OPTIMIZING OUTDOOR SPACES: LANDSCAPE ELEMENTS FOR THERMAL COMFORT IN HEALING GARDENS

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Abstract. Healthcare architecture emphasizes the significance of outdoor spaces, particularly healing gardens. This study focuses on improving the thermal environment of such gardens, crucial in extreme climate regions. Although hot summers and cold winters pose challenges, landscape elements such as greenery and water bodies provide effective solutions. Using Envi-met modeling, this research quantitatively evaluates the impact of landscape elements on thermal comfort in China. It presents three sets of cases, each with three schemes, evaluating their effectiveness. Findings demonstrate that water features significantly outperform trees and lawns in enhancing thermal comfort. Compared to lawns, water features lower air temperatures by 4.9°C in summer and raise them by 2.4°C in winter. Their cooling effect extends up to 32 m, notably in leeward areas. Comfort studies show that the Physiological Equivalent Temperature (PET) remains below 38°C above water bodies on hot summer days, indicating a warm state, and exceeds 15°C at noon in winter, indicating a neutral state. Trees provide shade in summer and block winds in winter, further enhancing comfort. These insights are vital for designing therapeutic garden landscapes, informing design guidelines.

Keywords: *healing gardens, hot summer and cold winter regions, landscape configuration, thermal comfort, Envi-met*

Introduction

With rising awareness of health and well-being, attention has focused on the role of rehabilitation environments in medical buildings, particularly how rehabilitation gardens impact patient recovery (Liu et al., 2018). Numerous studies indicate that a healthy and comfortable hospital environment can stabilize patients' emotions and enhance staff performance (Yuan et al., 2022). Improving the indoor environment of hospitals can reduce costs associated with airborne disease transmission by 9% to 20% (Singer, 2009). Additionally, the outdoor environment of hospitals plays a significant role, with high-quality landscape gardens serving as a hallmark of a well-functioning hospital (Georgi, 2011; Gesler et al., 2004; Jiang, 2014). The outdoor rehabilitation gardens in hospitals provide patients and medical professionals with a relaxing and leisure space, serving as excellent therapeutic areas. Multiple studies have shown that natural environments created by planting various specific plants can help alleviate pain, anxiety, and psychological stress for both patients and non-patient populations (Wood et

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al., 2013; Curtis et al., 2007). Furthermore, rehabilitation gardens themselves offer inherent potential benefits. Diverse landscape elements can promote physical and mental well-being through various sensory experiences (Anderson, 2011). The sounds present in natural landscapes can also alleviate severe pain and soothe tense emotions (Diette et al., 2003).

However, urbanization has led to high population density, resulting in increasingly severe urban heat island effects. Heatwaves drive users away from rehabilitation gardens. Ali Katal and others have found a noticeable increase in overheating time both indoors and outdoors in three Canadian cities (Zou et al., 2022). Research indicates that extreme weather conditions in both summer and winter can impact human health (Macintyre et al., 2021). The Urban heat island effect increases the energy consumption of buildings. Research by Santamouris et al. (2013) suggests that for tropical countries, a 1°C increase in summer temperatures leads to a 1.66% increase in electricity usage. Recent research data shows that under equivalent conditions, the annual total energy consumption of hospitals is more than twice that of office buildings (Ji and Qu, 2019). High-energy-consuming buildings emit heat, which can also reduce the thermal comfort of outdoor recreational spaces around the buildings.

In response to this dilemma, Algretawee and others studied appropriate mitigation strategies to improve urban microenvironments (Hayes et al., 2022). Sun and Yu (2021) explore strategies to modify urban microenvironments and enhance thermal comfort by altering temperature, humidity, and wind speed parameters. Research has also found that green landscaping in high-density urban areas can improve the environment, alleviate the urban heat island effect, and enhance user comfort (Algretawee, 2022; Gachkar et al., 2021). The vegetation, water bodies, and other landscape elements in garden greening can regulate the urban microclimate (Moohammed et al., 2014) owing to the transpiration of plants and the high heat capacity of water (Jacobs et al., 2020; Widayanti et al., 2022). However, a significant amount of research has focused on individual landscape factors, such as the cooling effects of various plant combinations, on the thermal environment (Li et al., 2023). Although Lai et al.’s (2020, 2019) research revealed the mechanisms and cooling effects of four main mitigation strategies. However, due to the lack of large-scale numerical simulation analysis and visual representation, it is difficult to accurately quantify the correlation between landscape configuration and the thermal environment.

Literature searches have revealed that a large number of papers on landscape thermal comfort mainly focus on building types such as urban parks, schools, residential neighborhoods, and so on (Fei et al., 2022; Yu et al., 2023; Yang et al., 2022). There is minimal attention and scarcely any quantitative analysis regarding the outdoor thermal comfort of hospital rehabilitation gardens (Khalid et al., 2019). Different from landscape spaces in other types of buildings, hospitals have a low per capita green space ratio (Ma, 2022). The users of rehabilitation gardens include patients, doctors, caregivers, and others. Prolonged stays in suboptimal landscape environments can lead to issues such as depression and low mood among patients (Georgi, 2011). Doctors also require a pleasant environment to alleviate the stress of their demanding work. The healing needs of hospital rehabilitation gardens are significantly higher than those of other types of landscaped spaces, making thermal comfort a critical focus. Compared to previous studies, the innovations of this paper are as follows:

(1) Previous studies on healing gardens have focused on the healing effects and mechanisms (Paraskevopoulou and Kamperi, 2018), while this study focuses on the

thermal comfort of healing gardens. Through simulation analysis of the thermal environment based on different landscape element layouts, it explores the correlation between landscape elements and environmental thermal comfort, particularly revealing the coupling relationships among various elements, and thus proposes optimized design strategies for thermal comfort.

(2) This study proposes three sets of research cases with three contrasting design schemes for each set, utilizing different combinations of variables such as water bodies, lawns, and trees. Using Envi-met modeling, comparative simulation analyses are conducted for 18 typical scenarios under different seasonal and wind conditions, providing visual representations and quantified data.

(3) While a significant portion of previous literature tends towards purely theoretical research (Guo et al., 2023), this study emphasizes the integration of theory and practice. Simulation schemes are simplified based on typical landscape design schemes of actual projects. The configuration and layout of landscape elements align with engineering practice, and corresponding design strategies can be more targeted in improving the healing environment of healing gardens, thereby enhancing the environmental quality of hospitals.

The framework of this study is as follows: The section “Introduction” describes the background, objectives, and innovations of the research The section “Materials and Methods” validates the model based on field investigations and establishes the research model. The section “Results” provides numerical simulations for 18 typical scenarios and conducts comparative analyses. The section “Discussion” analyzes the reasons based on simulation results and discusses the limitations of this study. Conclusions, future research directions, and implications are presented in the section “Conclusion.” The flow is illustrated in *Figure 1*.

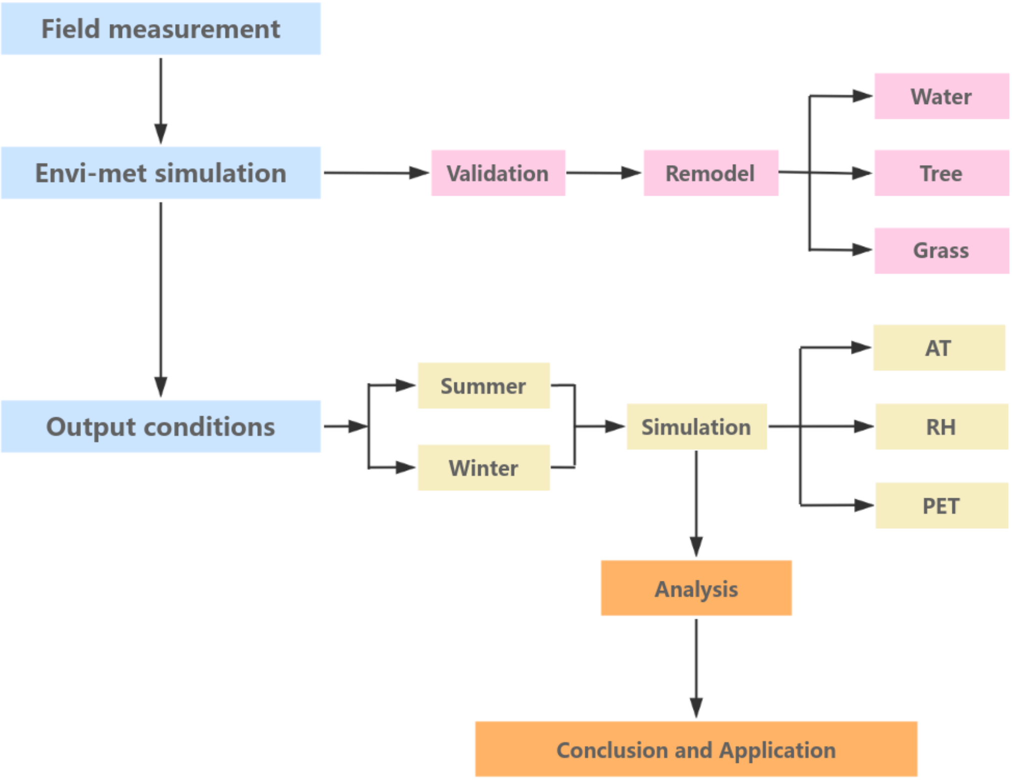


Figure 1. *The flow diagram of this methodology*

Materials and methods

The approach adopted in this research comprises four primary stages. Initially, a representative healthcare facility featuring a therapeutic garden was identified for conducting on-site measurements. Subsequently, a three-dimensional model was developed for numerical simulations, and the suitability of model boundary conditions was assessed by comparing measurement data against simulation outcomes. Following this, a site model was constructed using Envi-met software, and the validated model was utilized to recreate the study area for simulation purposes. In the third phase, thermal environment distribution maps were generated based on simulation results from the recreated model, elucidating the fluctuation of thermal conditions in response to different landscape configurations. Lastly, correlation analysis was performed to elucidate the interplay and synergies among various mitigation strategies.

