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Examining the Microclimate Pattern and Related Spatial Perception of the Urban Stormwater Management Landscape: The Case of Rain Gardens

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Abstract: This study examines the microclimate pattern and related spatial perception of urban green stormwater infrastructure (GSI) and the stormwater management landscape, using rain gardens as a case study. It investigates the relationship between different rain garden design factors, such as scale, depth, and planting design, and their effects on microclimate patterns and human spatial perception. Taking an area in Blacksburg, Virginia, as the study site, twelve rain garden design scenarios are generated by combining different design factors. The potential air temperature, relative humidity, and wind speed/direction are analyzed through computational simulation. Additionally, feelings of comfort, the visual beauty of the landscape, and the overall favorite are used as an evaluation index to investigate people's perception of various rain garden design options. The study found that a multilayer and complex planting design can add more areas with moderate temperature and higher humidity. It also significantly improves people's subjective perception of a rain garden. Furthermore, a larger scale rain garden can make people feel more comfortable and improve the visual beauty of the landscape, highlighting the importance of designing larger and recreational bioretention cells in GSI systems. Regarding depth, a relatively flatter rain garden with a complex planting design can bring stronger air flow and achieve better visual comfort and visual beauty. Overall, by examining the microclimate pattern and related perception of rain gardens, this study provides insight into better rain garden design strategies for the urban stormwater management landscape. It explores the potential of rain garden design in urban GSI and responds to climate change.

Keywords: landscape microclimate; green stormwater infrastructure (GSI); rain garden design; landscape perception; landscape design guideline

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1. Introduction

1.1. Overview

Landscape design is an essential component of urban stormwater management and green infrastructure systems. It has been found that landscape planning and design can contribute to stormwater control, microclimate regulation, and an improvement in the quality of the urban living environment. Due to its potential contributions to the living and built environment, stormwater management landscape design has become an important aspect of the contemporary landscape industry [1]. However, it is important to note that focusing only on drainage or stormwater management functions may overlook the other existing design and research opportunities of green stormwater infrastructure (GSI). Rain gardens, as one of the most common and widely used components of GSI, also face the same problem. The recent landscape performance metrics (LAF) address the importance and potential of GSI in urban green infrastructure systems and regional environmental restoration, of which microclimate control and adjustment are crucial functions. Therefore, besides stormwater management, the microclimate impacts of GSI, and its related design guidelines need more in-depth study [1]. Thus, further research is necessary to understand the microclimate impacts of GSI in-depth. This research takes the rain garden, a typical form of GSI, as a case study to investigate its microclimate impact patterns under different design options, involving basic rain garden design variables. Meanwhile, people's subjective feelings about a rain garden design can indicate its impacts on the living environment. A survey involving people is taken as a supporting research approach in this research to enhance the microclimate impacts study.

1.2. GSI and Related Landscape Design

Stormwater management landscape design plays an important role in the construction of urban GSI [2]. Expanding the current sewer systems in an urban environment can be a costly approach. Instead, it is possible to achieve greater capacity for managing stormwater runoff by redirecting drainage to designated retention and infiltration sites using landscape and environmental design strategies [3]. Many cities are now realizing the importance of embracing sustainable stormwater management (SSWM) practices, where GSI and related landscape design can make remarkable contributions [4]. SSWM has the potential to address various hydrological, ecological, social, and economic functions, while optimizing a significant portion of the traditional urban drainage infrastructure [5]. The best stormwater management integrates a technical, environmental, and social approach [6]. GSI, as a crucial part of SSWM, can potentially benefit urban development by benefiting regional ecological restoration, regulating the microclimate, improving the landscape's visual beauty, and supporting citizens' recreational activities [7]. Typical stormwater management landscape design strategies include green roofs, retention basins or ponds, rain gardens, vegetative swales, wetlands, drainage channels, and green pervious pavements [8]. Different solutions can be integrated to form efficient GSI systems. Overall, GSI and related stormwater management landscape design have become an important component of the contemporary landscape industry [9] and are receiving increasing attention from various fields, such as urban planning, civil engineering, and environmental science.

