STUDY ON MICROCLIMATE REGULATION FOR CAMPUS WATERFRONT WITH DIFFERENT WATER SYSTEM STRUCTURES IN SUMMER HOT AND WINTER COLD REGIONS

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ABSTRACT

University campuses, characterized by their expansive scale and high proportion of green spaces, serve as crucial climate regulators in densely populated urban areas. In particular, the various water system structures within these campuses play a significant role in enhancing the microclimate of waterfront spaces. This research further elucidates the microclimatic regulatory functions of different water system configurations in waterfront areas located in regions with hot and humid conditions, thereby providing theoretical support for climate-adaptive development in similar urban environments. This study focuses on Xihua University, located in the suburbs of Chengdu, China, employing field measurements of the microclimate and numerical simulations using ENVI-met to conduct a comprehensive analysis of the microclimatic conditions at five distinct locations representing three types of water bodies on campus: overland permeable natural waterways, drainage channels, and ornamental lake surfaces. Notably, this research performs simulation analyses under extreme climatic conditions characterized by hot and humid conditions, assessing the microclimate regulation efficiency of various waterway structures based on meteorological factors such as air temperature, relative humidity, and wind speed. The research findings indicate that the efficiency of microclimate regulation varies significantly among different water systems within campus waterfront spaces. During the summer, the microclimatic regulatory function of the campus water system is relatively limited; however, in winter, the open landscape lake demonstrates a pronounced capacity for microclimate regulation. Additionally, factors such as the openness of waterfront spaces, surrounding buildings, and vegetation also exert a notable influence on the microclimatic environment. Moreover, in the development of urban waterfront spaces within regions characterized by hot and humid conditions, it is essential to consider the influence of vegetation, buildings, and surface materials on the microclimatic environment associated with water systems. Additionally, the arrangement and configuration of buildings and plants should be tailored to reflect seasonal variations in local climate conditions, thereby creating waterfront activity spaces that are well-adapted to these climatic factors.

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KEYWORDS

water system structure, campus waterfront space, microclimate, warm summer and cold winter areas

1. INTRODUCTION AND BACKGROUND

Colleges and universities serve as vital learning and living environments for faculty and students, constituting a significant component of urban public spaces. The quality of the microclimatic environment has a direct impact on the comfort of outdoor activities for these individuals, particularly in Chengdu, which is situated in a region characterized by hot and humid conditions; this challenging climate presents considerable obstacles to public activities on campus. Currently, the microclimate environment--the climatic conditions in the local environment on-site during the production and living processes--of campuses in cold regions has garnered increased attention from scholars (Shuo & Hongyuan, 2020). Utilizing on-site measurements, ENVI-met simulations, and other methodologies, a quantitative analysis was performed on the spatial layout patterns of campus buildings (Li-di, Yi-meng et al., 2019), the relationship between the enclosure degree of campus plazas and the microclimate environment (Weiwei & Yanan, 2019), energy-saving design strategies for campus complexes (Liang, Liqiang et al., 2018), comparative analyses of the microclimatic regulation functions of various types of green spaces (XIONG Y, 2018), as well as indicators such as floor area ratio, paving coverage ratio, and building density (Shaojie, Zihui et al., 2022). This study elucidated the key landscape elements and principles that influence microclimates in cold-region campuses and proposed specific methods and pathways for optimizing their spatial design (Chen, Cui et al., 2021; Deng, Jia et al., 2022; Fuladlu, 2021).

From a climatic perspective, while cold climates are recognized as extreme, the hot and humid climate characteristic of summer in certain regions also qualifies as another form of extremity. Consequently, some scholars have begun to focus on the microclimatic characteristics of summer campuses in these humid and hot areas (Qiong, Jian-qiong et al., 2060), explicitly indicating that improvements in indicators such as summer wind environment, air temperature, and relative humidity are crucial for enhancing outdoor activity comfort (Chao, Zhuoxin et al., 2021; K, R et al., 2024; Shangkai, Yu et al., 2022; Yan, Xuelian et al., 2023; Yihao, Siyu et al., 2022; Yuting & Qiang, 2023). In contrast to regions characterized by warm winters and hot summers, Chengdu faces not only the challenges posed by a hot summer climate but also the impacts of a cold winter climate, an area that has been relatively under-researched. Therefore, conducting simultaneous studies on the microclimate environments of campus spaces during both winter and summer in Chengdu is of significant importance.

Water systems constitute a vital element of campus landscapes, and their microclimatic regulation functions have been substantiated by extensive research (Wong, He et al., 2021; Xu, Lin et al., 2022; Zhao & Fong, 2017). However, regarding campus landscape spaces, research on water systems primarily concentrates on the planning and design of rainwater retention strategies informed by Low Impact Development (LID) and sponge city concepts (C & Y, 2011; L & Y, 2015; Yan-hong, Dong-dong et al., 2017; Zhong, Qiaomei et al., 2020). This focus emphasizes measures for conserving water resources and protecting aquatic environments while neglecting the critical regulatory functions that water systems provide in campus waterfront areas (Q, 2009; Z. P. Y, 2019; Z. Y. Y & P, 2015). Furthermore, there is a lack of discussion concerning the comparative analysis of microclimate regulation efficiencies among different water system structures. Consequently, a comparative analysis of the microclimatic regulation efficiency of various water system structures at Xihua University will enhance our understanding of the beneficial role that campus water systems play in microclimate regulation from a scientific and quantitative perspective.

The primary aim of this study is to investigate the variations in microclimate regulation provided by water bodies situated within building perimeters in regions characterized by hot and humid conditions. This research seeks to identify the optimal spatial configuration of water bodies for campus environments under such climatic conditions, thereby offering valuable insights for the planning and design of waterfront spaces on campuses. To achieve this objective, we will systematically address the following three questions:

1. What role do water bodies play in regulating microclimates within building perimeters in areas with hot and humid conditions?
2. Are there seasonal differences in the microclimate regulation functions of various water body structures (in terms of scale)?
3. What constitutes the most suitable water body structure for regions experiencing hot and humid conditions?

2. STUDY SITE

2.1 Fundamental information

Xihua University is situated in the Pidu District of Chengdu (30.7°N, 103.9°E) and is recognized as a large-scale comprehensive institution, encompassing an area of approximately 2 km^2. The campus features a greening system primarily composed of lawns, trees, and artificial lakes, achieving a greening rate of 66.1% and coverage rate of 72.7%. Leveraging the natural advantages provided by the Tuojiang River, a tributary of the Minjiang River, the university has developed an artificial lake spanning over 100 acres and established an intricate network of waterways throughout the campus. This diverse array of water landscapes includes lakes, canals, and interconnected natural water systems, thereby laying the groundwork for comparative studies on the microclimate regulation efficiency associated with various water system structures in waterfront spaces (Figure 1).

2.2 Climatic characteristics

According to the climatic zoning classification in China (Using the average temperature in January, the average temperature in July, and the average relative humidity in July as the primary indicators, China is categorized into a total of seven distinct climate zones), Chengdu is situated in a region characterized by hot and humid conditions, exhibiting climate features of high temperatures during summer, low temperatures in winter, prolonged spring and winter seasons, and a relatively short autumn. In order to further elucidate the climatic characteristics and the dates of extreme weather events in Chengdu, we conducted an analysis of the EnergyPlus meteorological data set (CHN_Sichuan.Chengdu.562940_CSWD) utilizing Climate Consultant 6.0. The results indicate (Figure 2 & Figure 3) that the temperature distribution in Chengdu during spring and autumn falls within the comfortable range, whereas in winter and summer

FIGURE1. Study area.

it is significantly below or above this range. Notably, throughout winter, the entire temperature distribution remains below the comfort threshold. Analyzing the daily average temperature distribution (Figure 4), we observe that midday represents the peak of summer temperatures, while morning and evening temperatures are comparatively lower and maintain a relatively stable level. This underscores that shading and sun protection during afternoon hours are crucial for microclimate regulation in outdoor spaces during summer. The annual distribution of solar radiation is markedly uneven (Figure 5), characterized by intense solar radiation during the summer, with peak values reaching up to 785 W/m^2, while exhibiting relatively lower levels in spring and winter. Similarly, the daily distribution of solar radiation demonstrates significant variability, necessitating shading during afternoon hours while requiring sunlight at other times, thereby revealing a distinct contradiction in its distribution patterns. The wind environment in Chengdu is suboptimal (Figure 6), maintaining consistently low wind speeds throughout the year. However, there is an improvement in wind conditions during summer; this enhancement coincides with elevated humidity levels that persist year-round. The mild temperatures experienced in spring and autumn combined with high humidity contribute to a comfortable microclimate; conversely, the cold winters and hot summers exacerbated by high humidity further deteriorate microclimatic conditions.

This study aims to investigate the variations in microclimate regulation efficiency among different water system structures under extreme weather conditions, while also conducting a detailed analysis of the annual trends in average daily temperature in Chengdu. The results indicate (Figure 7) that January 1st is the coldest day in Chengdu, with an average daily temperature of 2.65°C, whereas July 22nd marks the hottest day, with an average daily temperature reaching 28.99°C.

FIGURE 2. Psychrometeric chart of Chengdu.