Field survey

Hangzhou, located in the southeastern region of China, is one of the country’s megacities. As of 2023, it has a population of 12.52 million. (*Fig. 2a*). It lies in the subtropical monsoon region (Lin et al., 2018), In the summer, Hangzhou experiences hot and humid weather, making it one of the hottest cities in the Yangtze River Basin. Conversely, in winter, it is cold and dry. Classified within China’s climate zones, Hangzhou is a typical city with hot summers and cold winters. Given its large population of permanent residents, migrant workers, and tourists, research on urban and architectural environmental comfort is of significant importance in Hangzhou (Mei et al., 2023). The project site is located within a large medical and elderly care building in Hangzhou City (*Fig. 2b*). The focus of the study is the central healing garden inside the building. On the north and south sides are 40-m-high comprehensive inpatient buildings, while on the east side is a 15-m-high podium building, and on the west side is a low-rise building with a height of 5 m. The current landscape of the central garden mainly features water features combined with greenery, with five monitoring points set up inside (*Fig. 2c*).

The study conducted measurements at point A in the central garden on January 10, 2024, using a KAN-WS01 handheld meteorological monitor, following the ISO 7726 standard (*Table 1*). During the on-site measurements, the equipment was positioned 1.4 m above the ground, collecting temperature, humidity, and wind speed data every hour. Each data collection session lasted 5 min, and the data was extracted from the equipment’s records. Simultaneously, data from the local meteorological station and observed climatic characteristics were reviewed. A simulation model was established in Envi-met based on design data and satellite imagery. As shown in *Table 1,* the unit grid in the model was set horizontally at 4 × 4 m and vertically divided using non-uniform grids to enhance data accuracy near the ground and reduce computational time. The model generated a simulation model consisting of 50 × 40 horizontal units and 30 vertical units. Boundary conditions were set based on typical annual meteorological data for Hangzhou, with wind speeds of 2.7 m/s in summer and 3 m/s in winter, and site materials were simplified according to on-site conditions.

This study established five monitoring points arranged in a cross pattern, located at the perimeter and the center of the project study area. These five points were selected for their representativeness. Observations in practice revealed that Point A is an area with higher activity during winter, while Point C sees more activity in summer. Point E, situated at the center of the landscape, facilitates the assessment of thermal environment changes at the site’s core. Points B and D are near buildings, allowing for further qualitative analysis of building heat exchange issues. The variable area of the project’s landscape configuration is located in the yellow section of the figure, covering an area of 40×64 m, totaling 2,560 m^2, as shown in *Figure 2*.

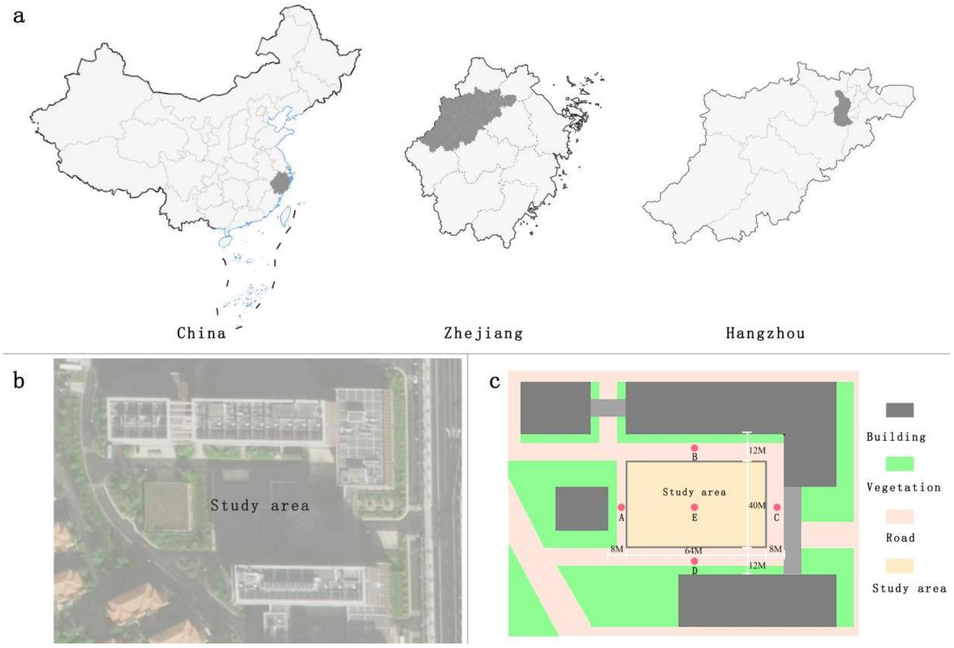


Figure 2. *Location and points A-E*

Table 1. *Equipment parameters*

KAN-WS01 Handheld meteorological monitoring instrument meteorological parameters				
Measurement elements	**Measuring range**	**Accuracy**	**Resolution ratio**	**Unit**
Wind speed	0~40	± 0.3	0.1	m/s
Air temperature	-20~50	± 0.3	0.1	℃
Relative humidity	0~100%	± 3%	0.1	%
Atmospheric pressure	300~1100	± 0.3	0.1	hPa

Model organization and validation

The microclimate simulation was conducted using the software ENVI-met, developed by Bruce and Fleer at the University of Bochum in Germany in 1998. This software, based on fluid dynamics and thermodynamics calculations, simulated the interactions among buildings, underlying surfaces, vegetation, and the atmosphere in urban environments, making it suitable for simulating microenvironments at small to medium scales. The version of the software used in this study was ENVI-met V5, with parameters detailed in *Table 2*. The study area was based on the original AutoCAD plan and supplemented with on-site inspections to abstract and extract the layout of buildings, vegetation, etc. On this basis, the model interface was imported with a Bmp format as a reference base map, and models for buildings, vegetation, materials, etc., were established. Corresponding monitoring points were set up in the model to obtain simulation data corresponding to the measured points.

Table 2. *Model input in Envi-met*

Category	Simulation parameters	Values used
Simulation parameters	Date	Jan. 10, 2024
	Time	9:00-18:00
	Total time	10 h
	Boundary condition	Simple Forcing
	Wind speed at 10 m	2.7 m/s (summer) 3 m/s (winter)
	Wind direction	202.5 (summer) 315 (winter)
	Roughness length	0.01
	Initial air temperature	Weather station data
	Initial relative humidity	Weather station data
Material setting	Soil initial temperature	Upper layer: 293 K Middle layer: 293 K Deep layer: 293 K
	Buildings	The albedo of walls for buildings: 0.3 Absorption of roof tile: 0.5
	Pavements	The albedo of concrete pavement gray: 0.6
Greenery setting	Grass	25 cm aver. dense
	Cylindric (conifers)	Heart-shaped, medium trunk, dense, medium (15 m)

Compared to other parameters, temperature parameters are relatively stable and less susceptible to significant changes due to specific factors. Therefore, the temperature was chosen for verification calculations in this simulation validation. Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) were employed as accuracy evaluation criteria. RMSE measures the error between simulated and measured values, while MAPE calculates the average absolute percentage deviation.

$$RMSE = \sqrt{\frac{1}{r}\sum_{i=1}^{r}\left(y_i^{'} - y_i\right)^2} \quad \text{(Eq.1)}$$

$$MAPE = \frac{1}{r}\sum_{i=1}^{r}\frac{\left|y_i^{'} - y_i\right|}{y_i} \times 100\% \quad \text{(Eq.2)}$$

where r is the total number of groups, y_i’ is the simulated value of the ith parameter, and y_i is the measured value of the ith parameter.

Based on recent studies on the accuracy of ENVI-met simulations, it is considered acceptable if the RMSE for temperature (Ta) is less than 1.31, and the MAPE is less than 5.00 (Chow et al., 2011). After computation, the RMSE value in this model was 0.6°C, and the MAPE value was 3.8%. Additionally, a linear regression test was conducted between the measured data and simulated data to assess the applicability and accuracy of the ENVI-met model. The linear regression results demonstrated a strong correlation ($R^2 > 0.8$) between the measured and simulated data (Tsoka, 2018). Data details can be found in *Figures 3* and *4*.

