forests

Article

Thermal Comfort Analysis and Optimization Strategies of Green Spaces in Chinese Traditional Settlements

Yanyan Cheng [1], Ying Bao [2,3,4,*], Shengshuai Liu [1], Xiao Liu [2,3,4,5,*], Bin Li [2,3,6], Yuqing Zhang [2,3,6], Yue Pei [4], Zhi Zeng [1] and Zhaoyu Wang [1]

1 Department of Architecture, North China University of Water Resources and Electric Power, Zhengzhou 450046, China
2 School of Architecture, South China University of Technology, Guangzhou 510641, China
3 State Key Laboratory of Subtropical Building and Urban Science, South China University of Technology, Guangzhou 510641, China
4 Architectural Design & Research Institute Co., Ltd., South China University of Technology, Guangzhou 510641, China
5 Energy Saving Technology Research Institute, South China University of Technology, Guangzhou 510641, China
6 Department of Architecture and Design, Politecnico di Torino, 10125 Torino, Italy
* Correspondence: arbaoy@scut.edu.cn (Y.B.); xiaoliu@scut.edu.cn (X.L.)

Abstract: The spatial pattern of Weizi settlements features distinct regional characteristics. Moreover, it contains profound wisdom in terms of traditional construction; therefore, studies on its association with the microclimate have important implications for improving the quality of human settlements. In the present study, Guanweizi Village in the Xinyang City of Henan Province was used as an example to analyze and evaluate the thermal comfort of green spaces. The impact of peripheral water bodies on the thermal comfort of outdoor green spaces in the settlement was studied, and the association between the components of outdoor green spaces and physiological equivalent temperature as an indicator of thermal comfort was explored. Further, factors negatively affecting the thermal comfort of green spaces were analyzed through the grid method. Thermal comfort in the Weizi settlement is somewhat correlated with the coverage of water bodies, roads, soil, greening, and buildings. Increasing the water area and creating multi-level greening spaces are effective measures to improve the thermal comfort of green spaces in the settlement. Our findings provide a theoretical basis and a pioneering example for future practices of environment design for human settlements.

Keywords: traditional settlements; ENVI-met; green spaces; outdoor environment; thermal comfort; regional characteristics

check for updates

Citation: Cheng, Y.; Bao, Y.; Liu, S.; Liu, X.; Li, B.; Zhang, Y.; Pei, Y.; Zeng, Z.; Wang, Z. Thermal Comfort Analysis and Optimization Strategies of Green Spaces in Chinese Traditional Settlements. *Forests* **2023**, *14*, 1501. https://doi.org/10.3390/f14071501

Academic Editor: Helmi Zulhaidi Mohd Shafri

Received: 2 June 2023
Revised: 10 July 2023
Accepted: 14 July 2023
Published: 22 July 2023

1. Introduction

During rapid urbanization, the spatial patterns of traditional settlements in many areas, being unable to adapt to the development needs of modern life, have been seriously damaged by rampant and extensive rural reconstruction [1]. Moreover, many environmental problems are arising from urbanization, such as a rise in temperature and heat waves, a drop in temperature and cold waves, air pollution, meteorological disasters, and ecosystem degradation [2]. These increasingly severe problems [3,4] have seriously compromised the quality and regional characteristics of traditional human settlements [5–7].

As green spaces in settlements are intended for activities closely related to daily life, their safety and comfort are gradually attracting attention. As such, the construction of the living environment is no longer merely intended to create comfortable living spaces inside buildings for people, but rather to create comfortable, safe, and healthy spaces outside of buildings for peoples' interactions, from a human-centered and perception-based perspective [8]. As the outdoor climate directly affects human perception, the thermal environment outside building spaces has garnered much research attention.

Previous studies on factors influencing the thermal environment outside building clusters have primarily focused on the spatial form, building layout, street space, underlying surface, green space, water body, and thermal comfort. Consequently, relevant progress has been made. First, the impact of spatial form on the thermal environment has been explored. For instance, Wang et al. studied thermal environment mitigation strategies for urban buildings of different densities in Toronto, and found that sunshine duration and average radiation play important roles in urban thermal comfort [9]. In another study, Zhou et al. explored the impact of urban spatial form on air temperature and proposed that building shading can effectively improve the thermal environment [10]. Further, Huang et al. studied the relationships among urban form, weather factors, and thermal comfort and observed that weather factors affect thermal comfort in urban environments [11]. Subsequently, Sun et al. studied the impacts of building density, floor area ratio, and green space ratio on the urban thermal environment and showed that an urban form significantly affects the thermal environment; in addition, increases in the building density increased the land surface temperature, while increased floor area and green space ratios decreased the land surface temperature [12]. Recently, Wu et al. studied the correlation between village morphological factors and water-cooling values and proposed that a higher water body rate and green space ratio, and a lower surrounding building density, can improve the cooling effect of water bodies [13]. Second, the impacts of building layout on the thermal environment have been studied. For instance, Jung et al. used an orthogonal experimental design to improve the urban microclimate and showed that the building coverage rate, building interval, and azimuth angle affect the outdoor thermal environment [14]. In another study, Liu et al. evaluated the impact of building layout on the thermal environment in residential districts and demonstrated that the temperature significantly differed across various building layouts [15]. Third, the impacts of street space on the thermal environment have been assessed. For instance, Du et al. studied the impact of street direction, street aspect ratio, and pavement material on the thermal environment in the street area [16], and Shao et al. studied the impact of street landscape on the thermal environment [17]. Fourth, some studies explored the impact of the underlying surface on the thermal environment. Specifically, Tsoka et al. studied different intervention schemes for the thermal environment with urban morphological characteristics in Thessaloniki, including microclimate parameters, such as earth surface and air, and average radiant temperature distribution. The authors reported significant reductions in the surface temperature by replacing conventional coatings with cooling materials featuring a higher albedo and emissivity [18]. Further, Kurazumi et al. studied the impact of the thermal environment in rural and suburban outdoor spaces on the human body, and proposed green space and water surface as natural factors that help reduce air temperature [19]. Recently, Xin et al. studied typical rural settlements in the Guanzhong Region and, using field measurements and ENVI-met data simulation, analyzed the dynamic changes in the thermal environment in rural areas. The authors used the root mean square error (RMSE) and mean absolute percentage error (MAPE) to verify the simulation model and physiological equivalent temperature (PET) to evaluate the outdoor thermal environment. They proposed that trees can significantly improve the outdoor thermal environment. In 1978, Hoppe et al. introduced meteorological factors, clothing, human activities, and human body parameters and proposed PET as an indicator of thermal comfort [20,21]. PET measures thermal comfort according to the energy balance of the human body. It is impacted by air temperature, wind speed, humidity, and average radiation temperature and can reflect thermal comfort more directly and comprehensively. PET is a meteorological indicator in a real sense and a comprehensive outdoor thermal comfort indicator, which can be used to evaluate the thermal environment in different seasons and under diverse climatic conditions [22,23]. Many recent studies have shown that thermal comfort could be greatly improved by optimizing the physical urban environment. For instance, Andreou et al. discussed the impacts of street structure, form, and ground reflectance on thermal comfort and proposed that the thermal comfort of the street microclimate is better in traditional urban areas than in modern urban clusters. Kariminia et al.

studied the thermal comfort and outdoor space utilization of urban squares and proposed that tourists are more sensitive to temperature changes than to other microclimatic factors, and that better air circulation and water evaporation can significantly increase thermal comfort [24,25].