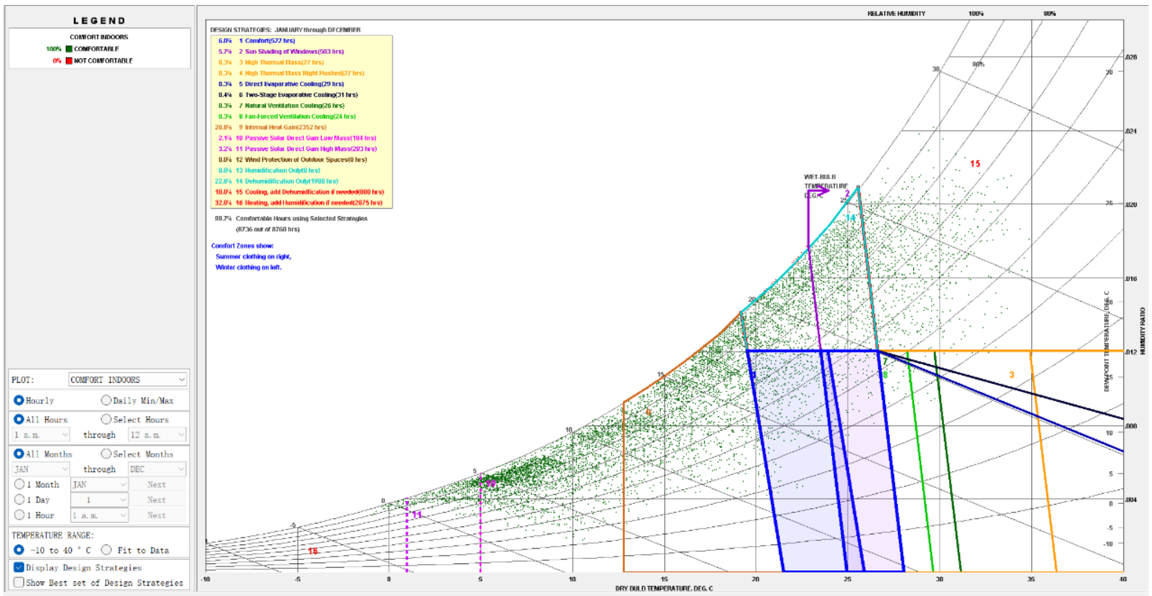


FIGURE 3. Monthly average temperature annual variation trend and comfort distribution range.

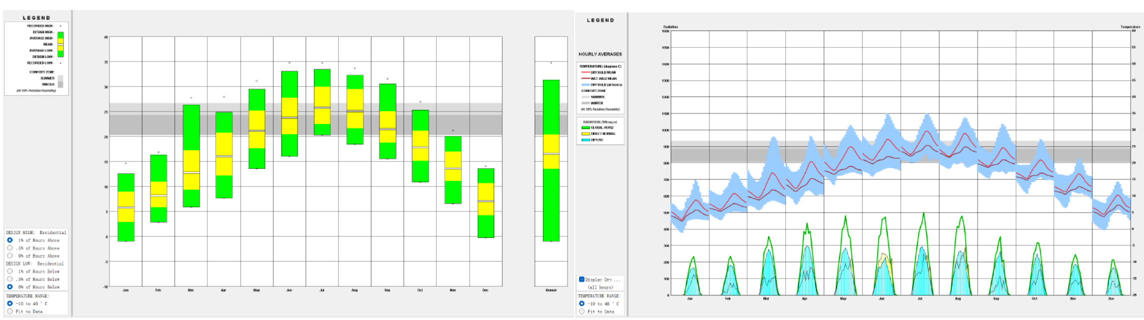


FIGURE 4. Annual temperature fluctuation trend by the hour.

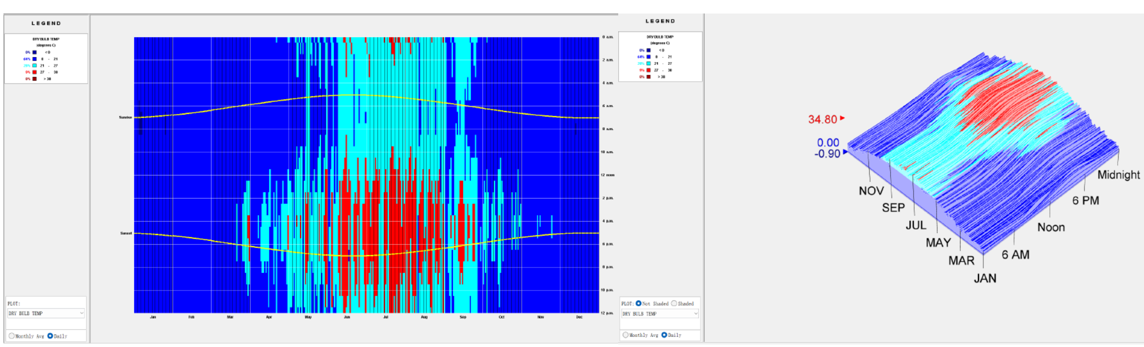


FIGURE 5. Trends in annual solar radiation and shading requirements.

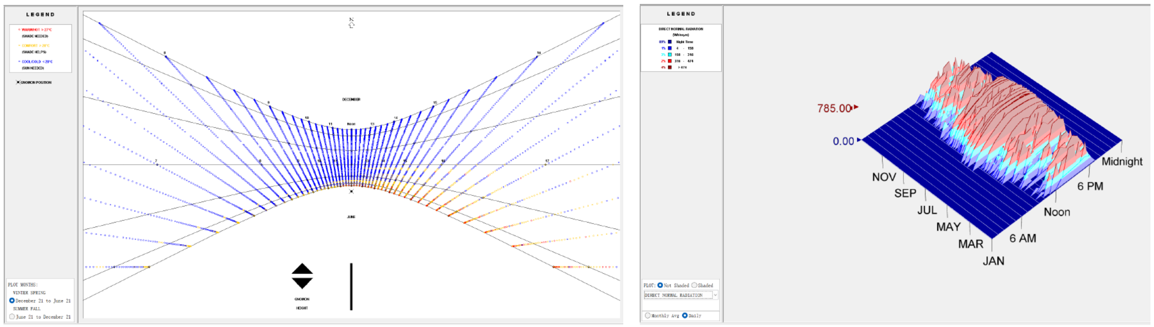


FIGURE 6. Trends in annual wind speed and relative humidity.

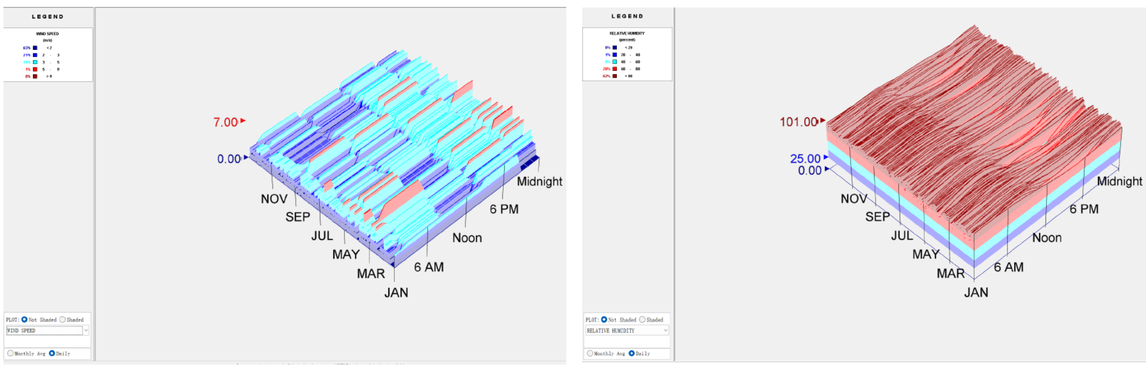
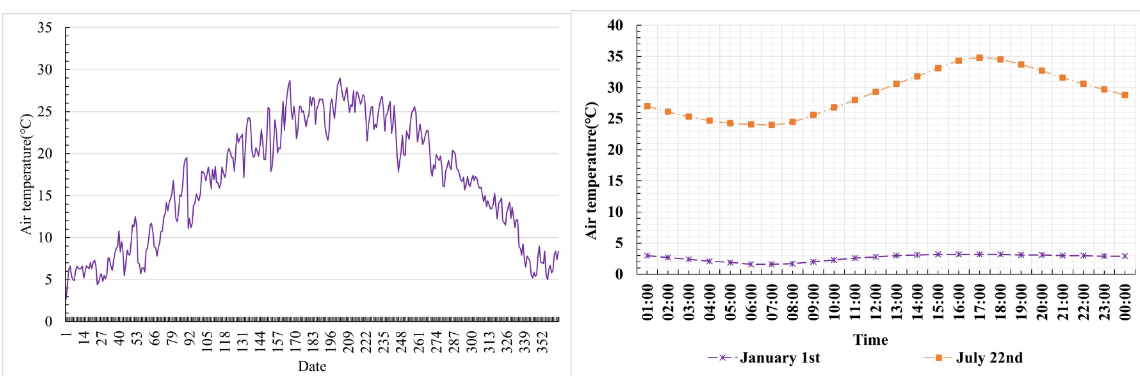