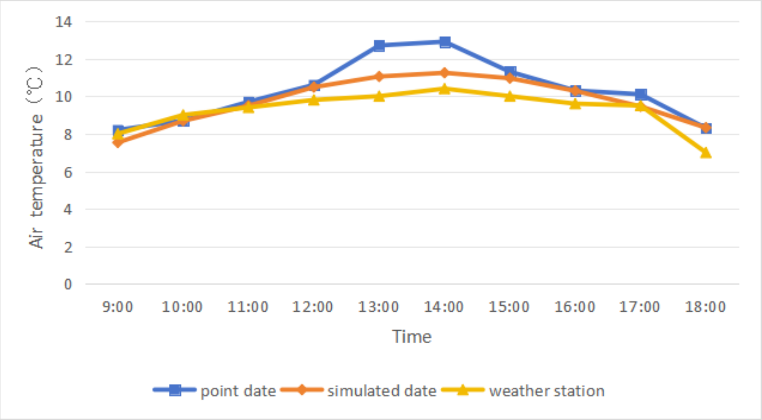


Figure 3. *The comparison of the measurement data and weather station date*

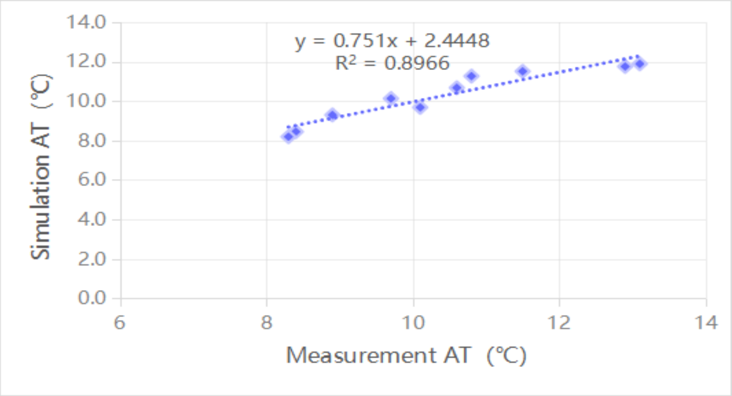


Figure 4. *Linear regression between the simulation AT and the measurement AT*

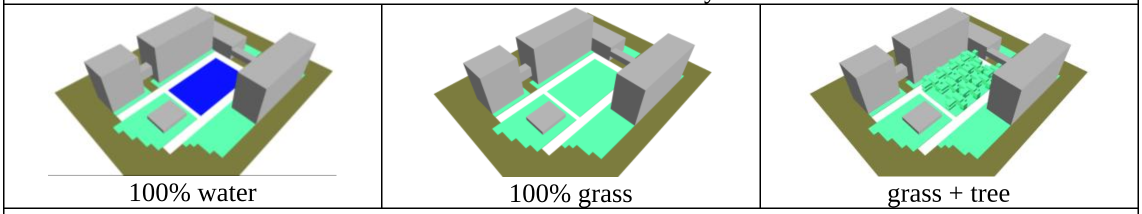
Remodeling

In recent years, research methods for landscape mitigation strategies have gradually shifted from qualitative environmental analysis to quantitative analysis (Zhang et al., 2022). Adjusting the coverage and layout of water bodies, lawns, and trees can influence landscape thermal comfort. For instance, studies in London and Paris have shown a correlation between spatial thermal environment and coverage indicators (Chatzipoulka et al., 2020). Numerous studies indicate that variations in landscape elements can affect the outdoor thermal environment of a site (Giridharan et al., 2008; Sun and Yu, 2021; Chang and Li, 2014). Many scholars conduct their research from the perspective of urban planning, employing GIS remote sensing technology for large-scale macroscopic analysis (Naeem et al., 2018; Zhang et al., 2013). Some researchers also utilize methods such as questionnaire surveys and on-site measurements to validate the impact of landscape elements on outdoor thermal environments (Giridharan et al., 2008; Liu et al., 2021). Certainly, a large number of studies employ numerical simulation methods to reveal the impact of landscape configuration on thermal environments. Some studies focus on the influence of vegetation coverage ratio on thermal environments (Wu et al., 2022). Some studies simulated the cooling effects of different proportions of landscape elements (Yu et al., 2023). However, many studies tend to be theoretical and lack engineering design feasibility. This study aims to reveal the correlation between typical landscape element combination layouts in actual projects and thermal environments.

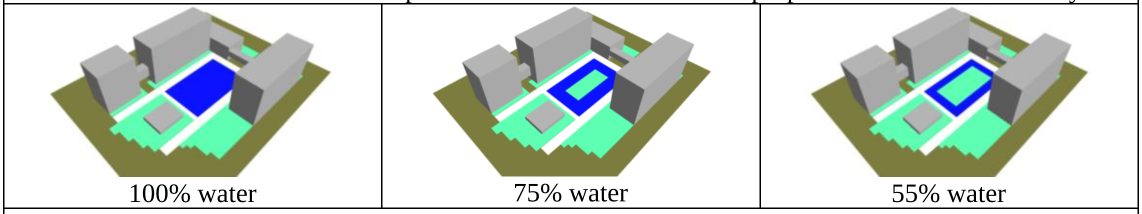
This paper first explored the correlation between individual landscape configurations and thermal environments. Therefore, Case 1 simulated the conditions of 100% water bodies and 100% lawns separately, while also comparing the simulation conditions of lawns combined with trees, revealing the effectiveness of maximizing the proportion of landscape elements. The study shows that people prefer to engage in leisure activities by the water (Liu et al., 2021). Therefore, designers prefer to incorporate water features in large-scale landscape gardens. Moreover, in the Yangtze River Basin of China, people’s lives are closely related to water, making water features a common landscape form in southern architectural scenes.

The research case in this paper focuses on a large rehabilitation hospital in a region characterized by hot summers and cold winters (*Fig. 5*). The predominant landscape feature in the onsite healing garden is water bodies, accounting for approximately 75% of the area. Therefore, Case 2 attempted to find the correlation between different widths of water bodies and the thermal environment. Three conditions were set: 100% water bodies, 75% water bodies, and 55% water bodies. In actual engineering projects, common landscape designs often revolve around water bodies, surrounded by lawns and trees, or water bodies interspersed within greenery. Hence, Case 3 seeked to reveal the differences in the thermal environment impact under the same water body area condition with different combinations of water bodies and trees. Subsequently, based on typical landscape design simplified schemes in engineering projects, the comfort levels of monitoring points were calculated for three conditions: without water bodies, water bodies surrounding layout, and water bodies centered layout.

Case 1: The impact of landscape elements such as water bodies, lawns, and trees on the thermal environment of enclosed courtyards


100% water | 100% grass | grass + tree

Case 2: The thermal environment impact of water bodies at different proportions on enclosed courtyards


100% water | 75% water | 55% water

Case 3: The thermal environment impact of different landscape element layouts on enclosed courtyards under the same water body area conditions. (The widths of the water bodies are 40 m, 16 m, and 8 m, respectively)

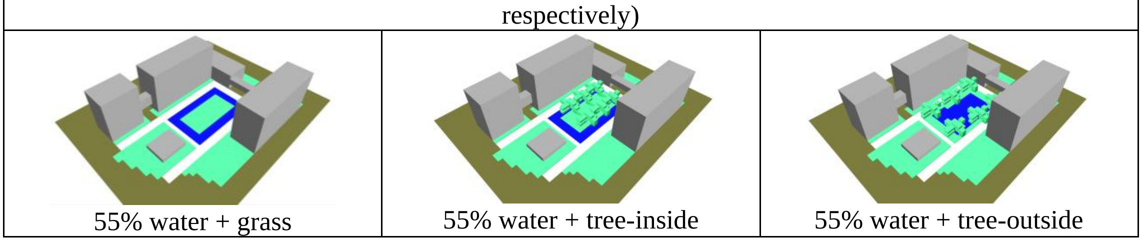

55% water + grass | 55% water + tree-inside | 55% water + tree-outside

Figure 5. *Envi-met scheme model*

Results

During field research, we found that the primary users of the healing garden include doctors, nurses, outpatient patients, inpatients, and patients' family members, who typically engage in activities between 9:00 a.m. and 8:00 p.m. This timeframe covers the hospital's operating hours, as the hospital opens at 9:00 a.m. and the evening primarily accommodates inpatient activities. Previous studies have indicated that during summer, the period with the poorest heat comfort usually occurs between 2:00 p.m. and 3:00 p.m. (Li and Liu, 2020; Fu et al., 2022; Ma et al., 2019). The on-site test results also indicated that the site temperature reached its peak for the day at that time. In research conducted in regions with hot summers and cold winters, it is crucial not only to focus on heat prevention during the summer but also on insulation during the winter. The on-site test results demonstrate that 9:00 a.m. was the lowest point for site temperature during winter. Therefore, this study considered 2:00 p.m. in summer and 9:00 a.m. in winter as important monitoring time points.

Case 1: The thermal environment is influenced by landscape elements such as water bodies, lawns, and trees

Air temperature map

According to *Figure 6*, the simulation results comparing three conditions indicate that, compared to lawns and trees, incorporating water features in the landscape can lower the ambient temperature in summer and raise it in winter. This was because water has a higher specific heat capacity, making it an excellent material for storing thermal energy. It can cool through evaporation in summer and absorb heat in winter.

During the hottest time of the day in summer at 14:00, the cooling effect of water features was significant, with temperatures noticeably lower above and around the water. Trees provided some shade and transpiration, resulting in better cooling effects than lawns, but inferior to water features. However, during the coldest time of the day in winter at 9:00, water features can elevate the ambient temperature, with temperatures noticeably higher around them.