1.3. The Rain Garden as an Important Component of GSI

In a GSI system, various techniques can be used for collecting rainwater from constructed surfaces and buildings and, subsequently, retaining and releasing it within the natural environment. Among them, the rain garden, as a typical low-impact development (LID), is a relatively convenient, efficient, and ecological approach [10,11]. As a typical stormwater management solution, the rain garden has demonstrated promising potential in promoting the protection of wildlife and biodiversity, improving visual and sensory pleasure, revitalizing recreational human activities, and creating a better garden microclimate [10]. The rain garden also serves as an important component in the stormwater chain in the built environment, which can achieve the function of run-off prevention, retention, filtration, amenity, and habitat, at the same time [10,12]. Vegetation, depressed landform at a certain depth, the retention soil mix, or filled materials are basic elements of rain garden design. In some cases, the drainage pipes, channel, and swale are facilitated and connected to the rain garden to guarantee efficient stormwater management [13]. Evaluating the performance of rain gardens is a widely researched topic among the existing studies on stormwater management landscape design [13,14]. Various assessment approaches, such as visual inspection, infiltration rate testing, and synthetic drawdown testing, are adopted in examining a rain garden's stormwater management functions [14]. However, microclimate regulation is also a critical function of rain gardens, which requires more in-depth evaluation and study.

1.4. Microclimate Impacts of GSI and the Urban Living Environment

Relating microclimate impacts and GSI, especially rain gardens, is not a common focus of existing, relevant research. The microclimate of an area is decided by a combination of various environmental factors, such as temperature, solar radiation, humidity, wind, and air [15]. The microclimate is significantly shaped by the presence of specific elements in the site, such as buildings, vegetation, and construction materials [16]. Microclimate regulation is not solely affected by the regional green infrastructure system, intra-scale GSI design, such as green streets, vegetative swales, and rain gardens, can also control the microclimate and influence related spatial perceptions [17]. However, examining the microclimate impacts of intra-scale GSI requires a more comprehensive evaluation, because more factors, such as visual pleasure, thermal comfort, and other human perceptions, need to be considered [18]. One crucial contribution of GSI to the microclimate is that it substitutes plants and vegetation for hard paved surfaces, which helps cool the summer landscape, bring more humidity, and improve the air quality [10,19]. Meanwhile, another major reason for the inclusion of vegetated elements in urban spaces that benefits the control of the microclimate is because it can mitigate the heat island effect and enhance urban esthetics at the same time [20,21].

The quality of the urban living environment can be affected by various factors and the microclimate is one of them. Better microclimate conditions provide the air quality, thermal comfort, and the landscape's visual beauty required for a good urban living environment [21]. Outdoor activities play a crucial role in urban life [22,23]. To foster a conducive environment for such activities, it is imperative to focus on the design of physical spaces and the creation of favorable microclimates, both of which are pivotal in enabling and encouraging outdoor pursuits [24]. Unfavorable microclimate conditions, such as high summertime temperatures and excessive CO_2 emissions in urban areas, can have a detrimental effect on outdoor comfort levels. This can lead to negative health effects, particularly among vulnerable populations, and increase stress levels [25].

2. Knowledge Gap and Research Framework

According to previous sections, several important points can be summarized, which consolidates the theoretical foundation and helps clarify the goals of this research. First, compared with the research on stormwater management functions of specific landscape design strategies and microclimate mitigation of regional GSI systems, the study of the microclimate impacts of intra-scale GSI and related landscape design, such as rain gardens, need more exploration. Second, regarding the microclimate study of rain gardens, more aspects need to be considered at the same time, including the thermal comfort, air quality, and the visual pleasure of the landscape. Third, based on the traditional rain garden evaluation methods, more comprehensive evaluation approaches integrating objective simulation and subjective perception studies should be considered in future research.