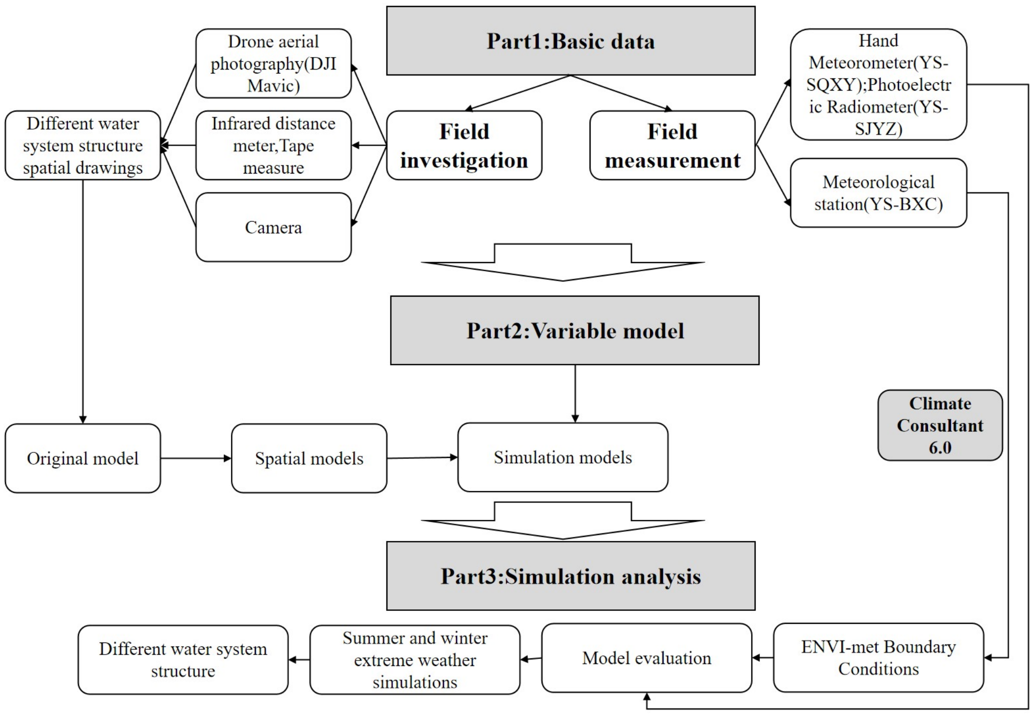
FIGURE 7. The annual temperature trend in Chengdu city.



3. RESEARCH FRAMEWORK

This study will adhere rigorously to the research framework of microclimate studies, encompassing 'field measurement-model verification-simulation analysis.' Initially, detailed spatial surveys will be conducted to characterize the study samples, accompanied by simultaneous microclimate measurements to gather foundational data. Subsequently, numerical models for each sample space will be developed and simulated using ENVI-met; the output data will then be compared with measured data to validate the accuracy of both the model and simulation

FIGURE 8. Research framework.



environment. Finally, these models will undergo simulations under extreme climatic conditions on July 22nd and January 1st to assess variations in microclimate regulation efficiency among different water system structures within campus waterfront spaces, ultimately identifying the optimal configuration for campus water systems (Figure 8).

4. METHOD

4.1 Measured microclimate

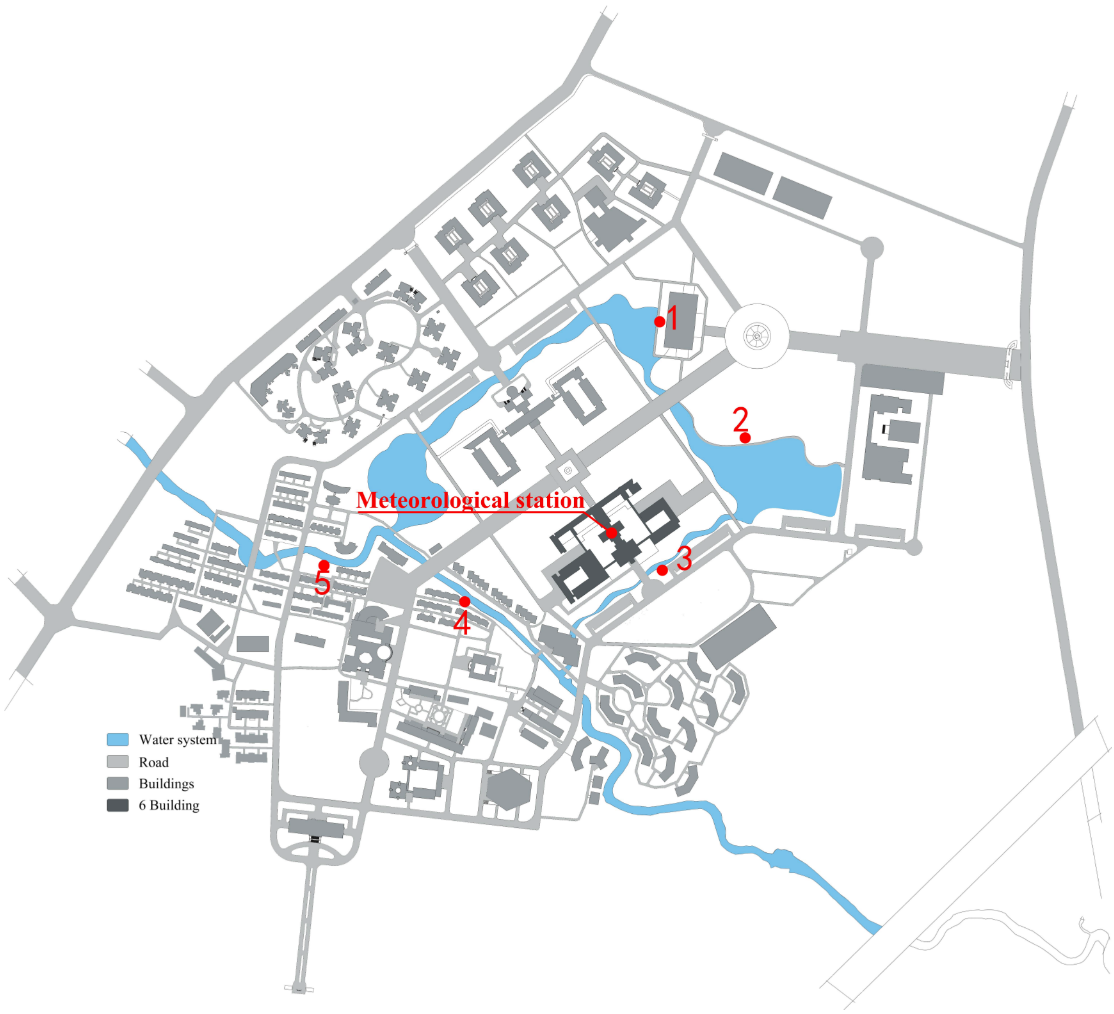
4.1.1 The date and time of the actual measurement

To ensure the accuracy of the measured results, we selected a clear day (October 26th) following three consecutive days of sunny weather as the measurement date, with continuous data recording conducted from 7:00 AM to 7:00 PM. Data were recorded every 10 minutes, with an hourly test interval. The average of six recorded data points from six consecutive measurements was calculated and used as the representative value for that time period.

4.1.2 Measurement point arrangement

Informed by the characteristics of three types of water systems (natural waterways, canals, and lakes) and their surrounding environmental features on campus, we established five measurement points to collect meteorological data throughout the campus. The specific measurement point was positioned at the geometric center of the area, ensuring no obstruction from plants or buildings. Additionally, an automatic meteorological station was installed on the roof of Building 6 to gather environmental meteorological data. The specific arrangement of measurement points is illustrated in Figure 9.

FIGURE 9. Layout of measurement points.



4.1.3 The empirical methodology

(1) Collection of background meteorological data

1. Acquire EPW data by downloading the climate package for the research area from the official EnergyPlus website (https://energyplus.net/): (CHN_Sichuan. Chengdu.562940_CSWD).
2. Utilize Climate Consultant 6.0 to export historical meteorological data for Chengdu, followed by visualization and analysis to identify periods of extreme weather events and notable climatic characteristics in the region.

(2) Real-time meteorological data collection on campus

An automatic weather station (model: YS-BXC) has been installed in the highest open area of the campus to collect meteorological data, including temperature, humidity, wind speed, wind direction, precipitation, solar radiation, and atmospheric pressure. The data collection interval is configured to 1 minute with continuous monitoring conducted over a period of 3 days.

(3) Meteorological data collection at measurement points

1. Formulate a Field Measurement Protocol: Organize a field measurement team according to the number of measurement points, assigning each member a handheld meteorological instrument (model: YS-SQXY) and a pyranometer (model: YS-SJYZ)
2. Detailed Field Measurement Procedure: Each team member continuously monitors one designated measurement point, with the equipment positioned 1.5 meters above ground level. Monitoring occurs from 7:00 to 19:00; due to significant outdoor interference, data collection is limited to daytime hours to ensure experimental safety. The data collection interval is set at 10 minutes, during which temperature, humidity, wind speed, wind direction, solar radiation, and atmospheric pressure are simultaneously recorded.

4.2 ENVI-met simulation

ENVI-met is widely recognized for its application in simulating outdoor microclimate environments. It employs computer modeling and utilizes specific computational algorithms to simulate microclimatic conditions, providing outputs such as temperature, humidity, wind speed, wind direction, and solar radiation—data that aligns with the requirements of this study. The version used in this research is ENVI-met 5.7.2. Despite its widespread use in outdoor environment simulations, ENVI-met has limitations in accurately calculating thermal radiation from ground surfaces and building facades, which can result in simulated temperatures being slightly lower than actual values. Given that this study focuses on comparing and analyzing the microclimate regulation effects of different water system spatial structures, the minor temperature discrepancies are deemed acceptable. Therefore, ENVI-met is considered an appropriate simulation tool for this study.

4.2.1 Model area

The water system exerts an influence on the microclimate regulation of a limited range of waterfront areas, whereas the microclimate environment in regions distant from the water system remains unaffected. Prior research has demonstrated that the impact of water systems on air temperature and relative humidity extends between 80m and 100m (X, 2022). Accordingly, this study centers around the measurement point and delineates an approximate sample area of 200m × 200m based on the distribution characteristics of adjacent buildings and vegetation (Figure10). In the 'Space' module of ENVI-met, the following model conditions are established: (1) The latitude and longitude of the simulation area are configured according to its actual geographical location: 30.7°N, 103.9°E; (2) The grid dimensions are determined based on the scale of the simulation space: dx=5, dy=5, dz=2; (3) Appropriate model parameters are assigned in accordance with the specific spatial characteristics of the measurement points.