In contrast, recent research findings on the thermal environment of outdoor green spaces in rural areas have been relatively limited, particularly those on the impact of water areas on microclimates in rural settlements. In addition, previous studies have mostly focused on the heat island effect of land settlements or the thermal comfort of settlements neighboring water on only one side. Weizi settlements, as a form of rural settlement surrounded by water on all four sides, are different from land settlements and settlements neighboring water on only one side. They are built based on the production and living experience of local residents. Through the literature review, we noted this research gap in previous studies. Rural areas are likewise subject to environmental-change-induced climatic impact. In some areas, due to the extensive reconstruction of traditional settlements, the spatial characteristics, as well as the ecological and environmental balance of the settlements, are damaged, resulting in frequent occurrences of problems, such as dust and droughts. In the face of modernization, these settlements are facing increasing climate-related challenges. In response to these climatic and environmental problems and their impacts in rural areas, the Fifth Plenary Session of the 19th CPC Central Committee held in 2020 placed strong emphasis on the goal of improving the rural living environment. In this context, it is of great importance and practical significance to rationally reconstruct and revitalize traditional settlements, as well as to evaluate and optimize the thermal environment of existing outdoor green spaces in traditional settlements. Previous studies on the microclimate of rural environments have mostly been based on the influence of natural water bodies on the microclimate, while areas of water within Weizi have been artificially constructed around the settlement. In the present work, we aim to determine whether such purposeful construction can regulate a microclimate. The significance of the present study lies in our finding that areas of water in Weizi do indeed exert a regulatory effect on the microclimate, although there is still room for optimization. The novelty of this research lies in the verification and analysis of thermal comfort in a rural settlement surrounded by water on all four sides.

Based on the impact that areas of water have on the microclimate of traditional villages, the present study evaluated the thermal comfort of outdoor green spaces and used local traditional construction experience to improve and create an outdoor environment with good thermal comfort. Using Guanweizi Village—a typical Weizi settlement in South Henan, China—as an example, we simulated the thermal environment of the settlement through field mapping of the village layout and ENVI-met modeling, and calculated PET with BIO-met. By maintaining the traditional residential building style, we analyzed the impact of peripheral water bodies on thermal comfort in the settlement. Finally, we proposed strategies to improve the thermal environment of Weizi settlements, providing a reference for the ecological revitalization and sustainable development of traditional villages [26–29].

2. Materials and Methods

2.1. Case Study Area

Guanweizi Village is located in the Yanhe Township of Guangshan County in Xinyang City, Henan Province, China. Surrounded by water bodies, the settlement has a square overall layout, demonstrating a typical settlement form with local characteristics (Figures 1 and 2). The village is surrounded by water bodies, which not only serve irrigation and cultivation purposes, as well as laundry cleaning and rainwater drainage functions, but also play roles in terms of defense and fire protection. More importantly, from the ecological perspective, they protect the whole area against floods and purify the settlement to some extent. In addition, together with plants, streets, and courtyard spaces, these water bodies regulate and improve the thermal environment in the settlement, which was precisely the focus of the present study.

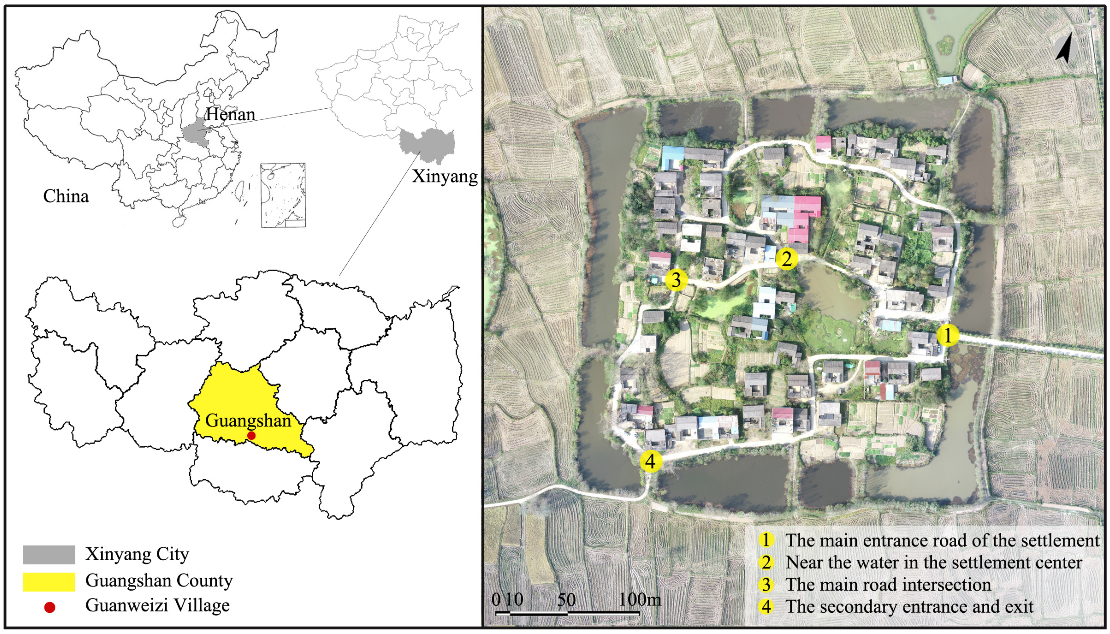


Figure 1. Scope of the case study area (map snapshot and photograph obtained by the author).

Figure 2. Photographs of the measurement points.

Four measuring points were selected in the present study, which reflected the environmental characteristics of the Guanweizi settlement. Point 1 was located at the main entrance road of the settlement, near peripheral water bodies and surrounded by multi-level greening and many trees. Point 2 was located at the settlement center, near the largest water body inside the settlement. Point 3 was located at the main traffic hub within the settlement, away from the internal water bodies. Point 4 was located at the secondary entrance and exit of the settlement, also near the peripheral water bodies, but with fewer trees and greening clusters than those at point 1. Each point is described in Table 1 and shown in Figures 1 and 2.

Table 1. Description of measuring points.

Measuring Point	Description
1	At the main entrance road of the settlement, near peripheral water bodies and surrounded by multi-level greening and many trees
2	Near water bodies at the settlement center
3	At the main road intersection at the settlement center, away from the internal water bodies
4	At the secondary entrance and exit of the settlement, near peripheral water bodies, but with fewer greening clusters and trees

2.2. Thermal Comfort Research Methodology

2.2.1. Low-Altitude Photogrammetry

Six control points for photography were evenly distributed in the survey area of Guanweizi Village, with 3D coordinates measured using RTK and orthophotographs obtained using a DJI UAV (Phantom 4RTK). The aerial photographs were collaged using Pix4Dmapper, and ground elevation was extracted using ArcGIS. The processed orthophotos were then imported into CASS, and ground objects were drawn. Finally, the elevation data were imported into CASS (Figure 3), which showed that the Weizi settlement is on flat land.

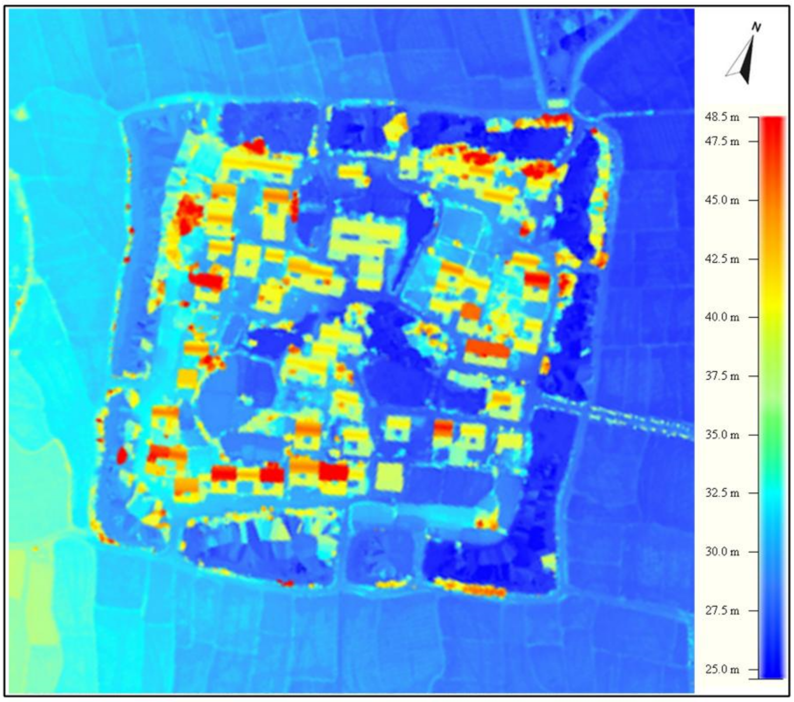


Figure 3. Elevation map of Guanweizi Village.