Summer temperature variation charts

According to *Figure 7*, it can be observed that the cooling effect of water features is significant compared to lawns and trees. This was particularly noticeable at monitoring points C and E. Monitoring point C was situated downwind from the prevailing summer wind direction, where the cooled air above the water feature was transferred to point C. Relative to the lawn condition, the water feature landscape achieved a maximum cooling effect of 4.9°C at 15:00. Monitoring point E was positioned directly above the water feature, where the cooling effect was pronounced. Compared to the lawn condition, the water feature landscape achieved a maximum cooling effect of 4.4°C at 14:00. In contrast, the cooling effect of trees ranged from 0.5 to 2°C compared to the lawn condition.

Winter temperature variation charts

According to *Figure 8*, it is evident that compared to lawns and trees, water features exhibit a more pronounced warming effect during winter at monitoring points B, C, and E. Monitoring point C was situated downwind from the prevailing winter wind direction, where the warmed air above the water feature was transferred to point C. The thermal insulation effect of the water feature landscape ranged from 1 to 2°C.

Monitoring point E, directly above the water feature, experienced a significant warming effect, with the maximum insulation effect of the water feature landscape reaching 2.4°C at 20:00. Monitoring point B showed that the warming effect of the water feature landscape remained around 1°C.

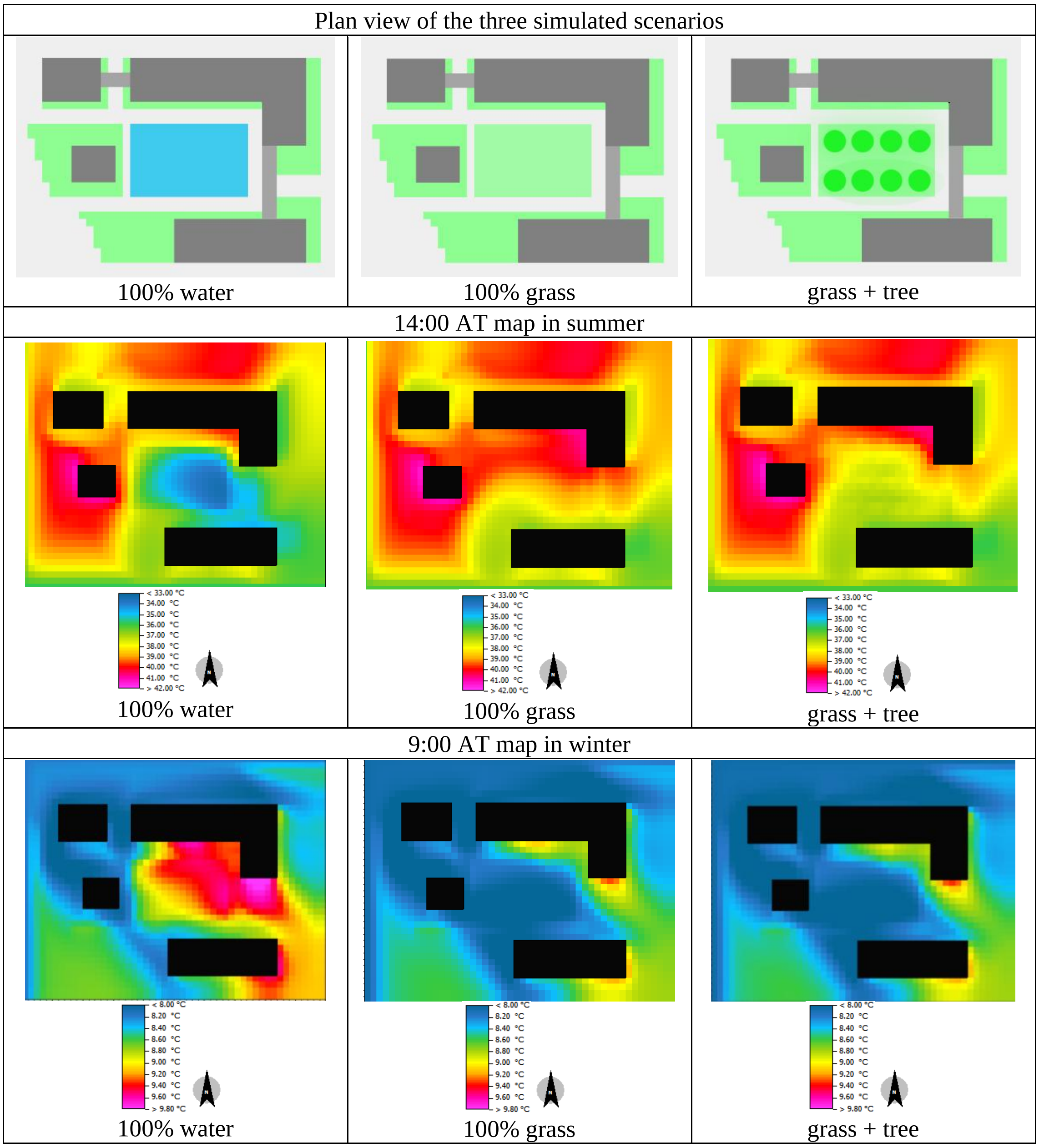


Figure 6. *Simulation of case1 in summer and winter*

Case 2: The impact of different proportions of water bodies on the thermal environment of enclosed courtyards

Air temperature map

According to *Figure 9*, in summer, the cooling effect of water features increased with the expansion of the water's surface area. Particularly during the hottest period of the summer at 14:00, the cooling effect of water features was most pronounced, with significantly lower ambient temperatures observed above the water and in the downwind areas. The winter temperature map demonstrated that large water bodies can effectively elevate site temperatures.

a

b

c

d

e

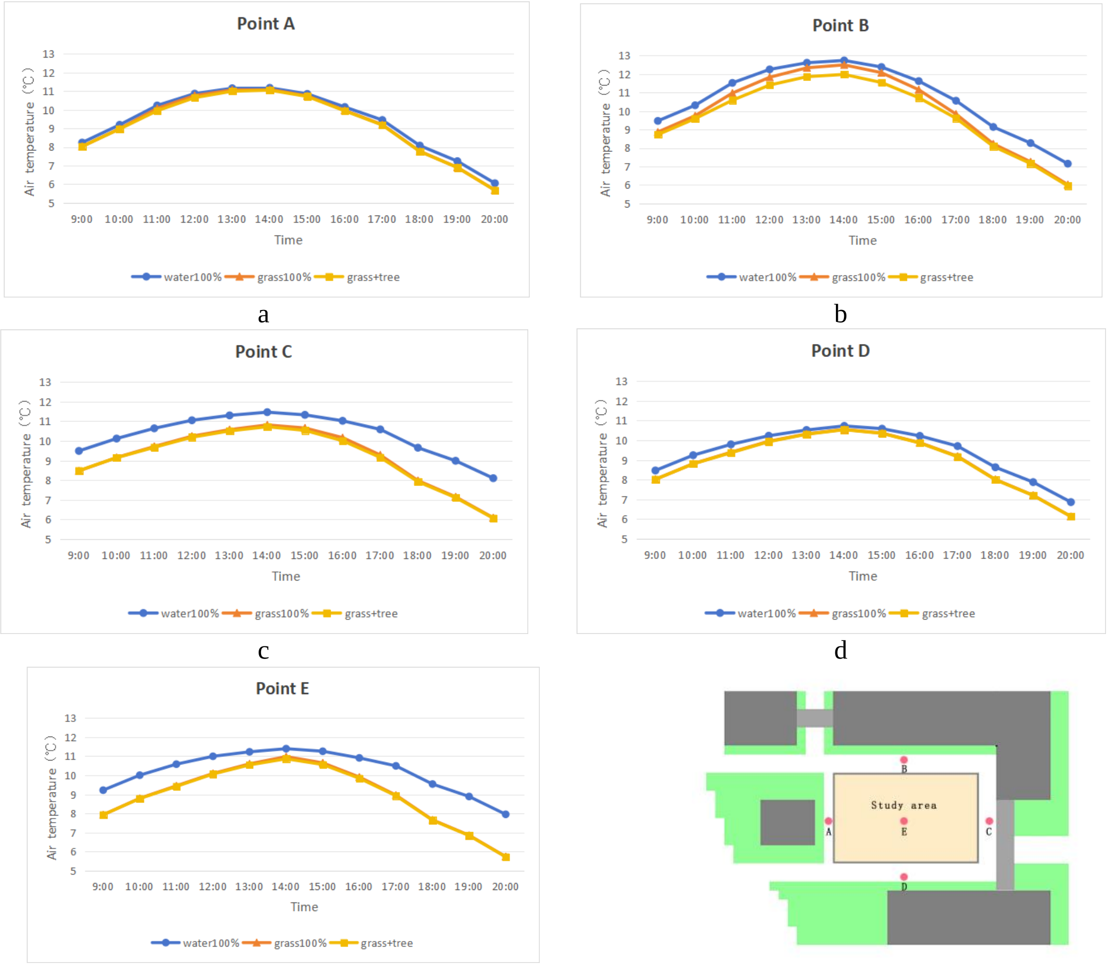
f

Figure 7. *Summer temperature variation charts for each monitoring point (a-e) and monitoring point distribution map (f)*

Based on simulation findings, regardless of summer or winter, the influence range of water landscapes on temperature is closely related to site wind speed and direction. The impact of water landscapes is particularly significant in the leeward areas of the site. By comparing temperature charts (*Fig. 9*), it was observed that water landscapes of different widths exhibit similar influence ranges. In the windward areas, the significant influence range of water landscapes is approximately 8 m, while in the leeward areas, it exceeds 32 m. Moreover, the wider the body of water, the greater its impact intensity.