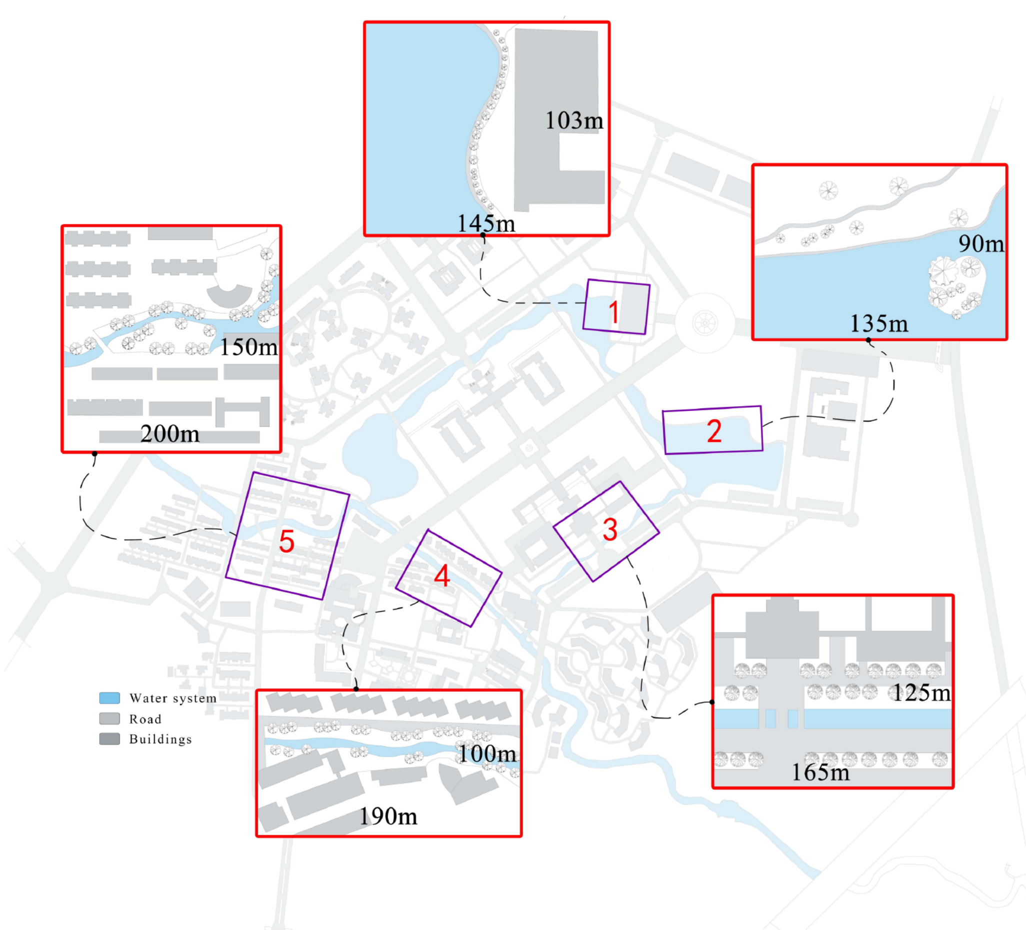
4.2.2 Model

Initially, we organized the spatial mapping data and constructed a three-dimensional model of the volume. Subsequently, we developed a numerical simulation model in ENVI-met tailored to the specified simulation area, with detailed model parameters provided in Table I.

4.2.3 Boundary conditions

In accordance with the research objectives, we constructed simulation environments for model validation corresponding to October 26, the coldest day on January 1, and the hottest day on

FIGURE 10. Sampling area for simulation model.



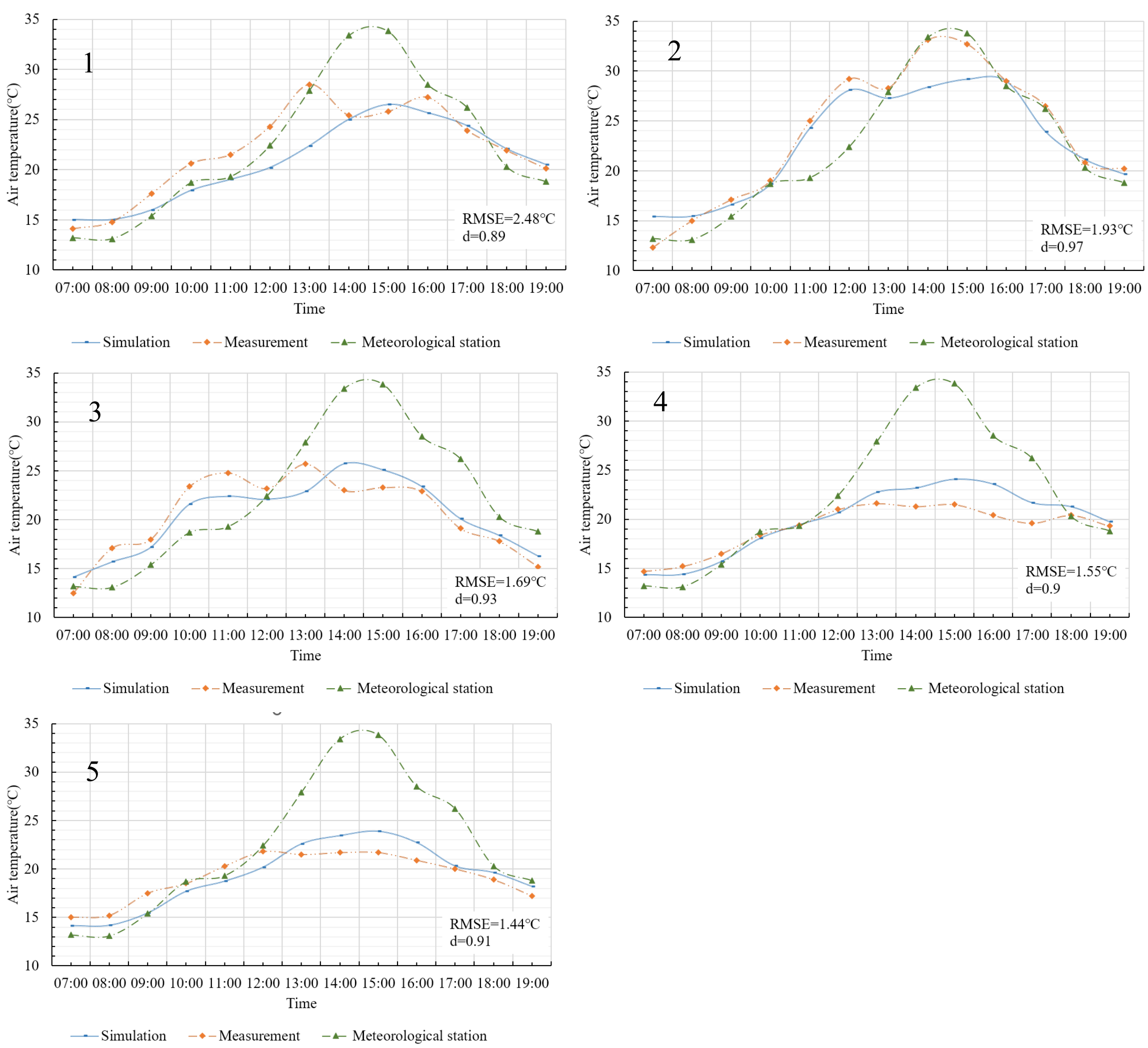
July 22. The specific boundary conditions are outlined as follows: Given that ENVI-met necessitates a preparation time of one hour for simulations, we executed a total simulation duration of 25 hours to acquire data for a full 24-hour period. Consequently, we designated the Start Time as 00:00 and set the Total Simulation Time to 25 hours. For the simulation environment on October 26, boundary conditions were derived from temperature, humidity, wind speed, and wind direction measurements obtained from an automatic weather station. In contrast, for both the coldest and hottest days' simulations, boundary conditions were based on temperature, humidity, wind speed, and wind direction data sourced from the Energyplus dataset.

4.2.3 Model Validation

To verify the simulation results, we calculated the root mean square error (RMSE) and the coefficient of determination (d). This method has been widely used to validate simulation models (Abdalazeem, Hassan et al., 2024; Fujiwara, Khomiakov et al., 2024; Han, Chong et al., 2024). The accuracy of this method has also received widespread acknowledgment (Forouzandeh, 2018; Li, Yang et al., 2023; Liu, Middel et al., 2024; Wu, Fang et al., 2023; Xin, Zhao et al., 2022). We conducted simulations of the original model within the simulation environment on October 26th and performed a comparative analysis between the simulated data and measured data to derive the value of d. The value of d ranges from 0 to 1, with values approaching 1 indicating greater reliability of the model. Generally, when d exceeds 0.9, we can deem the model as reliable (Eckmann, Morach et al., 2018). The analysis of the simulation results in conjunction with the fitting of the measured data (Figure 11) demonstrates that the simulated outcomes for all five measurement points exhibit a strong correlation with the observed data, thereby indicating that both the models and simulation environments for each measurement point are reliable.