2.2.2. ENVI-Met Software for Data Simulation

ENVI-met, a piece of software developed by Bruse and Fleer in 1998, is currently updated to version 5 [30]. Based on the principles of thermodynamics and hydromechanics, this software dynamically simulates interactions between the surface and plants in small-scale human settlements with air [26].

In the present study, simulations for Guanweizi Village were conducted using ENVI-met to obtain the distribution of PET, as the thermal comfort indicator, in the green spaces of the settlement [31].

2.2.3. PET as the Thermal Comfort Indicator

In the present study, PET was selected as the thermal comfort indicator, which refers to the corresponding temperature when the skin and body temperatures reach the same thermal state as that of the typical indoor environment in a given indoor or outdoor environment [12,15,32]. With reference to the corresponding relationship between PET and human thermal perception evaluation (Table 2) [16], as well as the dynamic ENVI-met-based simulation of the thermal environment in the village, the correlations between various spatial components of the Guanweizi settlement and the thermal comfort indicator PET were comprehensively analyzed [33].

Table 2. Physiological equivalent temperature (PET) and the corresponding human thermal sensation.

PET (°C)	**≤4**	**4–8**	**8–13**	**13–18**	**18–23**	**23–29**	**29–35**	**35–41**	**≥41**
Thermal sensation	Very cold	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot
Physiological stress level	Extreme cold stress	Strong cold stress	Moderate cold stress	Slight cold stress	No	Slight heat stress	Moderate heat stress	Strong heat stress	Extreme heat stress

2.2.4. Grid Analysis

The grid method is primarily applied to urban planning, landscape design, and architectural design. Typically, large-scale grids are used for urban planning, landscape planning, and landscape ecological evaluation, while medium-to-small-scale grids are used for graphic and architectural design [17].

Guanweizi Village is nearly 304 m long from the east to west and 300 m long from the north to south. Therefore, in the present study, the settlement was divided using grids measuring 38 m × 37.5 m into 64 grid units in total (Figure 4), and the coupling relationships between the spatial components of Guanweizi Village (including the water body, road, greening, soil, and building coverage) and PET were discussed in detail on the basis of medium- and small-scale grids.

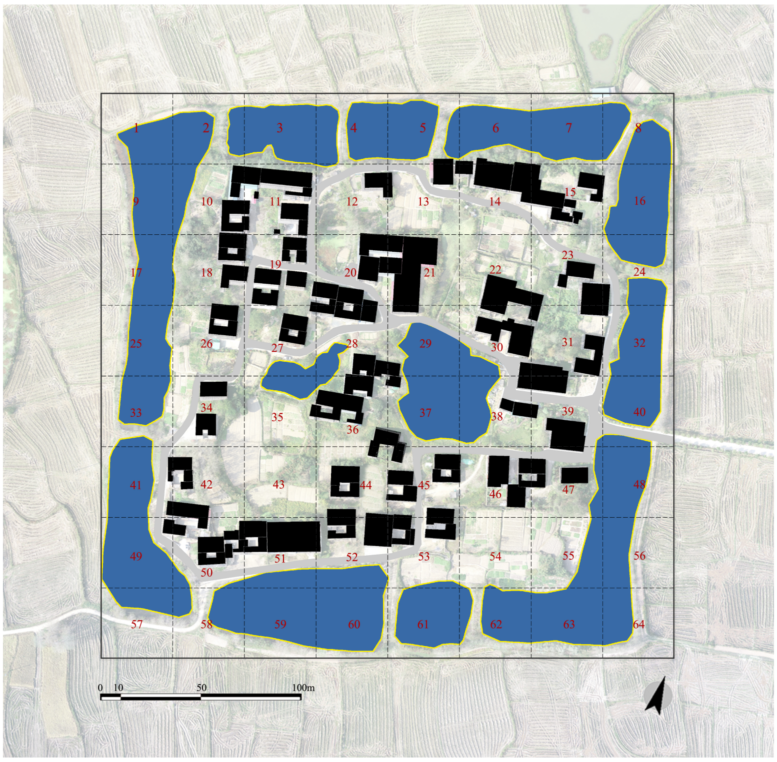


Figure 4. Grid of Guanweizi Village.

2.3. *ENVI-Met-Based Thermal Environment Simulation*

2.3.1. Measurement of Thermal Environment-Related Indicators in Guanweizi Village

According to the climatic characteristics of Xinyang City, the hottest months are June and July. The data were measured during 08:00 and 17:00 at an interval of 1 h on 21 June 2021, a clear day with moderate wind but no clouds. Air temperature and relative humidity were measured at 1.5 m above the ground level (around the head and neck of an adult) and recorded at an interval of 1 min in accordance with ISO 7726, using the UT332+ temperature humidity meter (air temperature range: 20 °C~70 °C, precision: ±0.2 °C; relative humidity range: 0%~99% RH, precision: ±2% RH).

2.3.2. Verification of ENVI-Met Simulation Results

In the present study, RMSE and MAPE were used to verify the simulation results [20,34], as shown in Equations (1) and (2):

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{n}\left(X_{\text{obs},i} - X_{\text{model},i}\right)^2}{n}} \tag{1}$$

$$MAPE = \frac{1}{n}\Sigma_{i=1}^{n}\frac{\left|X_{\text{obs},i} - X_{\text{model},i}\right|}{X_{\text{obs},i}} \times 100\% \tag{2}$$

where X_{obs} indicates the measured data, X_{model} indicates the simulated data, and n indicates the times of measurement.

Since solar radiation and temperature are closely correlated and air temperature directly affects PET, the correlation between air temperature and PET is the strongest [18]. Therefore, this verification primarily focused on error analysis of the measured and simulation data of air temperature and relative humidity. As is shown in Table 3, the air temperature RMSE ranged between 1.20 °C and 1.51 °C, and the relative humidity RMSE ranged between 2.01% and 2.31% [35]; MAPE ranged between 3.44% and 5.92%, which was less than 10% [36]. This indicates a relatively small error between the measured data and the simulation data, meaning that the model can effectively simulate the thermal environment of the village [37,38].

Table 3. Goodness-of-fit analysis of the measured and simulated data.

Meteorological Parameters	Evaluation Indicators	Point 1	Point 2	Point 3	Point 4
Air temperature	RMSE (°C) MAPE (%)	1.51 5.92	1.34 4.72	1.40 5.29	1.20 4.22
Relative humidity	RMSE (%) MAPE (%)	2.31 3.70	2.19 3.60	2.13 3.47	2.01 3.44

2.3.3. ENVI-Met Modeling Parameter

ENVI-met was used to model the Guanweizi Village settlement, with grid resolutions set at dx = 2 m, dy = 2 m, and dz = 2 m (dx and dy are horizontal resolutions, and dz is a vertical resolution). The simulation period was set between 18:00 20 June and 24:00 21 June, with data collected from 13:00 to 15:00, 21 June. According to the actual temperature and seasonal characteristics, the thermal environment in this period varied greatly, with the air temperature reaching the highest at 15:00. Therefore, simulated data during this period were selected for analysis. The simulation parameters are set out in Table 4.

