primarily because the southern and eastern parts of the central urban district, along with the northwestern part of the Shawan District, contain large contiguous ecological wetlands and forested grasslands. Protective green spaces have the fewest landscape patches and the smallest green space area.

Table 1: The urban green landscape of the central urban area is composed

Landscape type	The number of green patches/per	The percentage of total plaques/(%)	Green space area/hm^2	The percentage of the total green space (%)
Park green	812	60.51%	1532.24	13.81%
Ecological green space	480	35.77%	9382.30	84.55%
Protective green space	50	3.73%	182.21	1.64%
Total	1342	100	11096.75	100

Referencing the classification standards for green patches adopted by most domestic scholars and based on the landscape characteristics of urban green spaces in City S, this study categorizes patch sizes into four scale levels: small patches (≤1 hm²), medium patches (1–10 hm²), large patches (10–50 hm²), and extra-large patches (≥50 hm²). As shown in Table 2, small and medium-sized patches account for only 19.95% of the total area but constitute 80.05% of the total number of patches. These are primarily distributed along roadways and within residential areas, exhibiting widespread distribution and close relevance to residents' daily lives. Large patches accounted for nearly one-third of urban green space area, representing 12.07% of the total number of patches. These primarily comprised riverfront parklands within cities, as well as extensive nature reserves and wetland conservation areas. Extra-large green patches had the largest area proportion but the smallest number, predominantly located in suburban areas. Their land use types were mainly contiguous agricultural land and forested mountain areas.

Table 2: Urban green space classification type

Plaque type	Patch area/hm^2	That's over /(%)	Patch quantity /Per	That's over /(%)
Plaques	260.14	2.34%	512	38.15%
Medium patch	1953.89	17.61%	622	46.35%
Large plaque	3567.93	32.15%	162	12.07%
More large plaques	5314.79	47.90%	46	3.43%
Total	11096.75		1342	
Bridge area	7.2784	0.4362	0.4015	91.0322

5 Analysis of Numerical Simulation Results

5.1 Urban Green Space Landscape Optimization Design Plan

In this study, validation data primarily consists of various monitoring records. Validation points are mainly distributed across residential areas, industrial zones, parks and green spaces, commercial districts, and cultural areas within the Third Ring Road of City S. A total of 30 monitoring points were selected to validate the model simulation results.

The numerical simulation of wind speed, SO_2 concentration, and temperature exhibits relatively small relative errors compared to measured values, meeting the accuracy requirements for urban-scale numerical simulations. Hence, the CFD can be considered a feasible technique in simulating the impact of the atmosphere environment. Factors including meteorological conditions (wind velocity, air temperature, relative humidity, sun radiation), the arrangement of urban environment components in space, building density, FAR, population density, green space proportion, and the topography of the region all play a certain role in

influencing the effect of the urban atmosphere environment.

In the current research, the principles of landscape ecology together with relevant theories of ecological planning are combined with the processes of urban development for the best possible planning of green spaces in City S. Centralization and decentralization are combined to provide a spatial structure of the green network of the city known as “four belts, three rings, seven wedges, and network connections.”

5.2 Simulation Analysis of Urban Wind Velocity Fields at Different Heights

Figure 3 presents the simulation outcomes. The bottom wind field at 10m height is significantly affected by buildings. In comparison to the bottom wind field at 1.5m height, an increase in wind speeds from 2.625 to 3m/s is noticeable, with the area ratio increasing from around 30% to 60%. In the middle wind fields, i.e., 30m and 50m, there is also a noticeable rise in maximum urban wind speeds, with the area ratio increasing from roughly 65% to 75%. Finally, in the top wind field at 100m height, the area ratio for maximum urban wind speeds rises to about 80%.