At the first measurement point, the simulated data consistently fell below the measured data during the period from 7:00 AM to 2:00 PM. This discrepancy can be attributed to the influence of thermal radiation from hard surfaces in proximity to the measurement point, which ENVI-met was unable to accurately quantify, leading to an underestimation in simulation results. At the second measurement point, the simulated data was significantly lower than the measured data during the period from 14:00 to 16:00. This discrepancy arises because ENVI-met tends to amplify the microclimatic benefits provided by water surfaces while neglecting the effects of increased solar radiation. In contrast, the simulation results for both the fourth and fifth measurement points were generally consistent with their corresponding measured results;

FIGURE 11. Model validation.



however, during the afternoon period from 13:00 to 18:00, simulated values were notably higher than observed values. This overestimation can be attributed to ENVI-met's inability to accurately represent flow characteristics in natural interconnected water systems, leading to an underappreciation of heat dissipation associated with water movement. Although ENVI-met exhibits certain biases in climate simulations for specific parameters, the trends observed in the simulation data are largely consistent with the measured results, thereby accurately reflecting the microclimatic conditions surrounding the measurement point. Consequently, both the model and simulation environment can be considered credible.

5. THE EFFICACY OF MICROCLIMATE REGULATION FOR CAMPUS WATERFRONT SPACES FACILITATED BY VARIOUS WATER SYSTEM STRUCTURES

The empirical results indicate that the waterfront space exerts a significant regulatory influence on the microclimate environment, exhibiting a dynamic trend of variation. During periods of low ambient temperature, the temperature within the waterfront space is markedly higher than that of the surrounding environment; conversely, as ambient temperatures increase, the temperature in the waterfront space becomes notably lower than that of its surroundings, demonstrating a more gradual pattern of thermal fluctuation (Figure 12). Among the five measurement points, Point 5 exhibited the lowest daily average temperature, which was 3.14°C below the ambient temperature, whereas Point 2 recorded the highest daily average temperature, exceeding the ambient temperature by 0.6°C. This phenomenon can be attributed to the dense vegetation at Point 5, which significantly attenuates solar radiation intensity, resulting in an average daily solar radiation of only 32 W/m^2. In contrast, Point 2 experiences a substantially higher average daily solar radiation of 319 W/m^2. These findings indicate that the microclimate regulation capacity of waterfront spaces is influenced not only by variations in water system structures but also by specific characteristics of landscape element composition.

A comparative analysis of the microclimate regulation effects of various water system structures in waterfront spaces indicates that natural water systems characterized by unimpeded flow exhibit superior microclimate regulation capabilities. The inherent fluidity of these unimpeded water systems facilitates the removal of environmental heat, thereby reducing the temperature within the waterfront space. Consequently, it can be anticipated that such natural water systems will maintain enhanced microclimate regulation effectiveness under extreme hot summer conditions; however, their performance during winter requires further simulation and validation. A water channel is a linear space created through revetment canalization, and its distinctive spatial configuration significantly facilitates the enhancement of the wind environment, thereby forming a wind corridor. Consequently, it exerts a pronounced effect on microclimate improvement, with an average daily temperature that is 1.9°C lower than that of the surrounding environment (Figure 13). Nevertheless, the anticipated performance of landscape ponds, which were predicted to exhibit stronger microclimate regulation at the outset of the study, did not surpass that of interconnected natural water systems and canals. Large water bodies demonstrate greater climate stability; therefore, their microclimate regulation capabilities require validation under extreme weather conditions. The simulation results further corroborate the accuracy of the empirical findings. As illustrated in Figure 14, interconnected natural water systems and canals provide superior wind environments, thereby influencing the microclimate conditions within waterfront spaces.

FIGURE 12. Daily temperature and humidity trends at each measurement point.

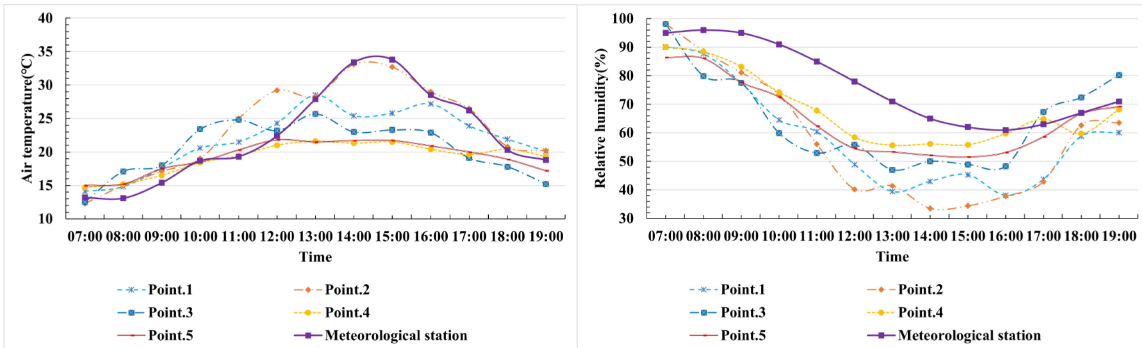


FIGURE 13. Daily wind speed trends at each measurement point.

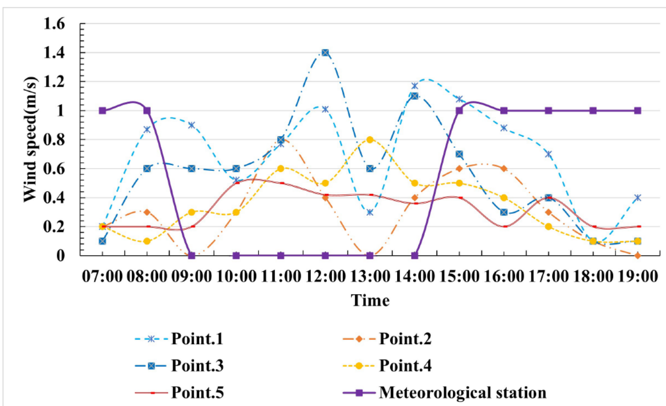
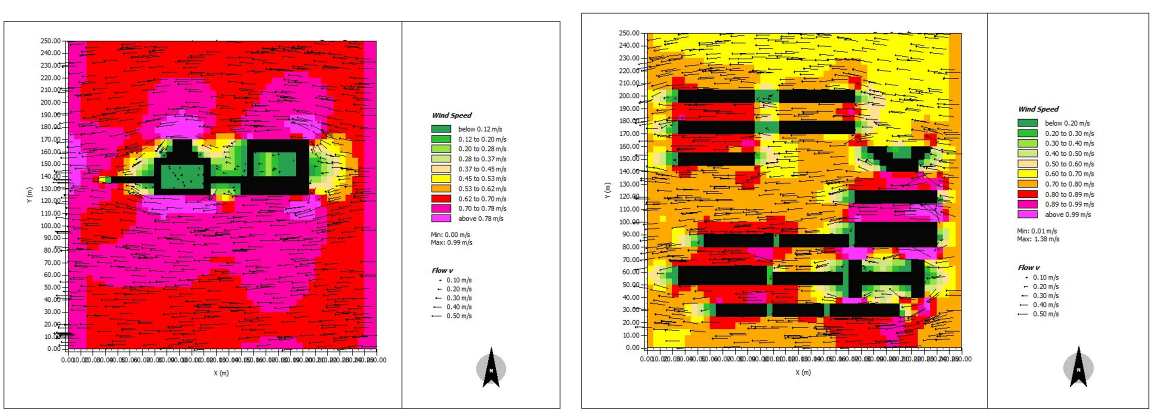


FIGURE14. 6:00 Wind environment simulation results (left: 3rd measurement point, right: 5th measurement point).



6. A COMPARATIVE ANALYSIS OF THE MICROCLIMATE REGULATION CAPACITIES OF VARIOUS WATER SYSTEM STRUCTURES UNDER EXTREME CLIMATIC CONDITIONS

6.1 Simulation results for the coldest day of Winter

The simulation results indicate that various water system structures within the campus contribute to the enhancement of the microclimate environment in waterfront spaces during the coldest day of winter. Notably, the regulation effect observed at measurement point 2 (open large water surface) is the most pronounced, achieving an improvement efficiency of 155%, with an average temperature that is 4.11°C higher than that of the surrounding environment (Figure15). The high specific heat capacity of water bodies (4.184 kJ/(kg·°C) plays an important role in improving the microclimate environment of waterfront spaces. For every 1°C rise in the temperature of 1 kg of liquid water, 4200J of heat can be stored, which is released at night to improve the microclimate environment. As for the wind environment, in the cold air flow area, the average daily wind speed in winter can reach 2.7m/s and the maximum wind speed can reach 4m/s. However, the simulation results show that the wind environment of all waterfront spaces has been improved and is relatively stable. This is mainly due to the insulation effect of water bodies, which form a smaller temperature difference with land and thus weaken the impact of cold on the microclimate (Figure 16).

The results presented above suggest that water bodies exert a more significant regulatory influence on environmental and climatic conditions compared to other factors. For instance,

FIGURE 15. Comparison analysis of water temperature and wind speed in different river systems.