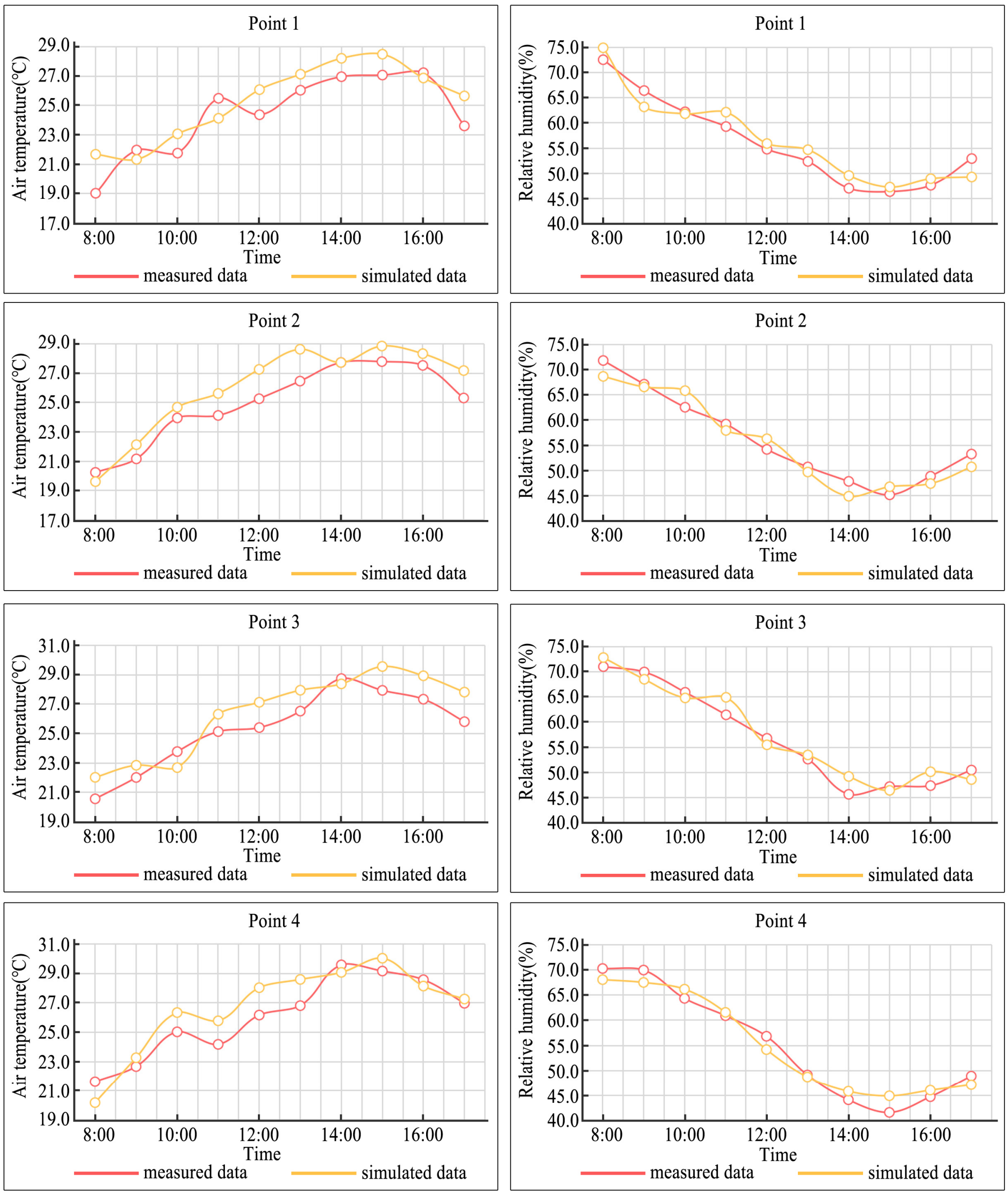
Table 4. The basic parameters of the simulation experiment.

	Parameters	Parameter Values
Simulation settings	Total simulation time (h) Output time interval (min) Number of grids (X × Y × Z)	30 60 233 × 231 × 15
Initial parameter setting	Simulation start date Simulation start time Initial temperature (°C) Wind speed at 10 m (m/s) Wind direction at 10 m (○) Relative humidity at 2 m (%) Specific humidity at 2500 m (g/kg)	20 June 2021 18:00 25.2 2.4 202.5 S-W 56 7

2.3.4. ENVI-Met-Based PET Calculation

The location for the calculation was set at 114.87° E and 31.78° N, and the time was set between 18:00 20 June and 24:00 21 June, 2021. During the calculation, the heat resistance of clothing for a summer outing was set to be 0.5 clo, activity level was 120 W, and human parameters were a standard male body shape (175 cm tall, 75 kg, and aged 35 years). During field measurement, the weather was clear with no clouds; thus, cloud cover was set to 0.

A PET distribution map at 1.5 m above the ground was created using BIO-met. According to the measured data, the temperature peaked at around 15:00; thus, PET distribution at this time was used for analysis. To test the reliability of the simulation data, we compared it with measured data (Figure 5) and used MAPE and RMSE for verification.



(a) (b)

Figure 5. Comparison of the simulated and measured data at 1.5 m above the ground at four measuring points used to verify the effectiveness of the ENVI-met software: (**a**) air temperature and (**b**) relative humidity.

3. Results

3.1. PET Simulation

As is shown in the PET distribution map of Guanweizi Village (Figure 6, left), at 15:00, when air temperature peaked, the PET in green spaces in the village center surrounded by circular water bodies ranged between 34.1 °C and 39.3 °C. This was accompanied by a warm thermal perception, but generally had good thermal comfort. The lowest PET was below 34.1 °C, which appeared in the area surrounded the water bodies and in the shaded region of some buildings, accompanied by a warm thermal perception. The PET values of the hardened road (with a hard concrete pavement) and dense building areas were higher, ranging between 41.9 °C and 47.1 °C, accompanied by a very hot thermal perception; however, the lowest PET ranged between 34.1 °C and 36.7 °C, recorded within a very small area of a shadow of a building.

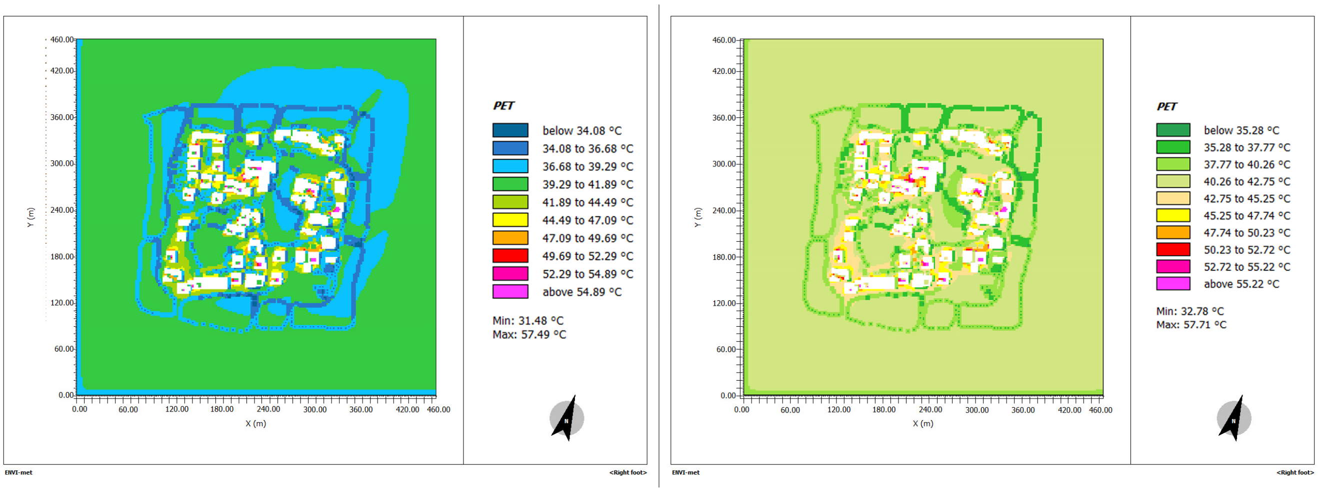


Figure 6. Distribution of physiological equivalent temperature (PET) values at 15:00 on 21 June 2021 (with water bodies on the left and without water bodies on the right).