Summer temperature variation charts

The analysis of *Figure 10* reveals that the cooling effect of water bodies of different sizes showed minimal variation at monitoring points A, B, and D. However, the most significant cooling effects were observed at monitoring points C and E. Monitoring point C, positioned downwind from the prevailing summer wind direction, facilitated the transfer of cooled air from above the water body to this location. The maximum cooling effect of the water feature landscape between 14:00 and 15:00 reached up to 3°C at monitoring point C. Similarly, monitoring point E, situated above the water body, experienced a notable cooling effect, with the maximum cooling effect of the water feature landscape reaching 3.4°C at 14:00.



a b c d e f

Figure 8. *Winter temperature variation charts for each monitoring point (a-e) and monitoring point distribution map (f)*

Winter temperature variation charts

Analysis of *Figure 11* indicates that the warming effect of water bodies of varying sizes showed minimal variation at monitoring points A, B, and D. However, the warming effect was more pronounced at monitoring points C and E. Monitoring point C, positioned downwind from the prevailing summer wind direction, facilitated the transfer of warmed air from above the water body to this location.

The water feature landscape experiences a warming of approximately 0.5-1°C at monitoring point C between 14:00 and 15:00. Monitoring point E, located above the water body, experiences a significant warming effect, with the water feature landscape warming by approximately 1-2°C at 14:00.

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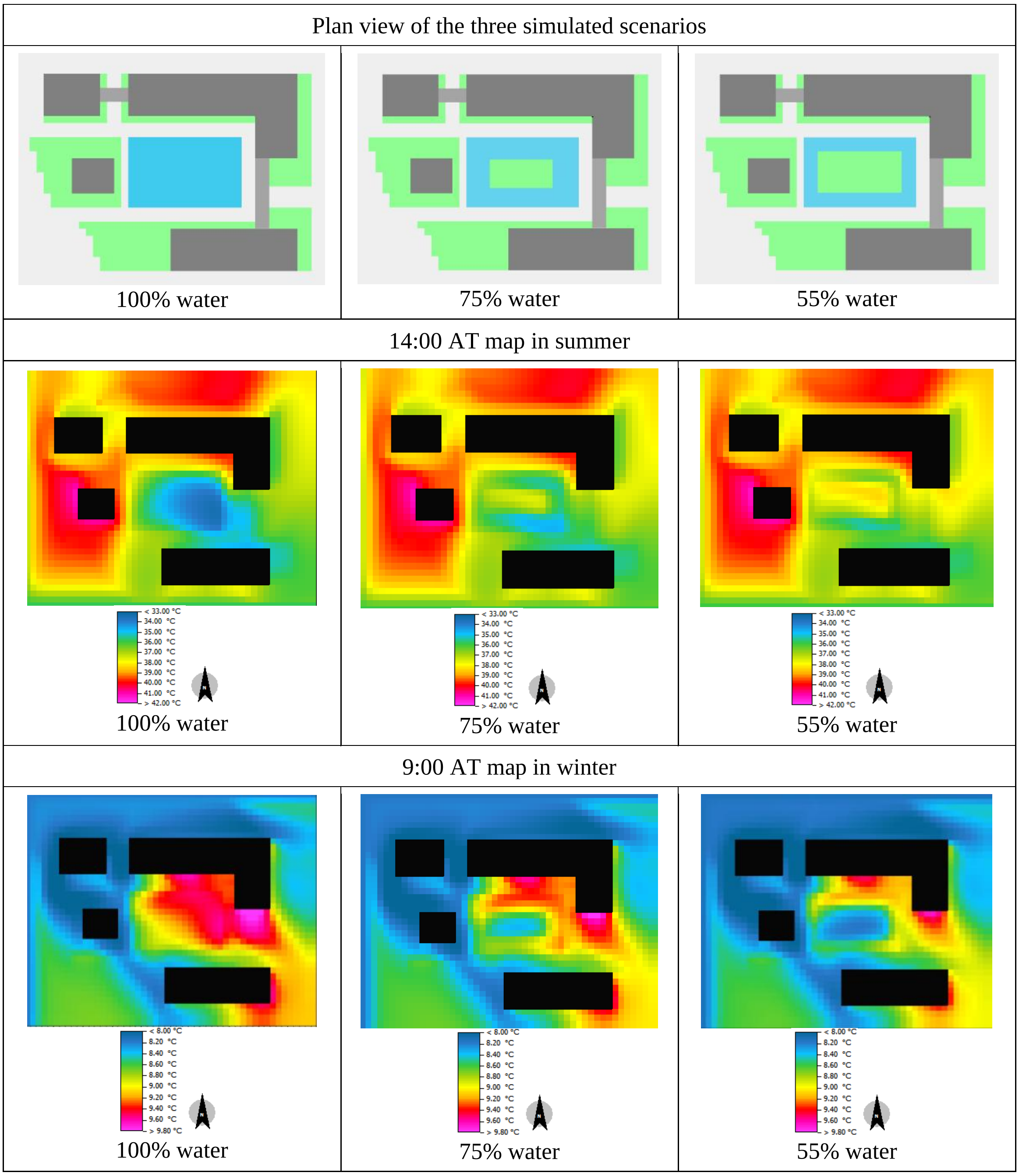
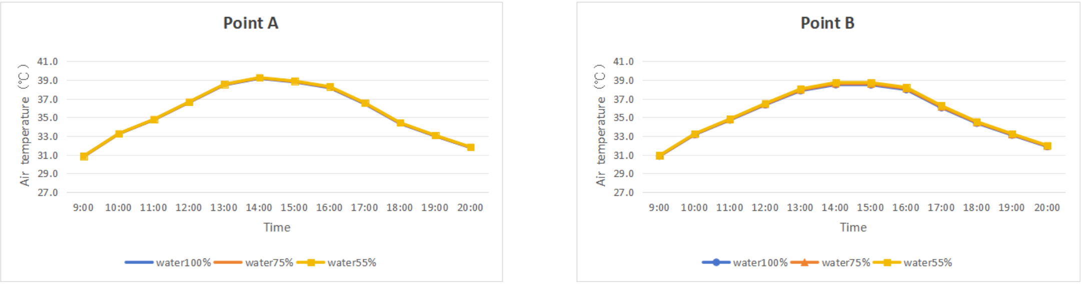
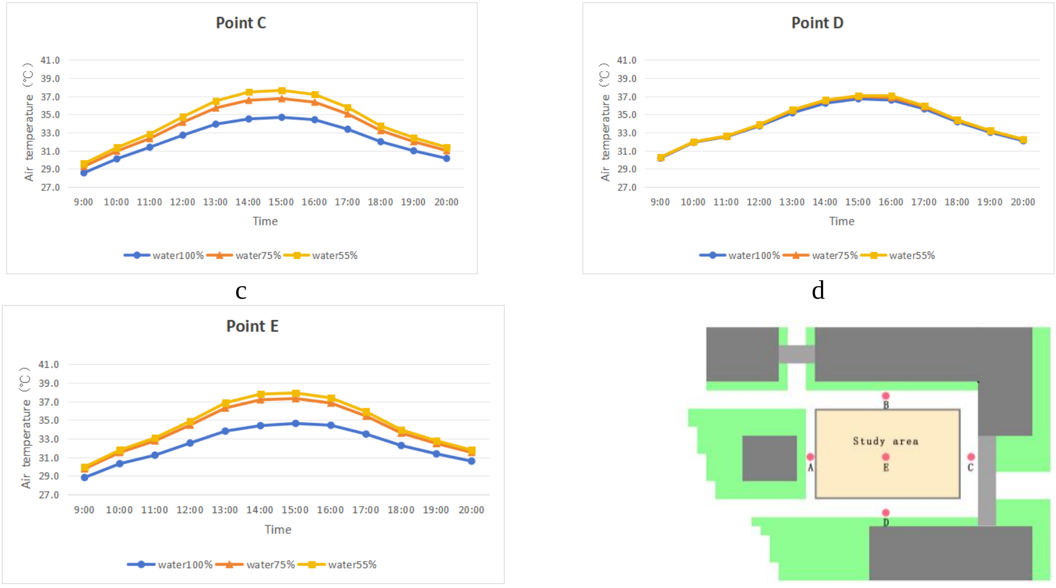