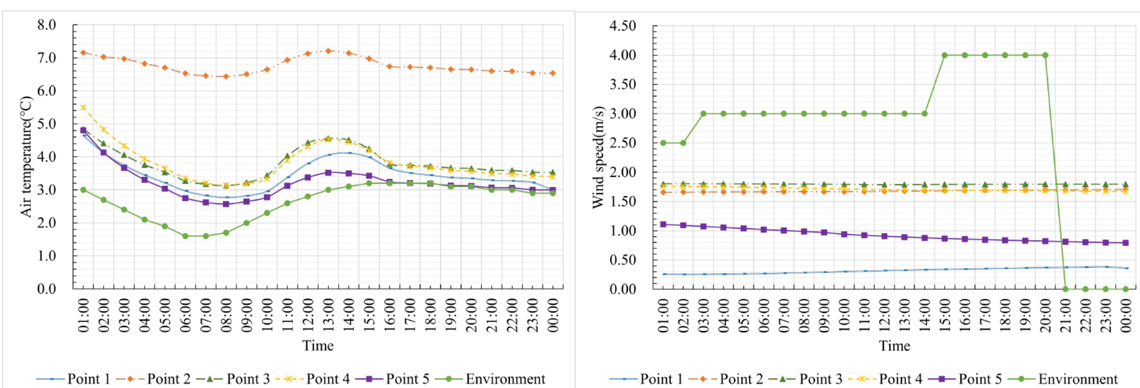
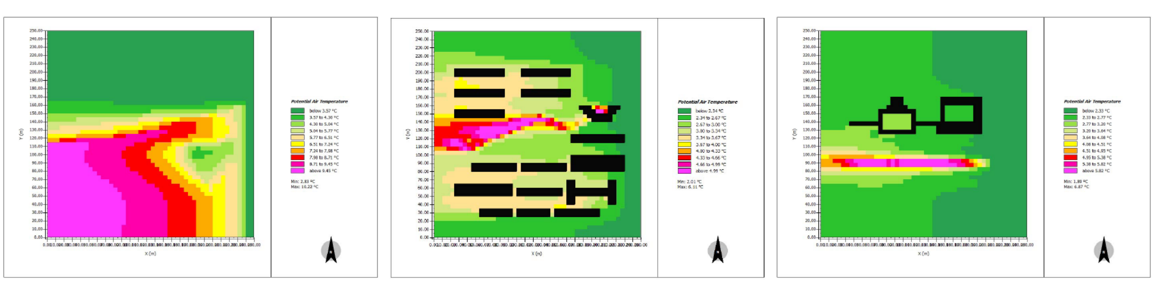


FIGURE16. Simulated temperature at 6:00 am for different water system structures (left: lake, middle: interconnected natural water system, right: canal).



both Measurement Point 1 and Measurement Point 2 are situated adjacent to open water surfaces; however, despite the superior wind conditions and shading provided by buildings at Measurement Point 1, its temperature is lower than that of Measurement Point 2 (Figure 17). While the building mitigates cold winds and exerts a notable influence on the microclimate of the area surrounding Measurement Point 1, resulting in an average daily temperature that is 0.8°C higher than that of the ambient environment, its regulation efficiency is significantly lower compared to Measurement Point 2. This discrepancy primarily arises from heat absorption by the building's facade and surface materials, which adversely impacts the local microclimate. Therefore, in regions characterized by hot and humid conditions, waterfront spaces should ideally be situated away from buildings, with lower surfaces composed predominantly of natural materials possessing high specific heat capacities to ensure adequate thermal provision for the environment.

In the case of permeable water system structures, continuous water flow tends to dissipate ambient heat, resulting in a suboptimal microclimate regulation capacity. The average daily temperature is observed to be 0.57°C higher than that of the surrounding environment (Figure18), particularly between 16:00 and 24:00, when the temperature of the waterfront space closely aligns with that of the ambient environment. This phenomenon occurs because while ambient temperatures gradually rise during the afternoon, the temperature within the waterfront space

FIGURE 17. Simulated wind speed at point 1(left) and point 2 (right) at 17:00.

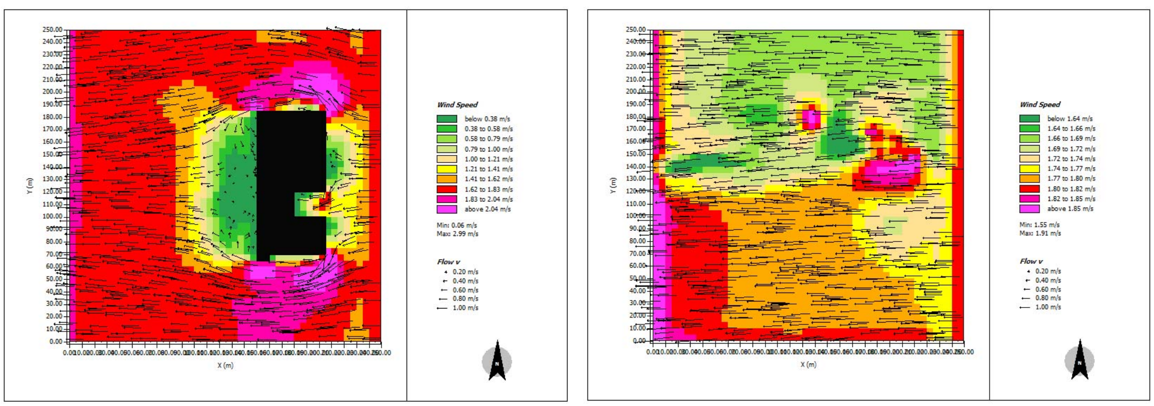
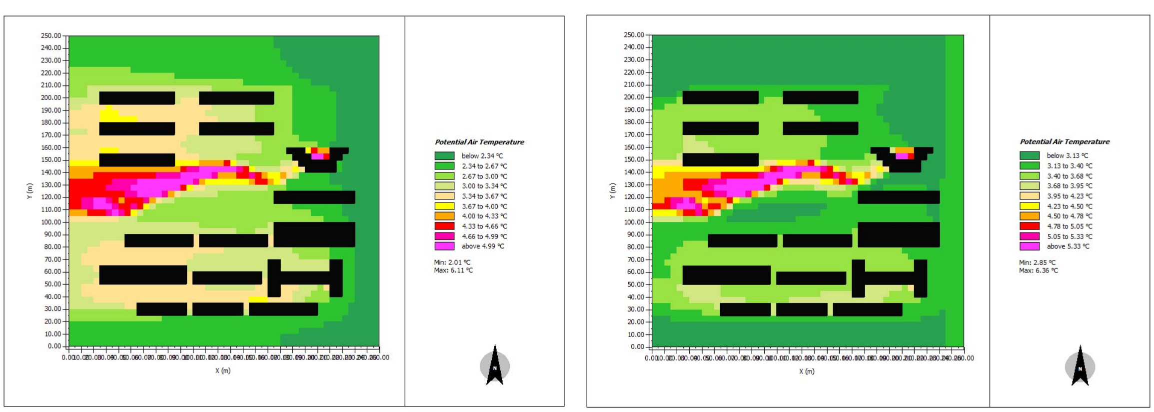


FIGURE 18. Simulated temperature results for the interconnected water system structure at 6:00 and 17:00.



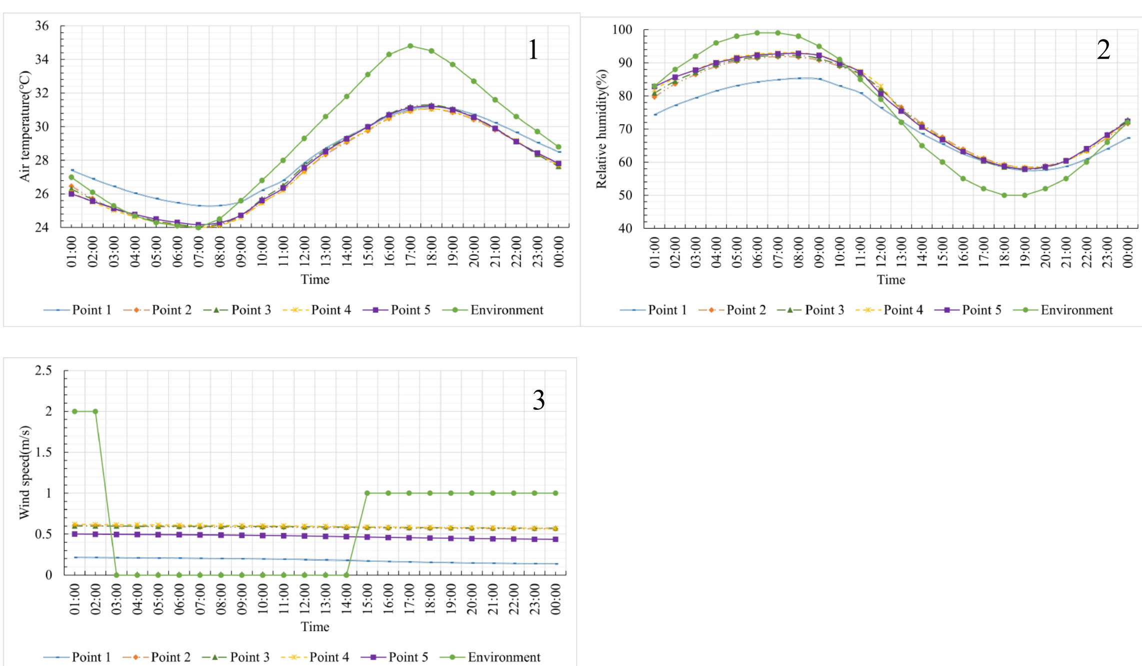
remains relatively stable due to water flow influences, ultimately leading to thermal equilibrium between these two areas. Consequently, it is evident that in winter months, permeable water system structures can adversely affect thermal comfort in waterfront spaces; thus, this factor should be considered when planning outdoor activity zones.

6.2 Simulation results for the hottest day of Summer

Extreme climatic conditions in regions characterized by hot and humid conditions are particularly pronounced, especially during the afternoon when intense solar radiation leads to a rapid increase in air temperature, reaching approximately 35°C. This phenomenon significantly affects the outdoor activities of faculty and students at numerous universities. The simulation results indicate that while water bodies exert some microclimate regulation effects in hot summer environments, their regulating efficiency is markedly lower than during winter months. For instance, the lowest daily average temperature recorded at the 2nd and 4th measurement points is 27.4°C, which is 1.6°C below the ambient temperature, resulting in a regulating efficiency of only 5.5%. This represents a substantial disparity compared to the 155% regulating efficiency observed at the 2nd measurement point in winter. The primary reason for this phenomenon lies in the high specific heat capacity of water bodies, allowing them to absorb significant amounts of heat. In winter, when ambient temperatures are low, this property can facilitate an increase in waterfront space temperatures; however, during summer months, it produces an opposing effect where elevated water temperatures contribute to heating the surrounding air and subsequently influence the microclimate of waterfront areas.