3.2. Correlation between Spatial Components and PET

Guanweizi Village was divided into 64 grids, each with a total area of 1425 m^2. Simultaneously, building, greening, road, water, and soil coverage of each grid were calculated. The summarized data, as well as PET values at 15:00, calculated based on the ENVI-met simulation, were used as the basic database of spatial components and thermal comfort of Guanweizi Village (Table 5) [39].

Table 5. Grid database of spatial components and physiological equivalent temperature (15:00) for Guanweizi Settlement.

Grid No.	Water Body Coverage	Road Coverage	Bare Soil Coverage	Greening Coverage	Building Coverage	PET (°C) Value
1	35.8%	0.0%	64.2%	0.0%	0.0%	39.8
2	49.7%	0.0%	29.0%	21.3%	0.0%	36.4
3	70.1%	0.0%	22.7%	7.2%	0.0%	37.0
4	64.6%	0.0%	35.4%	0.0%	0.0%	37.2
5	60.3%	0.0%	39.0%	0.0%	0.7%	37.6
6	56.4%	0.0%	35.9%	6.8%	0.9%	36.7
7	69.6%	0.0%	29.7%	0.7%	0.0%	36.0
8	46.3%	0.0%	47.0%	6.7%	0.0%	37.8
9	53.4%	0.0%	46.6%	0.0%	0.0%	36.4
10	22.1%	0.0%	23.0%	34.0%	20.9%	36.8

Table 5. *Cont.*

Grid No.	Water Body Coverage	Road Coverage	Bare Soil Coverage	Greening Coverage	Building Coverage	PET (°C) Value
11	0.0%	4.9%	34.9%	0.0%	60.2%	38.2
12	0.0%	10.8%	28.6%	50.9%	9.7%	36.3
13	0.0%	11.0%	26.3%	50.4%	12.3%	36.8
14	0.0%	9.9%	32.2%	22.7%	35.2%	39.8
15	0.0%	2.6%	21.3%	34.7%	41.4%	37.8
16	72.9%	0.0%	13.0%	13.1%	1.0%	36.7
17	51.1%	0.0%	48.9%	0.0%	0.0%	37.5
18	1.6%	0.0%	14.2%	63.8%	20.4%	36.2
19	0.0%	17.2%	42.6%	6.0%	34.2%	38.9
20	0.0%	12.9%	34.8%	13.5%	38.8%	38.6
21	0.0%	0.0%	28.4%	25.2%	46.4%	39.1
22	0.0%	0.0%	8.4%	68.9%	22.7%	37.3
23	0.0%	8.8%	32.4%	38.6%	20.2%	38.4
24	49.4%	5.4%	38.7%	1.3%	5.2%	36.7
25	55.2%	0.0%	44.8%	0.0%	0.0%	36.5
26	0.0%	8.9%	20.1%	55.0%	16.0%	36.0
27	10.2%	13.0%	44.8%	18.0%	14.0%	38.4
28	10.7%	12.3%	45.1%	1.5%	30.4%	38.9
29	48.4%	10.8%	10.4%	17.9%	12.5%	37.0
30	12.0%	11.7%	32.1%	8.7%	35.5%	37.9
31	0.0%	1.6%	4.1%	67.3%	27.0%	36.5
32	56.0%	7.5%	35.4%	0.0%	1.1%	36.5
33	45.1%	1.7%	47.3%	5.9%	0.0%	37.4
34	0.0%	10.3%	27.8%	45.6%	16.3%	38.2
35	18.7%	0.0%	9.1%	70.1%	2.1%	37.0
36	2.9%	0.0%	21.5%	35.1%	40.5%	38.6
37	70.1%	0.0%	19.9%	4.0%	6.0%	36.8
38	36.5%	7.9%	31.0%	11.0%	13.6%	37.2
39	0.8%	24.2%	32.7%	4.2%	38.1%	37.4
40	55.9%	11.4%	32.7%	0.0%	0.0%	37.9
41	56.9%	9.3%	28.1%	0.0%	5.7%	36.6
42	0.0%	0.0%	20.2%	51.6%	28.2%	36.2
43	0.0%	0.0%	14.2%	85.8%	0.0%	36.0
44	0.0%	0.0%	52.3%	5.9%	41.8%	39.9
45	0.0%	13.6%	41.2%	11.9%	33.3%	37.7
46	0.0%	9.5%	30.2%	28.6%	31.7%	37.5
47	16.6%	12.3%	22.8%	28.8%	19.5%	37.8
48	54.8%	0.0%	45.2%	0.0%	0.0%	37.5
49	79.8%	5.7%	11.0%	0.0%	3.5%	37.4
50	6.3%	7.3%	41.3%	0.0%	45.1%	38.6
51	21.9%	14.4%	26.9%	0.0%	36.8%	38.3
52	24.6%	9.5%	41.2%	0.0%	24.7%	38.0
53	2.5%	9.8%	23.9%	42.4%	21.4%	38.2
54	1.5%	0.0%	0.0%	95.5%	3.0%	35.7

Table 5. *Cont.*

Grid No.	Water Body Coverage	Road Coverage	Bare Soil Coverage	Greening Coverage	Building Coverage	PET (°C) Value
55	32.4%	0.0%	6.8%	60.8%	0.0%	35.9
56	33.2%	0.0%	66.8%	0.0%	0.0%	36.6
57	24.2%	0.0%	75.8%	0.0%	0.0%	39.2
58	36.6%	0.0%	63.4%	0.0%	0.0%	39.1
59	74.1%	0.0%	25.9%	0.0%	0.0%	37.4
60	75.7%	0.0%	24.3%	0.0%	0.0%	36.5
61	72.9%	0.0%	27.1%	0.0%	0.0%	36.6
62	56.1%	0.0%	43.9%	0.0%	0.0%	37.2
63	76.6%	0.0%	23.4%	0.0%	0.0%	36.8
64	26.8%	0.0%	73.2%	0.0%	0.0%	37.2

In the present study, the basic grid data (Table 5) were imported into SPSS, and Pearson correlation analysis was conducted between the PET and the basic spatial components of the Guanweizi settlement, including the water, road, bare soil, greening, and building coverage (Table 6). The PET was negatively correlated with water and greening coverage, and positively correlated with road, soil, and building coverage. By comparing the correlation coefficients, the order of correlation strength was as follows: greening coverage > water coverage (slight difference) in the case of negative correlations, and building coverage > bare soil coverage > road coverage in the case of positive correlations.

Table 6. Pearson correlation analysis between grid analysis data of settlement space components and the corresponding physiological equivalent temperature (PET).

		Water Body Coverage	Road Coverage	Bare Soil Coverage	Greening Coverage	Building Coverage
Pearson correlation between settlement space components and PET	r	−0.328 **	0.281 *	0.481 **	−0.331 **	0.494 **
	Sig.	0.008	0.024	0.000	0.007	0.000

** Correlation significant at the 0.01 level (two-tailed); * correlation significant at the 0.05 level (two-tailed).

3.3. Impact of Water Bodies on the Thermal Environment

To verify the impact of water bodies around the village on the thermal environment, along with the original model, another copy was created. The copy had only one variable (excluding water bodies around the village), while the other parameters remained consistent with those in the original model. The simulation results were as follows.

According to the data measured at 15:00 on 21 June 2021, during summer, the PET in green spaces at the village center with water bodies ranged between 36.7 °C and 39.3 °C, accompanied by a warm thermal perception. In contrast, that in the green spaces without water bodies ranged between 40.3 °C and 42.8 °C, accompanied by a very hot thermal perception. From the comparison between scenarios with and without water bodies, the PET values around the water bodies and inside the settlement were reduced by approximately 5 °C, on average, and the air temperature was reduced by approximately 3 °C, on average, in the presence of water bodies (Figures 6 and 7). However, with water bodies around the settlement, the PET values outside the water bodies increased (south and west sides in figures on the left). As is shown in Figure 6, the PET in greening areas at the edge of the water bodies ranged between 34.1 °C and 36.7 °C, while those in areas without greening ranged between 36.7 °C and 39.3 °C, reaching the high values shown in blue.