***Figure 9.** Simulation of case 2 in summer and winter*



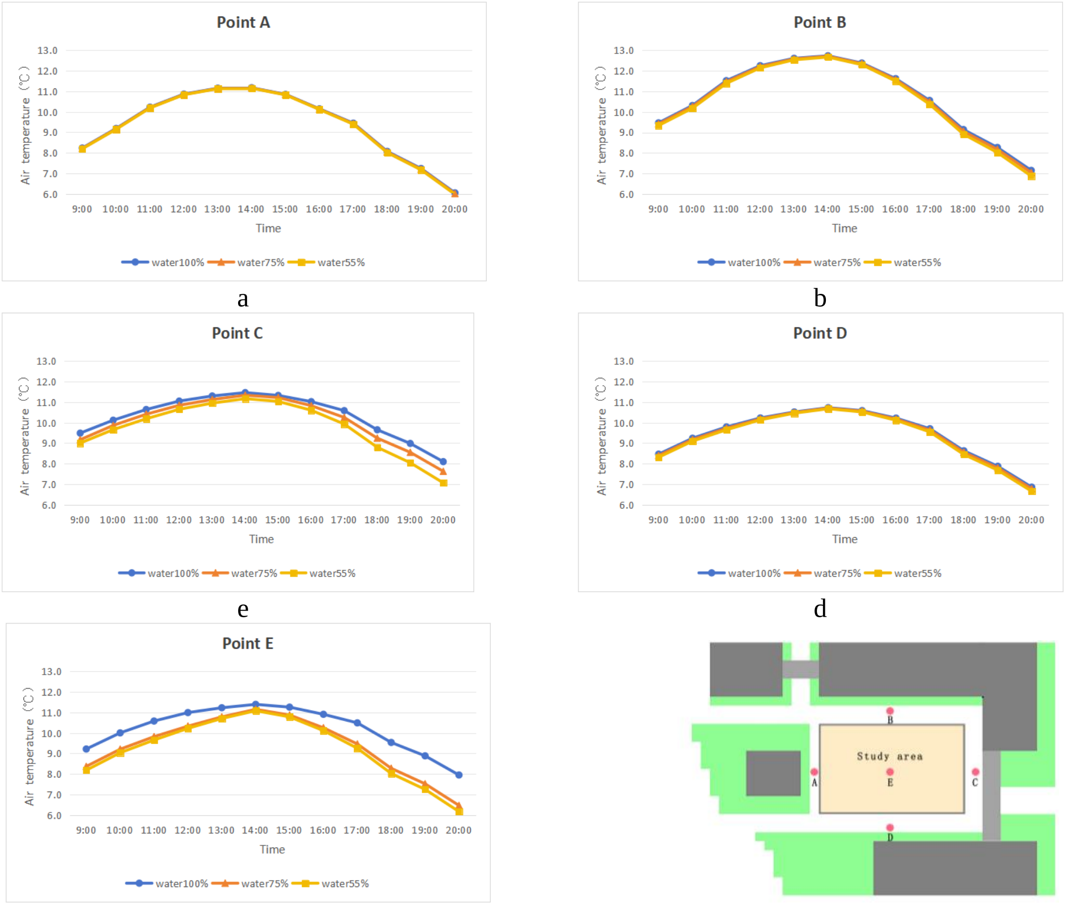
a

b



c d e f

Figure 10. *Summer temperature variation charts for each monitoring point (a-e) and monitoring point distribution map (f)*



a b e d e f

Figure 11. *Winter temperature variation charts for each monitoring point (a-e) and monitoring point distribution map (f)*

Case 3: The impact of different landscape element layouts on the thermal environment of enclosed courtyards under the same water body area conditions

Air temperature map

Based on the findings from *Figure 12,* when comparing the simulation results of three scenarios with equal proportions of water body landscape area, it is observed that during the peak heat period of summer at 14:00, the cooling effect of the surrounding water body landscape is more evenly distributed, while the cooling impact of the centralized water body landscape is predominantly concentrated above the larger water body. Conversely, during the coldest part of the day in winter at 9:00, under identical conditions, the temperature in the southeast area of the site experiences an increase when trees are planted. This observation suggests that trees can effectively shield the site from unfavorable monsoon winds, decrease wind velocity, and offer thermal insulation, thereby improving the overall comfort of the site.