A comparison of the simulation results for different water system structures (Figure 19) reveals that the daily average temperatures at measurement points 2 to 5 range from 27.4°C to

FIGURE 19. Comparison and analysis of simulation results of different river system structures. 19-1: daily air temperature changes; 19-2: daily relative humidity changes; 19-3: daily wind speed changes.



27.5°C, whereas measurement point 1 exhibits a significantly higher daily average temperature of 28.1°C, which is only 0.9°C lower than the ambient temperature, particularly pronounced during nighttime hours. This phenomenon can be attributed to the thermal radiation emitted by surrounding buildings and hardened materials affecting measurement point 1, leading to continuous heating of the air temperature. During the night, both the water body and hardened surfaces release substantial amounts of heat, thereby influencing the microclimate in proximity to this measurement point (Figure 20). Regarding relative humidity, the 1st measurement point exhibited significantly lower nighttime humidity levels compared to the other points, a phenomenon influenced by the surrounding hard surfaces. As the water body heats and evaporates, it contributes to a higher humidity environment in the waterfront space, particularly during hot afternoon hours when relative humidity in this area is approximately 10% greater than that of the ambient conditions. This results in a hot and humid microclimate that is notably uncomfortable for regions characterized by summer heat and winter cold (Figure 21).

Regarding the wind environment, the simulation results across all measurement points align with the environmental data, except for measurement point 1, which is obstructed by buildings and exhibits an average wind speed of 0.18 m/s—0.4 m/s lower than that of the surrounding environment (Figure 22). This indicates that in summer, due to prolonged solar exposure, the temperature differential between water and land diminishes, subsequently affecting air

FIGURE 20. Point 1 temperature and humidity simulation results at 6:00.

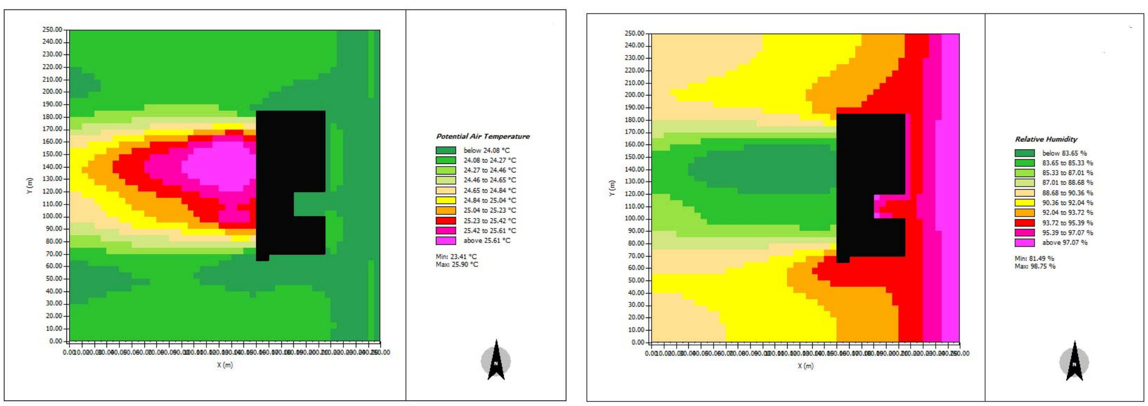


FIGURE 21. 17:00 relative humidity simulation results at Point 1 (left) and Point 5 (right).

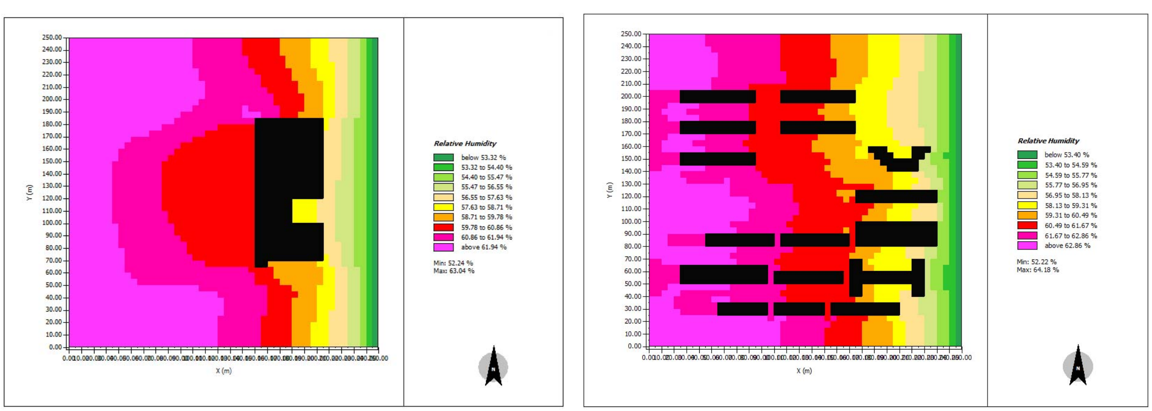
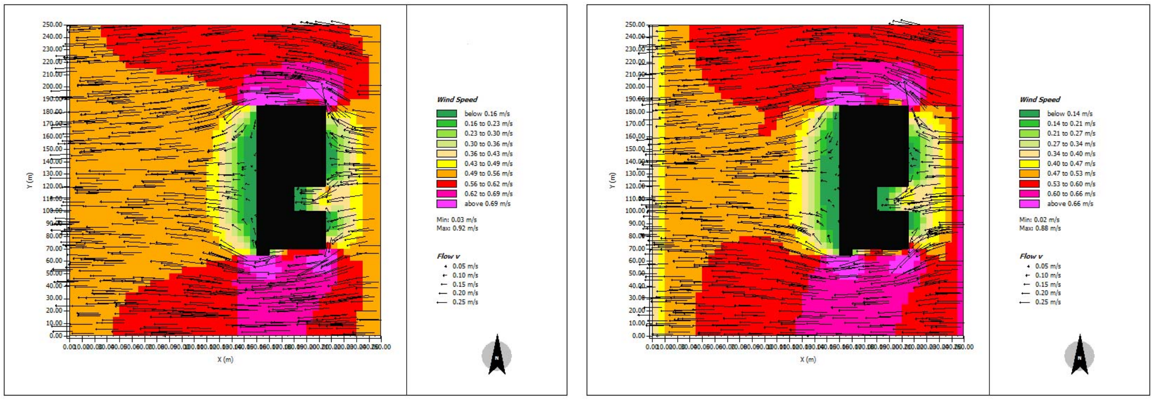


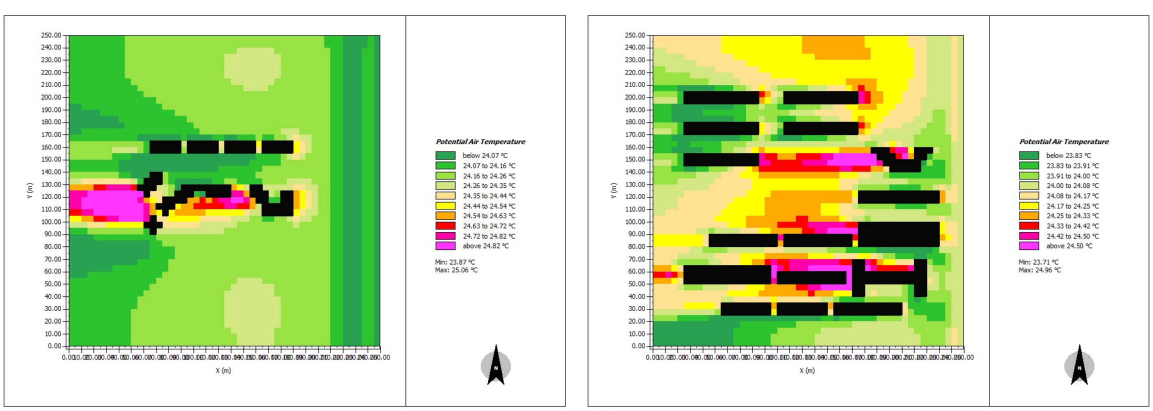
FIGURE 22. Point 1 wind speed simulation results at 6:00 (left figure) and 17:00 (right figure).



flow patterns. This observation is further corroborated by simulation results showing that the average nighttime wind speed significantly exceeds that of the ambient conditions (Figure 19-3). Consequently, it can be concluded that in extreme summer climate scenarios, the influence of water bodies on the wind environment within waterfront spaces is limited. However, following rapid cooling of water temperatures at night, an increased temperature gradient between land and water enhances air movement, thereby improving wind conditions to some extent.

Although water bodies play a limited role in regulating the microclimate of waterfront spaces during extreme summer conditions, their significant capacity for heat absorption renders them notably effective in microclimate regulation at peak environmental temperatures around 17:00 (Tab. II). Conversely, in winter climates, permeable natural watercourses that typically facilitate heat dissipation fail to exhibit their intended function under extreme heat conditions; instead, they transport upstream heat to the measurement point, resulting in slightly elevated ambient temperatures compared to surrounding areas. Additionally, the hardened materials flanking both sides of the water channel further exacerbate the degradation of the microclimate environment near the measurement point, leading to higher daily average temperatures than those observed at other measurement points (Figure 23).

FIGURE 23. Simulation results of continuous natural waterway waterfront space temperature at 6:00.