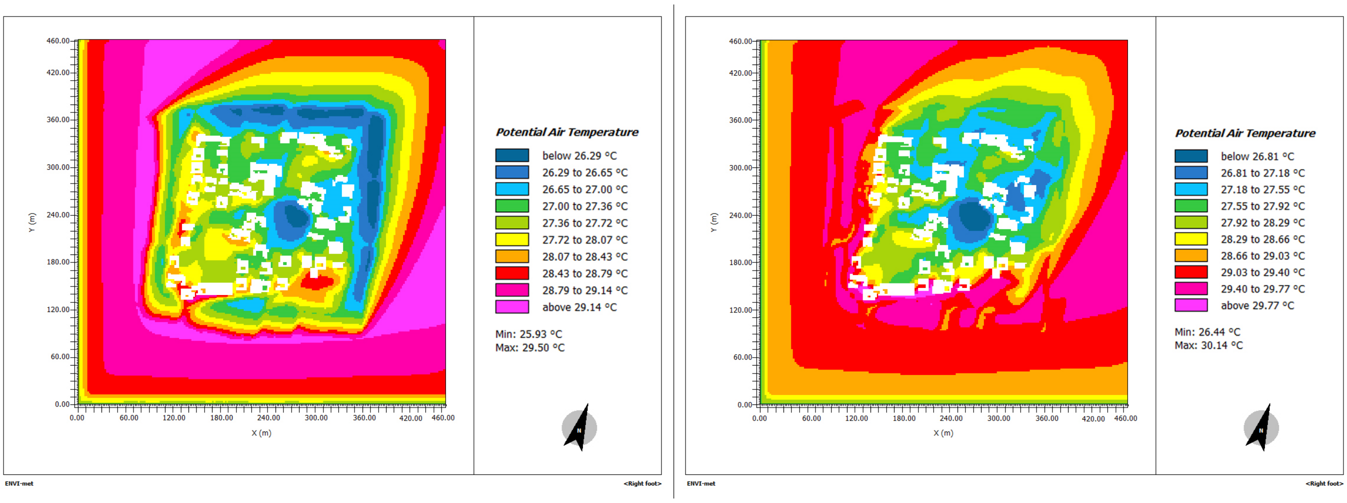


Figure 7. Air temperature distribution at 15:00 on 21 June 2021 (with water bodies on the left and without water bodies on the right).

4. Discussion

Our literature review revealed that previous studies have mostly focused on the heat island effect of land settlements or the thermal comfort of settlements neighboring water on only one side. For example, Kurazumi et al. studied the relationship of effective temperature (ET), an indicator for the evaluation of outdoor space thermal environments, with human physiological and psychological responses, through subject experiments in 2019. By studying the influence of the thermal environment on the human body in rural and suburban outdoor spaces, natural elements such as green space and water surfaces have been proposed as conducive to reducing air temperature [19]. In 2013, Theeuwes et al. mitigated the heat island effect by introducing open surface water into urban design. By using the WRF mesoscale meteorological model, an idealized circular city was designed. It was concluded that the cooling effect of a water body depends nonlinearly on the partial water coverage, area and distributed wind direction of individual lakes in a city [40]. Sayad et al. proposed two solutions to improve urban thermal comfort through an ENVI-met simulation experiment in 2021: increasing the vegetation ratio relative to air flow and increasing the water surface area within the outdoor space [41]. The combined effect of the increased vegetation ratio and linear water bodies provides the best solution for achieving the optimal thermal comfort level in an outdoor space. In 2022, Wu et al. studied the spatial and temporal distribution characteristics of the water temperature cooling value in Zhoutie Town of Yixing City through field measurement, numerical simulation, etc. They analyzed the correlation between the village morphology and water-cooling value, proposing that the increase in water and greening ratio and the decrease in surrounding building density was conducive to enhancing the water-cooling effect [13]. The above literature only employed a limited number of methods, such as effective temperature evaluation, ideal model construction, field measurement, and digital simulation, to study the influence of an area of water on an outdoor thermal environment. However, this study more systematically adopted the actual measurement, digital simulation, PET outdoor thermal environment evaluation, and grid-based correlation analysis of the experimental data. In addition, the above literature mainly focused on the study of natural water areas, while we focused on artificial areas of water in the particular form of Weizi settlements. This was based on our years of team research on Weizi settlement morphology, since there have been very few studies on Weizi settlements in China.

Based on ENVI-met simulation results, the impact of peripheral water bodies on the thermal comfort of settlements was analyzed. This clearly showed a direct regulatory effect of water bodies on PET and air temperature. Therefore, water bodies can effectively improve the local microclimate and, consequently, PET [42]. Accordingly, an increased water body area can favorably improve the PET and air temperature of Weizi settlements. This is because, although water bodies can effectively reduce the surrounding temperature and increase relative humidity and wind speed, due to heat ventilation, air temperature drops to some extent, thereby increasing PET. With less greening in the south and west and more in the north and east, PET did not increase in the north and east, indicating that waterfront spaces combined with green shade can significantly reduce PET [43].

However, simulation results also indicated that the local temperature around water bodies may increase due to solar refraction. Moreover, Pearson's correlation analysis revealed that, under these circumstances, PET is negatively correlated with greening coverage [44,45]. Therefore, PET may be reduced by combining waterfront spaces and green shade to avoid a local high temperature around the water bodies.

Furthermore, the simulated data showed relatively higher PET values in hard concrete pavement, soil, and dense building areas. This is a result of an increased air temperature due to increased heat radiation from the hard concrete pavement, soil, and building surfaces. Therefore, building density should be adjusted through the reasonable use of hard paving, and the high building density in some areas should be appropriately reduced to improve the local microclimate [46].

Based on grid data and Pearson correlations between PET and the coverage of water bodies, greening, roads, soil, and buildings, a PET ranging between 34 °C and 36 °C is typically accompanied by good thermal comfort due to the relatively higher water body and greening coverage. However, a PET exceeding 36 °C is generally accompanied by poor thermal comfort due to the relatively higher road, soil, and building coverage. Hence, the rational design of water bodies and greening coverage would be an effective means to increase the thermal comfort of Weizi settlements.

The present study has certain limitations as it only focused on a Weizi settlement surrounded by water on all four sides without analyzing partially enclosed settlements, such as those surrounded by water on only two or three sides. According to the current research findings, it is expected that an uneven distribution of the cooling effect will be seen in Weizi settlements surrounded by water on only two or three sides, compared with those surrounded by water on all four sides. This incomplete selection of typical settlement samples is a limitation of this study. More settlements featuring different enclosure types will be selected to conduct further research on the influence of the degree of water enclosure on thermal comfort. In addition, the air speed and average radiation temperature will also be incorporated into field measurements in our subsequent study to obtain more scientific data.

5. Conclusions

In the present study, fundamental data of air temperature, relative humidity, and solar radiation were obtained through field measurements in Guanweizi Village. Further, ENVI-met was used for simulation, and the distribution results of PET, a thermal comfort indicator, were obtained for Guanweizi Village on the summer solstice.

Based on the results of fundamental data analysis, grid units with better thermal comfort were concentrated near water bodies or greening clusters. Thus, water and greening coverage are the major factors affecting the thermal comfort of spaces in Guanweizi settlement. Water bodies in Guanweizi Village can regulate air temperature and relative humidity in surrounding areas, thereby playing pivotal roles in improving the thermal comfort of the settlement.