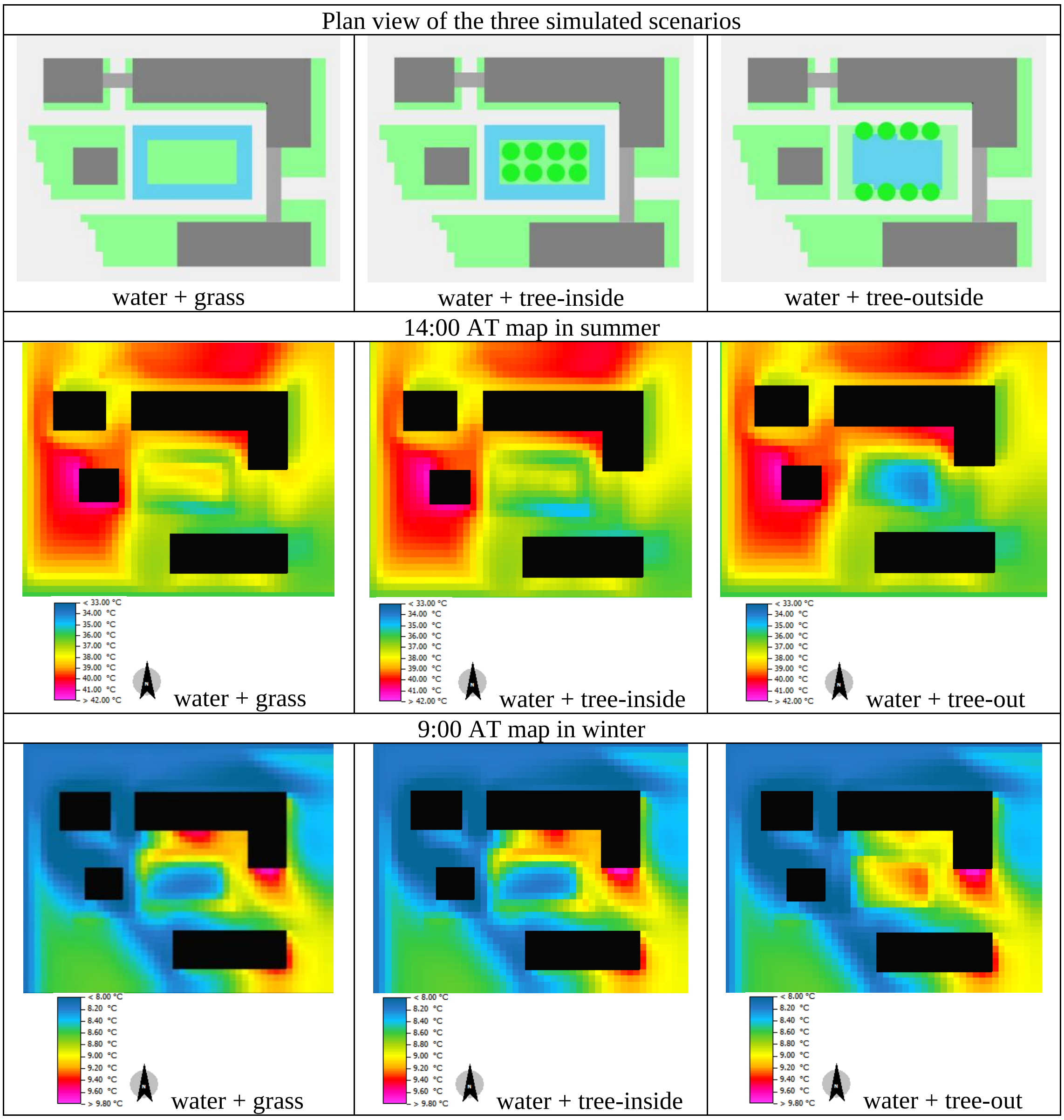


***Figure 12.** Simulation of case 2 in summer and winter*

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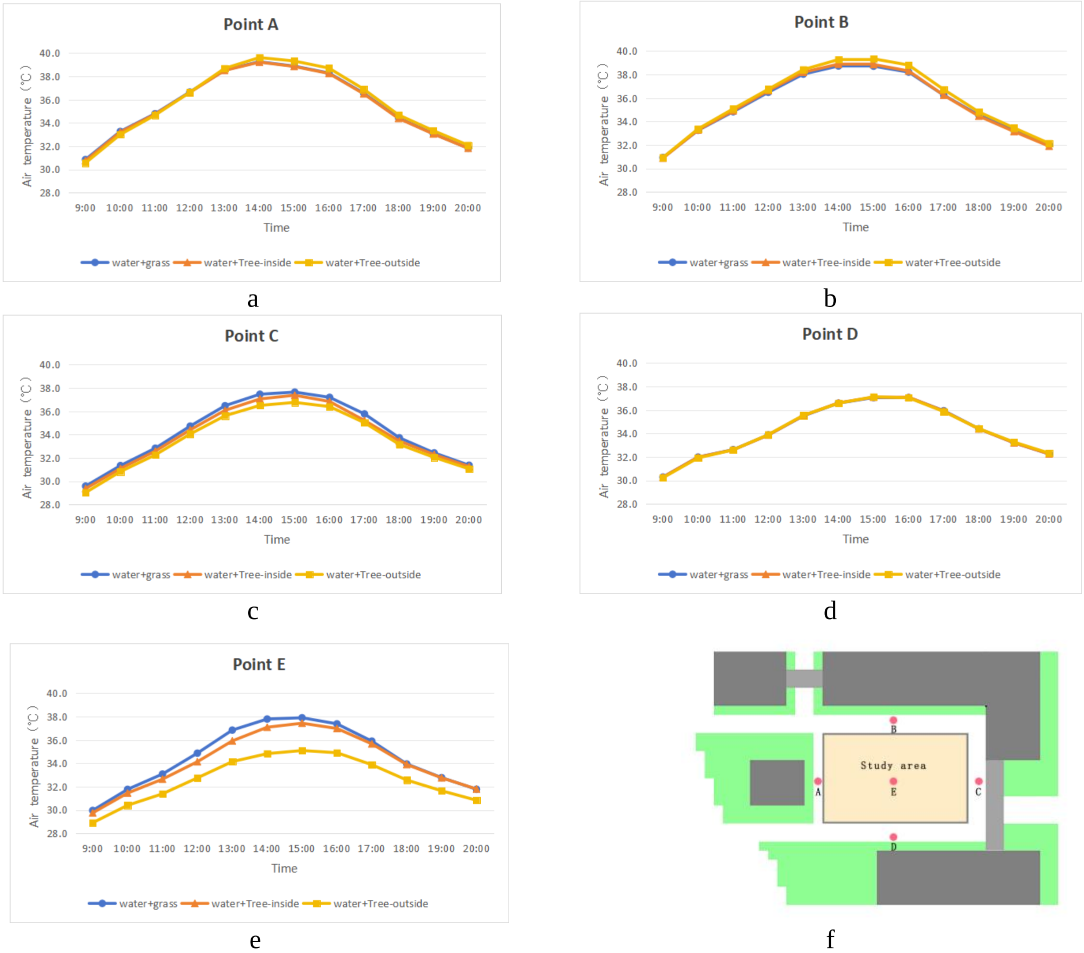
Summer temperature variation charts

According to *Figure 13*, it can be observed that under the same water body area conditions, there is little temperature difference at monitoring points A, B, C, and E. Monitoring point E, situated above the water body and benefiting from the shading effect of trees, experiences a significant cooling effect, with the maximum temperature difference reaching 3.6°C at 14:00.



a b c d e f

Figure 13. *Summer temperature variation charts for each monitoring point (a-e) and monitoring point distribution map (f)*

Winter temperature variation charts

According to *Figure 14*, with the same water body area, there is little temperature difference among monitoring points A, B, C, and E. Monitoring point E, located above the water body, exhibits a more pronounced thermal insulation effect, with temperature differences of 1-1.5°C observed in the morning and evening.

Calculation of comfort in typical landscape design scenarios

In addition to temperature indicators, thermal comfort is often used as a quantifiable measure of the effectiveness of mitigation strategies (Dzyuban et al., 2022; Migliari et al., 2022). An increasing body of research suggests that thermal comfort is a combination of

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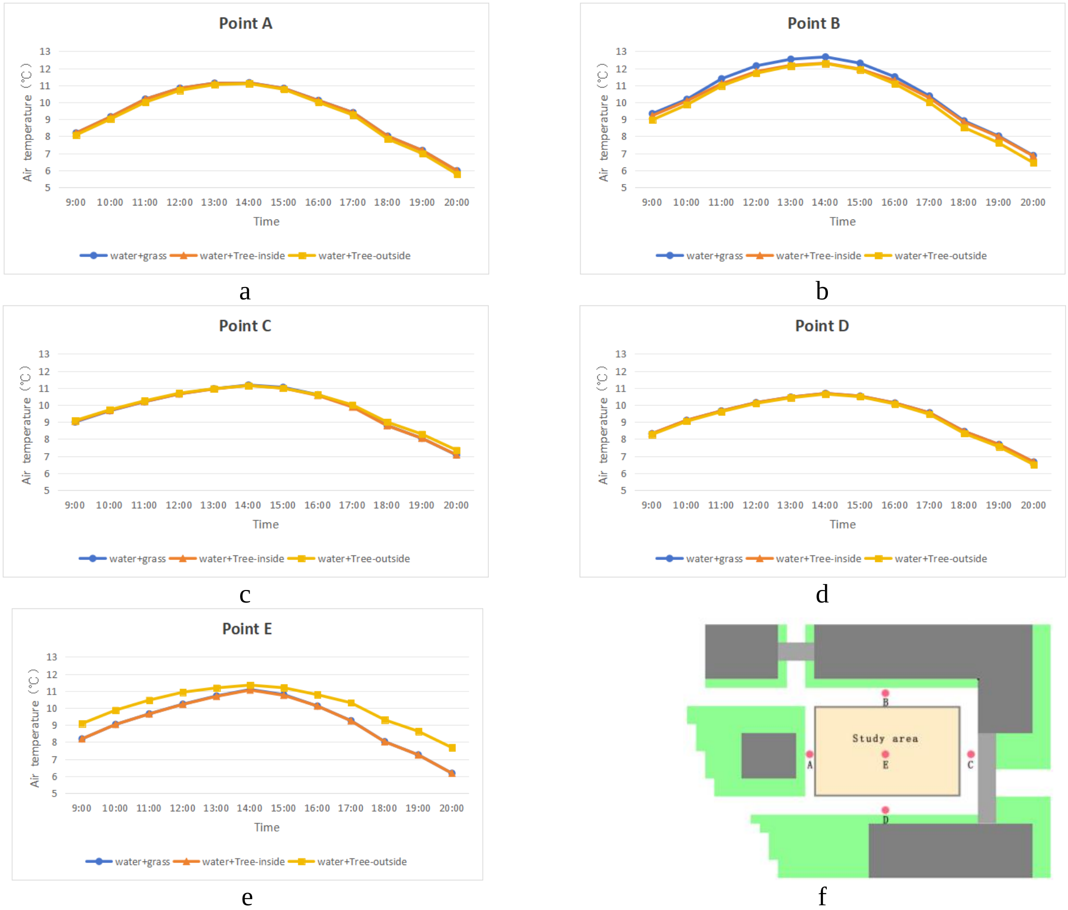
physiological sensations and psychological satisfaction. Since the 1970s, several models based on thermal perception have been developed, with current thermal comfort models numbering in the dozens (Shaw, 1972; Nagano and Horikoshi, 2011). The four most widely accepted ones are: PMV, PET, SET*, and UTCI (Ji et al., 2022; Li et al., 2020). PET (Physiological Equivalent Temperature) has been validated in many field studies, demonstrating good accuracy, and has been recommended by VDI (2008) (Cohen et al., 2013). PET is based on the Munich Energy-balance Model for Individuals (MEMI) to establish the human body's equilibrium equation (Ji et al., 2022). However, PET varies in different climate zones. For instance, in a Mediterranean coastal climate, the neutral PET range is between 20-25°C, while in Taiwan's humid subtropical climate, the neutral PET range is between 26-30°C (Lin et al., 2010). In this study area, the PET model modified by Liu et al. (2016) for the local climate of Changsha is adopted as the standard for assessing thermal comfort (*Table 3*). This choice is made because Changsha shares similar climate characteristics with Hangzhou, being at the same latitude and belonging to the same summer-hot and winter-cold region.



a b c d e f

Figure 14. *Winter temperature variation charts for each monitoring point (a-e) and monitoring point distribution map (f)*

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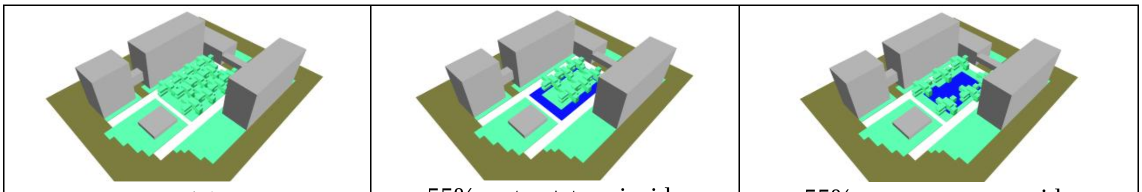
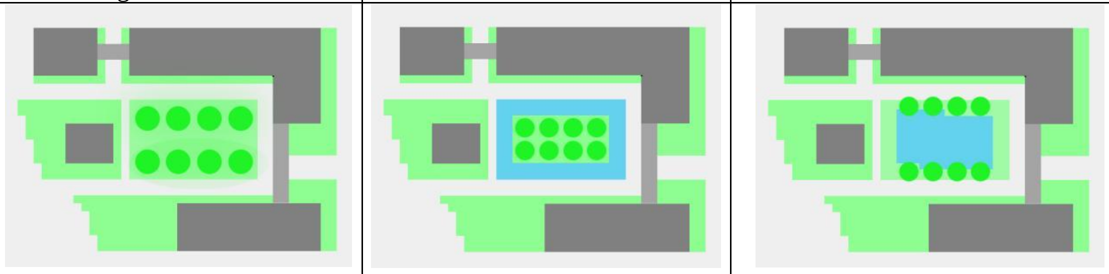
Table 3. *PET ranges and outdoor thermal sensation levels*

Scale	**< -3.5**	**-3.5~-2.5**	**-2.5~-1.5**	**-1.5~-0.5**	**-0.5~ + 0.5**	**+ 0.5~ + 1.5**	**+ 1.5~ + 2.5**	**+ 2.5~ + 3.5**	**> + 3.5**
Thermal sensation	Very cold	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot
PET range (°C)	<-8	-8~-1	-1~7	7~15	15~22	22~30	30~38	38~46	>46

In actual engineering design, landscape gardens typically consist of water bodies, trees, lawns, and paving. In this section of the study, we simplify the layout of the main landscape elements for modeling purposes. We compare three scenarios: one without water bodies, one with water bodies arranged around the area, and one with water bodies centrally positioned (*Fig. 15*).