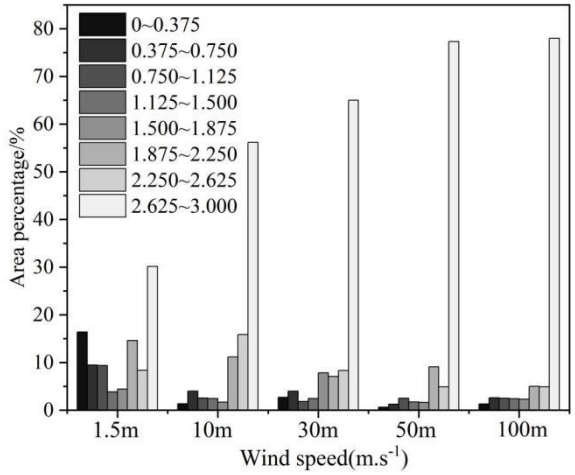


Figure 3: Different height city wind speed simulation analysis

As depicted in Fig. 4 below, the outcome from the dispersion of SO_2 concentrations in urban areas in various vertical heights is presented. It is obvious from the figure above that as the height of elevation rises in the cities, there is a decrease in the concentration of SO_2. Furthermore, due to the urban wind speed, there will be an increase in the spatial diffusion ability of SO_2, resulting in an improved urban environment. For the lower concentration layer up to 1.5 m high, the spatial diffusion capability of the pollutants increases but the concentrations remain comparatively low. Only point source pollution occurs in Tiexi, Dadong, and Huanggu districts, but the pollutants diffuse towards the outskirts of the cities. Most SO_2 concentration values fall within the range of 0 to 0.05169 mg/m³.

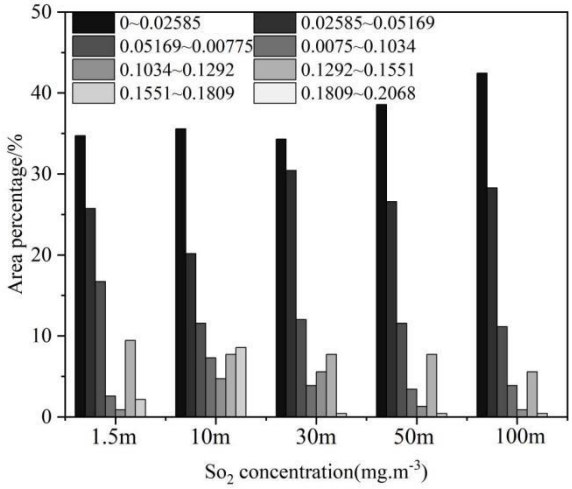
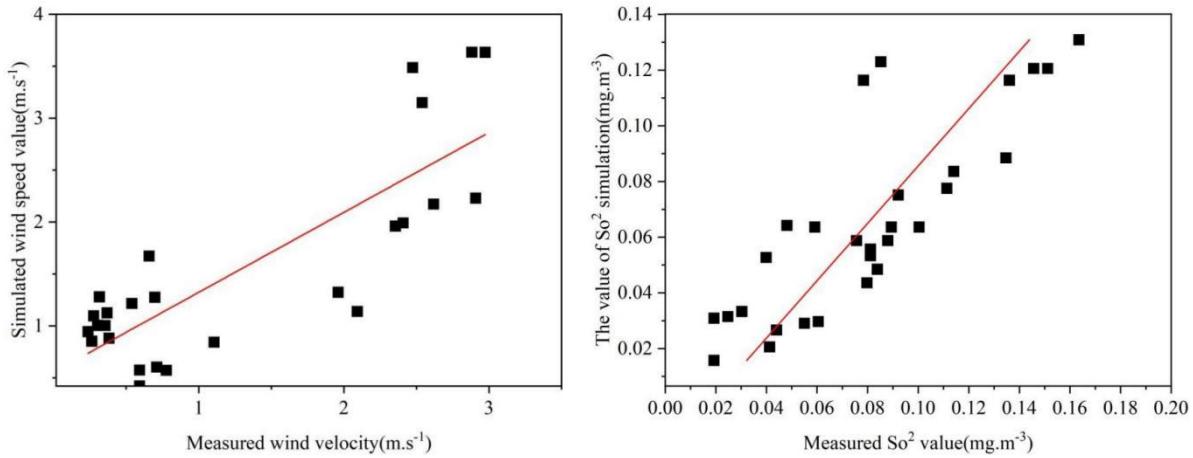


Figure 4: SO_2 concentration field space diffusion simulation analysis

5.3 CFD Simulation Results Verification

The trend between simulations and measurements is displayed in Figure 5 below. Several domestic and foreign researchers have confirmed the precision of results from CFD numerical simulations. In this case, validation mostly focused on using different validation points from monitoring stations. These validation points were located in residential zones, industrial zones, parks and gardens, business centers, and cultural zones inside the Third Ring Road of City S. Thirty validation points were used to validate the simulation outcomes. It was found that simulations for wind speed, SO_2 concentration, and temperature showed smaller relative errors compared to the measured values. As a result, it can be considered feasible to use CFD for simulating atmospheric environment impacts.