Therefore, this research focuses on examining the microclimate patterns of the stormwater management landscape by taking rain gardens as the case study. It aims to explore the relationship between different rain garden design factors, important microclimate patterns, and the public's spatial perception. Considering that the microclimate covers various metrics and measurements, the potential air temperature, relative humidity, and wind speed and direction, as important indicators on the quality of the urban living environment, are simulated and analyzed in this research. Figure 1 shows the basic framework for this research. Overall, three main research questions are developed and answered in this study: (1) Will the factors of scale, depth, and planting design affect the microclimate impacts (potential air temperature, relative humidity, and wind speed/direction) of the rain garden design? (2) How can these factors change the distribution of potential air temperature, relative humidity, and wind speed/direction in a rain garden design? (3) How can the research findings help and guide rain garden design to build better urban green infrastructure systems.

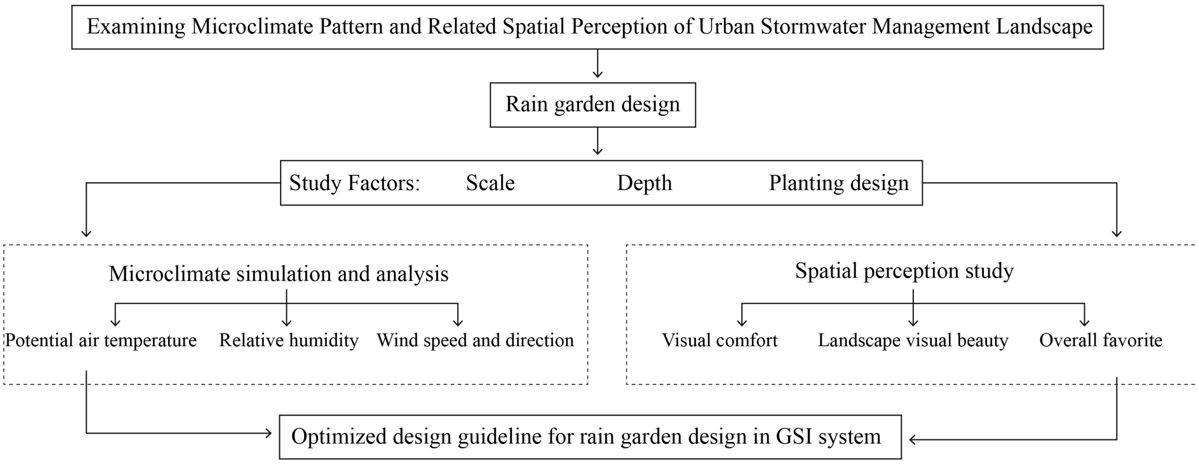

Figure 1. Research framework.

3. Research Methods

3.1. Rain Garden Prototype Design

This research takes an area in Blacksburg, Virginia, United States, as the study site (Figure 2). The geographic coordinates of the area are approximately 37°13′ N and 80°25′ W. To ensure the universality of the study site, the selected area consists of several basic elements of a common urban area, including streets, buildings, paved hardscapes (entrance plaza), and unpaved landscape spaces (lawn). The geographic and climate information used in the microclimate analysis process is based on this study site.