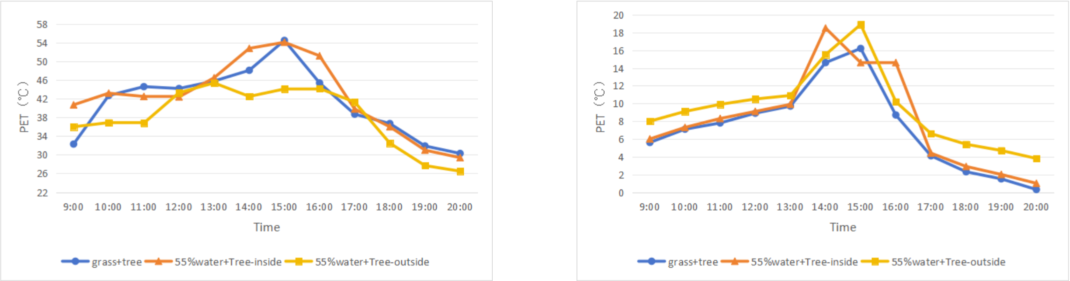
grass + tree 55% water + tree-inside 55% water + tree-outside



grass + tree 55% water + tree-inside 55% water + tree-outside

Figure 15. *Typical landscape simplified layouts*

Based on the simulation results, air temperature, relative humidity, wind speed, and average radiation temperature were extracted. These were then combined with parameters such as the thermal resistance of clothing worn by individuals and their activity levels. Using RayMan software, the winter and summer PET values for monitoring point E were calculated. The calculation results are shown in *Figure 16*.



a b

Figure 16. *Summer PET value at monitoring point e (a) winter pet value at monitoring point e (b)*

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Based on the analysis of the summer PET map, it can be observed that beneath monitoring point E lies a water feature landscape, where PET temperatures remain below 46°C throughout the day, avoiding excessively hot conditions. Before 11:00 AM and after 5:00 PM, PET values were below 38°C, indicating a warm state of thermal comfort. Analyzing the winter PET map revealed that scenarios incorporating water bodies can elevate the PET values of the site for 2 h throughout the day, with PET values exceeding 15°C, indicating a Neutral state of thermal comfort. Among these scenarios, the one with a water body in the center and surrounded by trees offered superior comfort, elevating PET values by 2°C throughout the day. Therefore, it is recommended to construct a landscaped platform above the water body, which can serve as a leisure area for doctors and patients alike during both summer and winter seasons.

Discussion

This study focuses on the thermal environment of healing gardens in healthcare buildings, primarily investigating the impact of different combinations of landscape elements such as water bodies, lawns, and trees on the thermal environment. The research findings indicate that water features can effectively reduce environmental temperature in summer, which is consistent with the mainstream research findings. (Lai et al, 2020, 2019). However, this paper provides a more precise comparison of temperature differences through numerical analysis at numerous monitoring points. Under the same measurement points and time conditions, the simulation results for summer show that compared to lawn landscapes, water features exhibit a maximum temperature difference of up to 4.9℃, while the cooling effect of trees and lawns is relatively weaker. Winter simulation results reveal that water features have a warming effect, with a maximum temperature difference of up to 2.4℃. The study also found that the proportion of water body landscape area influences the thermal environment. By comparing the simulation results of water bodies with different widths, it was observed that larger water body areas have a greater impact on the thermal environment in both summer and winter. This contrasts with the findings of Yu et al. (2023), possibly due to differences in boundary conditions—the present study was conducted in an enclosed central courtyard, while the previous study focused on urban open spaces. Further research is needed to confirm this discrepancy. The study also conducted research on thermal comfort. Analysis of the PET map in summer indicates that when there is a water body landscape below monitoring point E, the PET temperature remains below 46°C throughout the day. Additionally, before 11:00 in the morning and after 17:00 in the afternoon, the PET values are below 38°C, indicating a warm state. In winter, PET map analysis shows that schemes incorporating water bodies can enhance the PET values throughout the day, with 2 h having PET values exceeding 15°C, indicating a neutral thermal comfort state.

Simulation results also revealed a correlation between the influence range of water body landscapes and the site's wind speed and direction (*Fig. 17*). Comparing thermal environment simulations of water bodies of different widths, it was found that the influence range of water bodies in the upwind area can reach 8 m, with consistent impact intensity. This finding aligns with the study by Fei et al. (2022), Yu et al. (2023) and Yang et al. (2022). However, a new discovery is that in the leeward area of the site, the impact of water body landscapes is significant, with an influence range exceeding

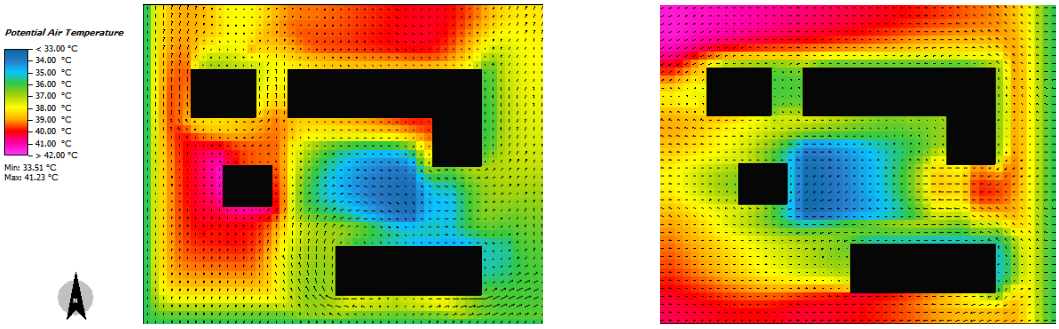
32 m. The wider the water body, the greater the impact intensity. Subsequent research will further explore the combined effects of different wind speeds and various landscape elements on the thermal environment of the site.

The landscape configuration in this study does not limit to a single element but investigates combinations of various landscape features. Through simulations of different combinations of trees, lawns, and water bodies, it was found that during the coldest period of winter days at 9:00, the shade provided by trees can reduce the site's temperature. It is recommended to plant deciduous vegetation on the southern side of recreational areas. Additionally, in simulations with trees, the wind-blocking effect of trees can decrease the site's wind speed during winter, preventing heat loss. Therefore, it is suggested to establish windbreaks in the upwind areas dominated by winter winds to enhance thermal comfort during winter. Based on the comprehensive research findings, the following design strategies are proposed in this paper:

(1) Where feasible, incorporate water body landscapes into rehabilitation gardens as they are beneficial for both patients' psychological well-being and physiological thermal comfort.

(2) It is recommended to centrally locate water body landscapes and construct landscape platforms above them to provide leisure spaces for doctors and patients in both summer and winter. This design allows individuals to enjoy proximity to water while maximizing the utilization of water bodies to optimize environmental thermal comfort.

(3) The layout of trees in landscape design should consider the local prevailing wind direction, taking into account shade provision in summer and wind protection in winter. Furthermore, it is advised to designate summer leisure areas in the downwind areas dominated by summer winds, providing comfortable spaces for thermal relaxation.



a b

***Figure 17.** Simulation under southerly wind conditions (a) simulation under easterly wind conditions (b)*

Conclusions

This study conducts thermal environment research on the healing gardens of typical medical buildings. By simulating the effects of various combinations of landscape elements on the thermal environment, it aims to summarize the underlying scientific principles.

This study examines the thermal environment of healing gardens in typical healthcare buildings, simulating various combinations of landscape elements to understand their impact on thermal conditions and to derive scientific principles.

(1) Water features effectively reduce environmental temperature in summer but have a warming effect in winter. Simulation results indicate that compared to lawn and tree landscapes, water features achieve a more significant temperature reduction in summer, up to 4.9℃, while in winter, they can increase environmental temperature by up to 2.4℃. Overhead activity spaces above water bodies maintain a warm state during the hottest summer days' morning and evening hours, with PET below 38℃, while at noon in winter, PET exceeds 15℃, indicating a neutral state.

(2) There is a strong correlation between the variation in environmental temperature and water body area, which is also influenced by wind direction. Research indicates that larger water bodies lead to more significant cooling effects in summer. Despite different widths, the impact range of water landscapes remains consistent, significantly affecting an area approximately 8 m upwind and exceeding 32 m downwind. The wider the water body, the greater its impact intensity.

(3) Trees provide excellent shade in summer and can shield against unfavorable winds in winter, reducing wind speed and enhancing thermal comfort. Therefore, it is recommended to plant deciduous vegetation in recreational areas and establish windbreaks in the predominant wind direction to improve the thermal comfort of healing gardens in both winter and summer.

In conclusion, the enhancement of environmental comfort in healing gardens of healthcare buildings is related to landscape configuration layout and site wind direction and speed. Through quantitative simulation analysis, this study reveals the underlying principles and provides effective design strategies for future landscape design.

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