The findings derived from the CFD-based simulation of the atmospheric conditions under the urban greening plan indicate that the plan can facilitate the movement of cooler air from suburban areas toward urban high-temperature zones, thereby helping to alleviate the urban heat island effect. Additionally, areas with high SO_2 concentrations continuously diffuse outward under the influence of prevailing urban winds, gradually decreasing in concentration. Furthermore, the maximum concentration values correspondingly decrease with increasing altitude. The optimized urban green space system demonstrates significant potential for improving urban atmospheric conditions, to solve such a problem. Hence, we can apply quantitative analysis method while preparing for the plan based on the result of the simulation. This approach facilitates the formation of a systematic urban green ecological network, maximizing the ecological efficacy of green spaces.



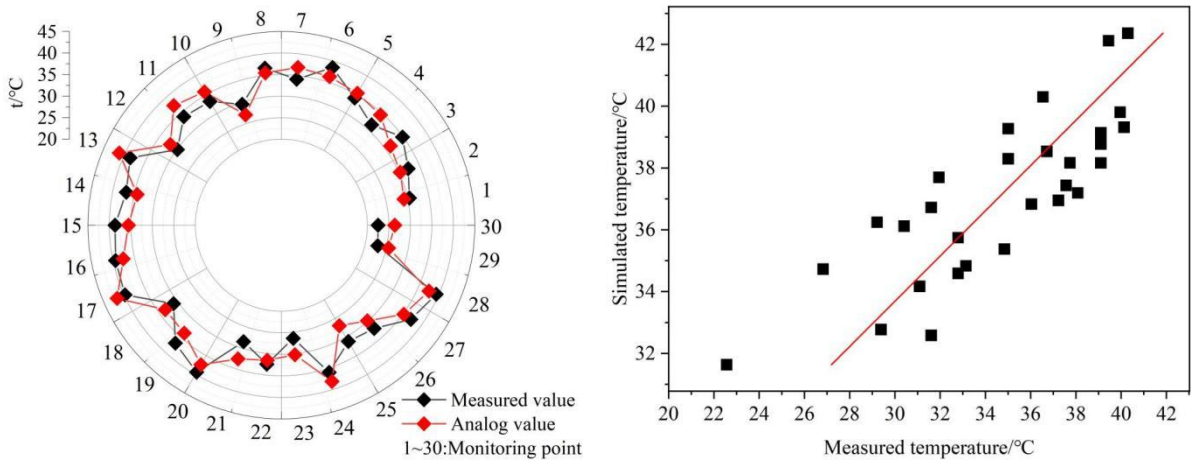
(a) CFD simulation results verify

(b)The contrast trend between temperature simulation and measured value

Figure 5: CFD simulation results verify

5.4 Optimization Strategies for Urban Green Space Landscape Planning

The outcomes of the CFD simulation conducted for the urban green space optimization scheme are presented in Figure 6. As indicated by the foregoing figure, the optimized urban zones align with the ventilation corridors identified in the CFD simulation. The analysis suggests that the optimized urban green space configuration is reasonable, as it can promote the flow of cool air from suburban areas into the urban area and mitigate the urban heat island effect. Additionally, it is apparent that zones with high concentrations of SO_2 continuously diffuse due to prevailing urban winds, reducing their concentration. The maximum concentration values also diminish as altitude increases. The optimized urban green space design holds great promise in improving the urban atmosphere and is, therefore, rational. In green space design, one can adopt quantitative analysis methods using the results obtained in the optimization numerical simulations. This will assist in creating an urban green ecosystem network that maximizes the ecological benefits of green spaces.



(a)Contrast trend

(b)Fitting result

Figure 6: The temperature simulation is compared to the measured value

6 Conclusion

The present study mainly investigates the central urban planning region of City S. By using the results of field surveys, the optimal planning method of the green space system is proposed, and known for its “four belts, three rings, seven wedges, and interconnected network.” The CFD simulation technique, coupled with RS and GIS techniques, has been applied to investigate and verify the accuracy of the simulation results in order to provide a basis for designing the optimized urban green space system. According to the analytical results, the differences between the measured data of wind velocity, SO_2 concentration, and temperature in the urban area and those obtained via numerical simulation are minimal, implying the correctness of the simulation results. Moreover, the optimal planning scheme of the green space system presents positive impacts on urban ventilation, SO_2 diffusion, and urban heat island mitigation.

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