Furthermore, the coupling relationships between the components of settlement spaces and PET values were summarized. On this basis, three suggestions regarding the strategy for improving the thermal comfort of Weizi settlements are summarized below:

1. Increasing air humidity and reducing air temperature: the area of water bodies and greening should be increased, and the area of bare soil should be reduced within the settlement area, where thermal comfort is poor.
2. Reducing thermal radiation: green plants should be grown on both sides of hardened roads in the settlement to increase shading and reduce solar thermal radiation; hard concrete pavement should be minimized and planting or permeable bricks should be used [47]. Green plants should be grown on both sides of roads, and surface phytoplankton should be increased to reduce the reflection of solar radiation [48,49].
3. Reducing high temperatures at the boundary of water bodies: multi-level greenery should be added around water bodies inside and outside the settlement, such as tall trees to shade the water bodies and thus reduce high temperatures at their boundary.

The significance of the present study lies in the site-specific consideration of the relationship between human settlements and water when designing settlements to create spaces with relatively comfortable microclimates. This work can provide a reference and inspiration for future research on the design of water-adaptive spaces in the context of human settlements.

Author Contributions: Conceptualization, Y.C. and X.L.; methodology, Y.C., Y.B. and X.L.; software, S.L., Y.B. and Z.Z.; validation, B.L., Y.Z., S.L. and Z.W.; investigation, Y.C., S.L., Z.W. and X.L.; data curation, S.L. and Z.Z.; writing—original draft preparation, Y.C., S.L., Z.Z., Z.W. and X.L.; writing—review and editing, Y.B., Y.P., Y.C., B.L., X.L. and Y.Z.; supervision, X.L. and Y.C.; funding acquisition, X.L. and Y.B. All authors contributed to the development of this work and elaboration of this article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the 2022 Guangdong Philosophy and Social Science Foundation (grant no. GD22XGL02); Guangdong Basic and Applied Basic Research Foundation (grant no. 2023A1515011137); Guangzhou Philosophy and Social Science Planning 2022 Annual Project (grant no. 2022GZQN14); Fundamental Research Funds for the Central Universities (grant no. QNMS202211); Department of Education of Guangdong Province (grant no. 2021KTSCX004); Department of Housing and Urban–Rural Development of Guangdong Province (grant no. 2021-K2-305243); Guangzhou Basic and Applied Basic Research Foundation (grant no. SL2024A04J00890); and State Key Laboratory of Subtropical Building and Urban Science, South China University of Technology (grant no. 2022ZA01).

Data Availability Statement: Data are available within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wei, G.; Bi, M.; Liu, X.; Zhang, Z.; He, B.-J. Investigating the impact of multi-dimensional urbanization and FDI on carbon emissions in the belt and road initiative region: Direct and spillover effects. *J. Clean. Prod.* **2023**, *384*, 135608. [CrossRef]
2. Liu, X.; He, J.; Xiong, K.; Liu, S.; He, B.-J. Identification of Factors Affecting Public Willingness to Pay for Heat Mitigation and Adaptation: Evidence from Guangzhou, China. *Urban Clim.* **2023**, *48*, 101405. [CrossRef]
3. He, B.-J. Green Building: A Comprehensive Solution to Urban Heat. *Energy Build.* **2022**, *271*, 112306. [CrossRef]
4. Liu, S.; Wang, Y.; Liu, X.; Yang, L.; Zhang, Y.; He, J. How does future climatic uncertainty affect multi-objective building energy retrofit decisions? Evidence from residential buildings in subtropical Hong Kong. *Sustain. Cities Soc.* **2023**, *92*, 104482. [CrossRef]
5. Wei, D.; Yang, L.; Bao, Z.; Lu, Y.; Yang, H. Variations in Outdoor Thermal Comfort in an Urban Park in the Hot-Summer and Cold-Winter Region of China. *Sustain. Cities Soc.* **2022**, *77*, 103535. [CrossRef]
6. He, B.-J.; Zhu, J.; Zhao, D.-X.; Gou, Z.-H.; Qi, J.-D.; Wang, J. Co-Benefits Approach: Opportunities for Implementing Sponge City and Urban Heat Island Mitigation. *Land Use Policy* **2019**, *86*, 147–157. [CrossRef]
7. Song, C.; Yang, J.; Wu, F.; Xiao, X.; Xia, J.; Li, X. Response characteristics and influencing factors of carbon emissions and land surface temperature in Guangdong Province, China. *Urban Clim.* **2022**, *46*, 101330. [CrossRef]
8. Li, B.; Guo, W.; Liu, X.; Zhang, Y.; Russell, P.J.; Schnabel, M.A. Sustainable Passive Design for Building Performance of Healthy Built Environment in the Lingnan Area. *Sustainability* **2021**, *13*, 9115. [CrossRef]
9. Wang, Y.; Berardi, U.; Akbari, H. Comparing the Effects of Urban Heat Island Mitigation Strategies for Toronto, Canada. *Energy Build.* **2016**, *114*, 2–19. [CrossRef]
10. Zhou, X.; Chen, H.; Wu, Y.; Xu, H. Impacts of Mobile Survey-based Urban Spatial Forms on Summer Afternoon Thermal Environments. *Landsc. Archit.* **2018**, *25*, 21–26. (In Chinese) [CrossRef]