In conclusion, the microclimate regulation capacity of water bodies in regions characterized by hot and humid conditions is not pronounced under extreme summer climate conditions; however, they can still absorb heat from the environment due to their high specific heat capacity, resulting in a slight reduction in ambient temperature. Conversely, this process also leads to an increase in the relative humidity of the waterfront space. During periods of elevated summer temperatures, the influence of buildings and surface materials on outdoor microclimates becomes more pronounced. Therefore, to enhance the microclimate environment of waterfront spaces in these areas, it is essential to manage surface materials and building density effectively.

7. DISCUSSION

7.1 The influence of the water system on the microclimate of campus waterfront spaces is notably limited

It is widely recognized that water bodies can generate local microclimates; regardless of the season, waterfront spaces consistently offer a more comfortable microclimate (Jang, Kim et al., 2022; Lu & Fu, 2019). However, our simulation analysis reveals that the microclimate regulation effects of interconnected natural water systems, canals, and lake surfaces are notably limited. In contrast, factors such as surface materials and proximity to buildings in waterfront spaces exert a more significant influence, aligning with findings from various studies on the impact of green spaces and built environments on microclimatic conditions (Hyun & Shin, 2018; R., M. et al., 2021). Consequently, in the investigation of microclimates within waterfront spaces, it is essential to rigorously control variables and perform multiple simulations alongside comparative analyses to elucidate the role of water systems in modulating the microclimate.

7.2 In regions characterized by hot and humid conditions, the microclimatic regulatory function of water systems is not pronounced during extreme summer weather conditions

The summer hot and winter cold regions differ from those characterized by either hot summers or cold winters, as their climatic environment is perpetually in a state of dynamic change, exhibiting both extreme heat and cold simultaneously. Consequently, designing climate-adaptive outdoor public spaces in these areas presents significant challenges. Although researchers have delineated specific design strategies for outdoor public spaces in extreme climates, including hot, humid, arid, and cold regions (Dhariwal, Manandhar et al., 2019; Fraqueza, Rocha et al., 2019; Julia & Dingkuhn, 2013) "However, our research also demonstrates that the microclimatic regulatory function of water systems varies significantly under two extreme climatic conditions in summer hot and winter cold regions. For instance, open water surfaces can store substantial amounts of heat during winter, thereby elevating the temperature of waterfront spaces, which is advantageous. Conversely, in summer, this same characteristic may lead to a rapid increase in water temperature and heightened evaporation rates, resulting in an extremely uncomfortable environment characterized by high temperatures and humidity during the afternoon, which is detrimental.

7.3 The microclimatic regulatory function of aquatic systems primarily relies on their distinctive specific heat capacity

In contrast to vertical interface elements such as buildings, vegetation, and topography, water systems function as horizontal elements that are not influenced by variations in solar radiation and wind conditions to modulate the microclimate. The primary mechanism of action is attributed to water's high specific heat capacity, which enables it to absorb and release greater amounts of heat, thereby impacting the microclimate (Min, Ming et al., 2016). Our study further substantiates this observation, as the temperature differential between the waterfront space and the surrounding environment is maximized during the hottest day simulation period, coinciding with peak solar radiation, attributable to the substantial heat absorption by the water body. At night, the temperature of the waterfront space decreases at a slower rate than that of the environment; for an equivalent 1°C reduction in temperature, water releases more heat. However, in the early morning hours, the water body emits more heat than land surfaces, resulting in lower temperatures and consequently causing a significant drop in waterfront space temperatures relative to their surroundings. On particularly cold days, this characteristic of aquatic systems becomes even more pronounced; specifically, measurement point 2—characterized by a larger surface area of water—exhibits a notably higher average daily temperature compared to other measurement points due primarily to its capacity for substantial heat absorption that effectively warms its environment.

7.4 A continuous natural water system may not effectively regulate the microclimate and, in fact, could potentially exert an adverse effect

Natural water systems have consistently been a focal point in the study of microclimates within waterfront spaces and are regarded as significant mediators of microclimate regulation (Dong, Zhang et al., 2022). In contrast, our study yielded an opposing conclusion. The simulation results indicate that waterfront spaces adjacent to connected natural waterways exhibit lower environmental temperatures in winter and higher environmental temperatures in summer. Through comparative analysis, we have determined that this phenomenon is primarily attributable to the water flow dynamics: in winter, it removes heat from the waterfront space, whereas in summer, it introduces heat into the site. This effect is particularly pronounced in campus landscapes where rivers are often obscured by dense vegetation. In winter, upstream river water receives minimal sunlight and remains quite cold, thereby influencing the ambient temperature of downstream areas. Conversely, during summer months, the upstream river water—having been heated by intense solar radiation—flows into the campus environment, subsequently raising temperatures within the waterfront space and impacting its overall comfort. Existing research has indicated that natural water systems possess a significant capacity for microclimate regulation (Patten, 2016), often attributed to the contributions of green spaces and vegetation in waterfront areas. In this study, we aimed to emphasize the microclimatic regulatory role of water by minimizing the emphasis on vegetation and green spaces; our findings reveal that the influence of water on regulating the microclimate within waterfront spaces is notably limited.

7.5 The influence of vegetation, surface materials, and architectural elements on the environmental microclimate is significantly more pronounced

As previously discussed, other research findings indicate that vegetation can offer shade in outdoor spaces and modify the wind environment, among various other benefits (Oke, Tapper et al., 2007). Natural surface materials can also modulate the microclimate in arid regions by mitigating heat radiation and employing various other strategies (Yilmaz, Mutlu et al., 2018). The strategic arrangement of buildings can facilitate the creation of wind corridors and provide shade for outdoor spaces, thereby enhancing the microclimate surrounding the structures. However, simultaneously, materials such as glass and concrete used in facades continuously radiate heat into the atmosphere, adversely affecting the microclimate in hot regions (Jaafar, Lakkis et al., 2022). However, this study reveals that water bodies exert a markedly limited influence on the microclimate of waterfront spaces, aligning with the findings of certain scholars in the field (Martins, Adolphe et al., 2016).

7.6 Sensitivity analysis

Although we have made efforts to ensure the accuracy of the research through methods such as controlling variables and model validation, some errors remain due to the specific characteristics of on-site measurements and numerical simulations. (1) During the field measurement of certain waterfront spaces, dense vegetation can inevitably obstruct solar radiation and temperature readings, while differences in surface materials may affect the consistency of variables. To minimize these effects, we selected measurement points that ensured spatial openness and conducted tests primarily on natural ground surfaces, thereby reducing errors caused by discrepancies between concrete, asphalt, and natural surfaces. (2) ENVI-met simulations tend to overlook the thermal radiation from ground surfaces and building facades, potentially leading to underestimations of environmental temperatures. To address this limitation, our simulation models were positioned far from buildings to minimize errors associated with facade thermal radiation. Additionally, since the ground material was kept consistent across all simulations, any remaining simulation errors do not compromise the comparative analysis of different water body spatial structures.

7.7 Limitation

While this paper elucidates the microclimate regulation functions of various water systems on campus in regions characterized by hot and humid conditions, it also highlights that the influence of water on the microclimate regulation of waterfront spaces is notably limited. Nevertheless, several limitations remain as follows: (1) The sample size is insufficient. Due to time constraints, we selected only Xihua University—an institution convenient for conducting experiments—as the focus of this study. Consequently, the unique characteristics of Xihua University may limit the generalizability of our findings. Therefore, in future research, we plan to broaden our scope by collecting campus samples from various locations within regions characterized by hot and humid conditions for comparative analysis, thereby reducing the uncertainty associated with results derived from a singular context. (2) A deficiency of comparative experiments exists. The landscape elements within the waterfront space at Xihua University exhibit a similar composition, resulting in an absence of comparative studies that examine different landscape elements with identical water system structures. This limitation hinders our ability to accurately assess the microclimate regulation effects of varying landscape elements on the waterfront space. In subsequent research, we aim to address this gap.

8. CONCLUSION

8.1 In cold winter climates, large water bodies exert a more pronounced effect on microclimate regulation

The research findings indicate that the influence of water bodies on the microclimate of waterfront spaces is more pronounced in winter than in summer. In winter climatic conditions, open landscape lakes exhibit the most significant microclimate regulation capacity, achieving a regulation efficiency of 155%. Consequently, in regions characterized by hot and humid conditions, waterfront areas featuring large water surfaces during winter provide a more favorable microclimate environment, making them better suited for outdoor activities.

8.2 In hot summer climates, the microclimate environment of waterfront spaces is primarily influenced by landscape elements such as vegetation and surface materials.

In comparison to the microclimate regulation provided by vertical surfaces, water bodies, as horizontal elements, exhibit a less pronounced microclimate regulation function. Consequently, during the summer months in regions characterized by cold winters, the microclimate regulation of waterfront spaces should primarily depend on landscape elements such as vegetation and surface materials, with the thermal capacity of water bodies serving as a supplementary factor.

8.3 In regions characterized by hot and humid conditions, permeable natural water systems exert a detrimental effect on the microclimate; therefore, their application in the development of urban waterfront spaces should be approached with caution

In summer climatic conditions, the capacity of water systems to regulate the microclimate of waterfront spaces is notably limited; additionally, increased evaporation can elevate environmental humidity, resulting in an uncomfortable combination of high temperature and high humidity. Consequently, in regions characterized by hot and humid conditions, it is advisable to avoid situating important outdoor public activity areas within waterfront zones. If such arrangements are necessary, they should be integrated with vegetation, green spaces, and other elements to effectively modulate the microclimate.

This study elucidates the differences in microclimate regulation within waterfront spaces of campuses featuring various water system structures under extreme climatic conditions typical of regions characterized by hot and humid conditions. Additionally, it reveals the varying regulatory effects of identical water system structures across winter and summer seasons. These findings provide a theoretical foundation for the climate-adaptive design of water system landscapes in similar climatic contexts.

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