11. Huang, C.H.; Tsai, H.H.; Chen, H.C. Influence of Weather Factors on Thermal Comfort in Subtropical Urban Environments. *Sustainability* **2020**, *12*, 2001. [CrossRef]
12. Sun, Z. Impact of urban morphology factors on thermal environment in high density urban areas: A case of Beijing within 5th ring road. *Ecol. Environ. Sci.* **2020**, *29*, 2020–2027. (In Chinese) [CrossRef]
13. Wu, Y.; Peng, C. Influence analysis of rural morphological factors on microclimate cooling effect of water body. *J. Southeast Univ. (Nat. Sci. Ed.)* **2022**, *52*, 179–188. (In Chinese) [CrossRef]
14. Sukjin, J.; Seonghwan, Y. Changes in Sunlight and Outdoor Thermal Environment Conditions Based on the Layout Plan of Flat Type Apartment Houses. *Energies* **2015**, *8*, 9155–9172. [CrossRef]
15. Liu, Z.; Zhao, X.; Jin, H. Thermal environment of riverside residential areas at Harbin in winter. *J. Harbin Inst. Technol.* **2017**, *49*, 164–171. (In Chinese)
16. Du, X.; Shi, Y.; Zhang, Y. Numerical Study and Design of Thermal Environment of Living Street Canyons in Guangzhou. *Build. Sci.* **2015**, *31*, 78–87. (In Chinese) [CrossRef]
17. Shao, Y.; Liu, B. A Study on Microclimate Parameters of Urban Street Space and Its Influential Factors. *Landsc. Archit.* **2016**, *135*, 98–104. (In Chinese) [CrossRef]
18. Tsoka, S. Investigating the Relationship Between Urban Spaces Morphology and Local Microclimate: A Study for Thessaloniki. *Procedia Environ. Sci.* **2017**, *38*, 674–681. [CrossRef]
19. Kurazumi, Y.; Kondo, E.; Fukagawa, K.; Yamato, Y.; Tobita, K.; Tsuchikawa, T. Effects of Outdoor Thermal Environment upon the Human Responses. *Engineering (1947-3931)* **2019**, *11*, 475–503. [CrossRef]
20. Xin, K.; Zhao, J.; Wang, T.; Gao, W.; Zhang, Q. Architectural Simulations on Spatio-Temporal Changes of Settlement Outdoor Thermal Environment in Guanzhong Area, China. *Buildings* **2022**, *12*, 345. [CrossRef]
21. Wang, H.; Hu, S. Analysis on the Applicability of PMV Thermal Comfort Model. *Build. Sci.* **2009**, *25*, 108–114. (In Chinese) [CrossRef]
22. Fiorillo, E.; Brilli, L.; Carotenuto, F.; Cremonini, L.; Gioli, B.; Giordano, T.; Nardino, M. Diurnal Outdoor Thermal Comfort Mapping through Envi-Met Simulations, Remotely Sensed and In Situ Measurements. *Atmosphere* **2023**, *14*, 641. [CrossRef]
23. Yang, F.; Qian, F.; Liu, S. Evaluation of Measurement and Numerical Simulation of Outdoor Thermal Environmental Effect of Planning and Design Strategies of High-rise Residential Quarters. *Build. Sci.* **2013**, *29*, 28–34+92. (In Chinese) [CrossRef]
24. Kariminia, S.; Ahmad, S.S. Dependence of Visitors' Thermal Sensations on Built Environments at an Urban Square. *Procedia Soc. Behav. Sci.* **2013**, *85*, 523–534. [CrossRef]
25. Kariminia, S.; Motamedi, S.; Shamshirband, S.; Petković, D.; Roy, C.; Hashim, R. Adaptation of ANFIS Model to Assess Thermal Comfort of an Urban Square in Moderate and Dry Climate. *Stoch. Environ. Res. Risk Assess.* **2016**, *30*, 1189–1203. [CrossRef]
26. Guo, C.; Fu, J.; Guo, Z.; Zhao, J. Rssearch on the Thermal Comfort Evaluation Framework of Vernacular Architecture under the Subjective and Objective Judgment Mechanism. *Archit. J. (Acad. Issue)* **2020**, *21*, 22–26. (In Chinese)
27. Cheng, Y.; Guo, W. An Analysis of the Principles That Create the Microclimate of Courtyards in Vernacular Houses Surrounded by Embankment. *Archit. J.* **2015**, *557*, 70–73. (In Chinese)
28. Guo, W.; Wang, X.; Zhang, G.; Li, W. Research on the Climate Adaptability of Traditional Villages and Houses: A Case Study of Hengtang Village in Dongyang City. *J. Hum. Settl. West China* **2021**, *36*, 134–140. (In Chinese) [CrossRef]
29. Guo, W.; Ding, Y.; Yang, G.; Liu, X. Research on the Indicators of Sustainable Campus Renewal and Reconstruction in Pursuit of Continuous Historical and Regional Context. *Buildings* **2022**, *12*, 1508. [CrossRef]
30. Bruse, M.; Fleer, H. Simulating Surface–Plant–Air Interactions inside Urban Environments with a Three Dimensional Numerical Model. *Environ. Model. Softw.* **1998**, *13*, 373–384. [CrossRef]
31. Nikolova, I.; Janssen, S.; Vos, P.; Vrancken, K.; Mishra, V.; Berghmans, P. Dispersion Modelling of Traffic Induced Ultrafine Particles in a Street Canyon in Antwerp, Belgium and Comparison with Observations. *Sci. Total Environ.* **2011**, *412–413*, 336–343. [CrossRef]
32. Cheng, Y. Weizi Folk House in Western Anhui—On the Construction Strategy of Traditional Architecture Adapting to the Climate. *Sichuan Build. Sci.* **2009**, *35*, 244–249. (In Chinese)
33. Fang, Z.; Lin, Z.; Mak, C.M.; Niu, J.; Tse, K.-T. Investigation into Sensitivities of Factors in Outdoor Thermal Comfort Indices. *Build. Environ.* **2018**, *128*, 129–142. [CrossRef]
34. Shi, D.; Song, J.; Huang, J.; Zhuang, C.; Guo, R.; Gao, Y. Synergistic Cooling Effects (SCEs) of Urban Green-Blue Spaces on Local Thermal Environment: A Case Study in Chongqing, China. *Sustain. Cities Soc.* **2020**, *55*, 102065. [CrossRef]
35. Ouyang, W.; Sinsel, T.; Simon, H.; Morakinyo, T.E.; Liu, H.; Ng, E. Evaluating the thermal-radiative performance of ENVI-met model for green infrastructure typologies: Experience from a subtropical climate. *Build. Environ.* **2022**, *207*, 108427. [CrossRef]
36. Kumar, S.; Kaur, T. Development of ANN Based Model for Solar Potential Assessment Using Various Meteorological Parameters. *Energy Procedia* **2016**, *90*, 587–592. [CrossRef]
37. Rosso, F.; Golasi, I.; Castaldo, V.L.; Piselli, C.; Pisello, A.L.; Salata, F.; Ferrero, M.; Cotana, F.; de Lieto Vollaro, A. On the Impact of Innovative Materials on Outdoor Thermal Comfort of Pedestrians in Historical Urban Canyons. *Renew. Energy* **2018**, *118*, 825–839. [CrossRef]
38. Salata, F.; Golasi, I.; Petitti, D.; de Lieto Vollaro, E.; Coppi, M.; de Lieto Vollaro, A. Relating Microclimate, Human Thermal Comfort and Health during Heat Waves: An Analysis of Heat Island Mitigation Strategies through a Case Study in an Urban Outdoor Environment. *Sustain. Cities Soc.* **2017**, *30*, 79–96. [CrossRef]

39. Xin, Y.; Shuang, H.; Qi, Z. Thermal Comfort Measurement and Landscape Reconstruction Strategy of Street Space Based on Decomposition Grid Method:A Case Study of Yangmeizhu Street. *J. Landsc. Res.* **2020**, *12*, 33–38+46. [CrossRef]
40. Theeuwes, N.E.; Solcerová, A.; Steeneveld, G.J. Modeling the Influence of Open Water Surfaces on the Summertime Temperature and Thermal Comfort in the City. *J. Geophys. Res. Atmos.* **2013**, *118*, 8881–8896. [CrossRef]
41. Sayad, B.; Alkama, D.; Ahmad, H.; Baili, J.; Aljahdaly, N.H.; Menni, Y. Nature-Based Solutions to Improve the Summer Thermal Comfort Outdoors. *Case Stud. Therm. Eng.* **2021**, *28*, 101399. [CrossRef]
42. Manteghi, G. A Field Investigation on the Impact of the Wider Water Body On-Air, Surface Temperature and Physiological Equivalent Temperature at Malacca Town. *Int. J. Environ. Sci. Dev.* **2020**, *11*, 286–291. [CrossRef]
43. Zheng, S.; Guldmann, J.-M.; Wang, Z.; Qiu, Z.; He, C.; Wang, K. Experimental and Theoretical Study of Urban Tree Instantaneous and Hourly Transpiration Rates and Their Cooling Effect in Hot and Humid Area. *Sustain. Cities Soc.* **2021**, *68*, 102808. [CrossRef]
44. Davtalab, J.; Deyhimi, S.P.; Dessi, V.; Hafezi, M.R.; Adib, M. The Impact of Green Space Structure on Physiological Equivalent Temperature Index in Open Space. *Urban Clim.* **2020**, *31*, 100574. [CrossRef]
45. Morakinyo, T.E.; Lam, Y.F. Simulation Study on the Impact of Tree-Configuration, Planting Pattern and Wind Condition on Street-Canyon's Micro-Climate and Thermal Comfort. *Build. Environ.* **2016**, *103*, 262–275. [CrossRef]
46. Chen, H.; Ooka, R.; Huang, H.; Tsuchiya, T. Study on Mitigation Measures for Outdoor Thermal Environment on Present Urban Blocks in Tokyo Using Coupled Simulation. *Build. Environ.* **2009**, *44*, 2290–2299. [CrossRef]
47. Huang, W.; Liu, X.; Zhang, S.; Zheng, Y.; Ding, Q.; Tong, B. Performance-Guided Design of Permeable Asphalt Concrete with Modified Asphalt Binder Using Crumb Rubber and SBS Modifier for Sponge Cities. *Materials* **2021**, *14*, 1266. [CrossRef] [PubMed]
48. Hong, X.-C.; Cheng, S.; Liu, J.; Dang, E.; Wang, J.-B.; Cheng, Y. The Physiological Restorative Role of Soundscape in Different Forest Structures. *Forests* **2022**, *13*, 1920. [CrossRef]
49. Hong, X.-C.; Liu, J.; Wang, G.-Y. Soundscape in Urban Forests. *Forests* **2022**, *13*, 2056. [CrossRef]