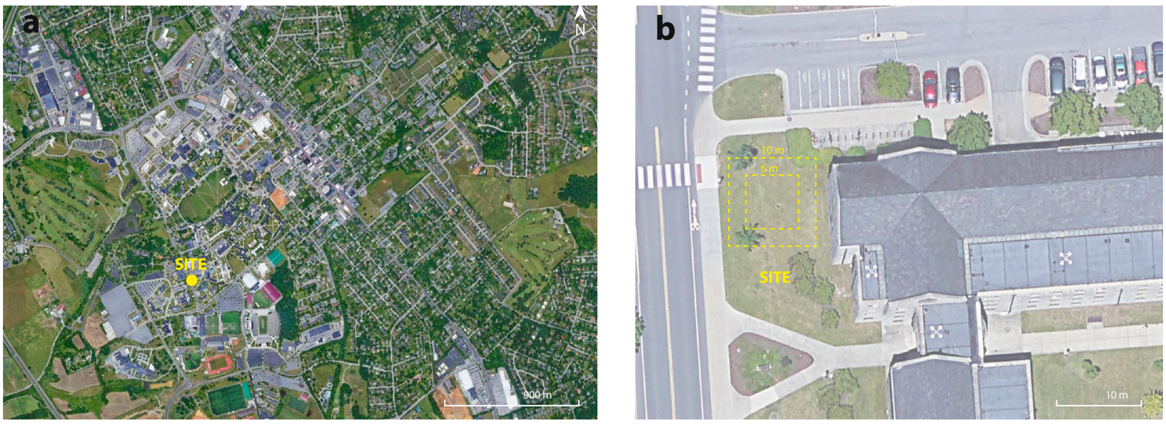

Figure 2. Diagram indicating the study factors and conceptual study site: (**a**) regional map; (**b**) site-scale map.

The scale, depth, and planting design are three important factors in a rain garden design from the perspective of landscape design, and they can affect the microclimate pattern and people's spatial perception of a rain garden [10]. Rain gardens are shallow depressions with planted trees and/or shrubs and/or groundcover, and planting design is an indispensable element of rain garden implementation [26]. Regarding the function of rain gardens, both the infiltration volume and storage volume can be affected by the scale and depth of rain gardens. Although the drainage calculation of rain gardens is not the focus of this research, important factors affecting drainage, especially the scale and depth, should be considered [27–29]. On the other hand, rain gardens are important retention cells in GSI, which should be designed and constructed based on the planning of the urban green infrastructure system. The location and scale of rain gardens cannot be ignored because these factors are closely related to the macro- and micro-planning and policies in the region [30]. Meanwhile, landscape architecture is a discipline dealing with the design of landform and terrain. Different landforms can potentially affect users' spatial perceptions and the visual experience, thus all types of topographic change on site are important to landscape designers [31]. Therefore, including depth as a study factor can help this research from the angle of landscape design and spatial perception [32].

Therefore, this research set the scale, the depth of the rain garden, and the planting design of the rain garden as study variables. For each variable, different levels are set up as well. According to Table 1, two scales of rain garden design (6 × 6 m^2 and 10 × 10 m^2), three types of planting design (only land cover/land cover and shrub/land cover, shrub, and tree), and two types of rain garden depth (depth of 0.5 m and depth of 1.0 m) are included in the study. By combining these factors, 12 types of rain garden design scenarios are generated. The simplified codes for the different rain garden design options are shown (Figure 3). To define different levels of planting design, the following strategies are utilized: for the planting design with "only ground cover (G)", the 25 mm tall fescues are used to cover the entire rain garden; for the planting design with "ground cover + shrub (GS)", the 25 mm tall fescues are used to cover half of the rain garden, while the 500 mm tall sword fern (*Nephrolepis exaltata*) are selected to occupy the other half; for the option "ground cover + shrub + tree (GST)", on the basis of the "ground cover + shrub", one young river birch (*Betula nigra*; 5 m high and 3.5 m crown width) is added to all 36 m^2 rain garden design scenarios, while three of the same trees are added to all 100 m^2 rain garden design scenarios.

Table 1. Study variables related to the rain garden design in this research.

Variables	Scale/m^2	Depth of Rain Garden/m	Planting Design
Levels	6 × 6 m^2 (36) 10 × 10 m^2 (100)	0.5 m (0.5) 1.0 m (1.0)	Only ground cover (G) Ground cover + shrub (GS) Ground + shrub + tree (GST)

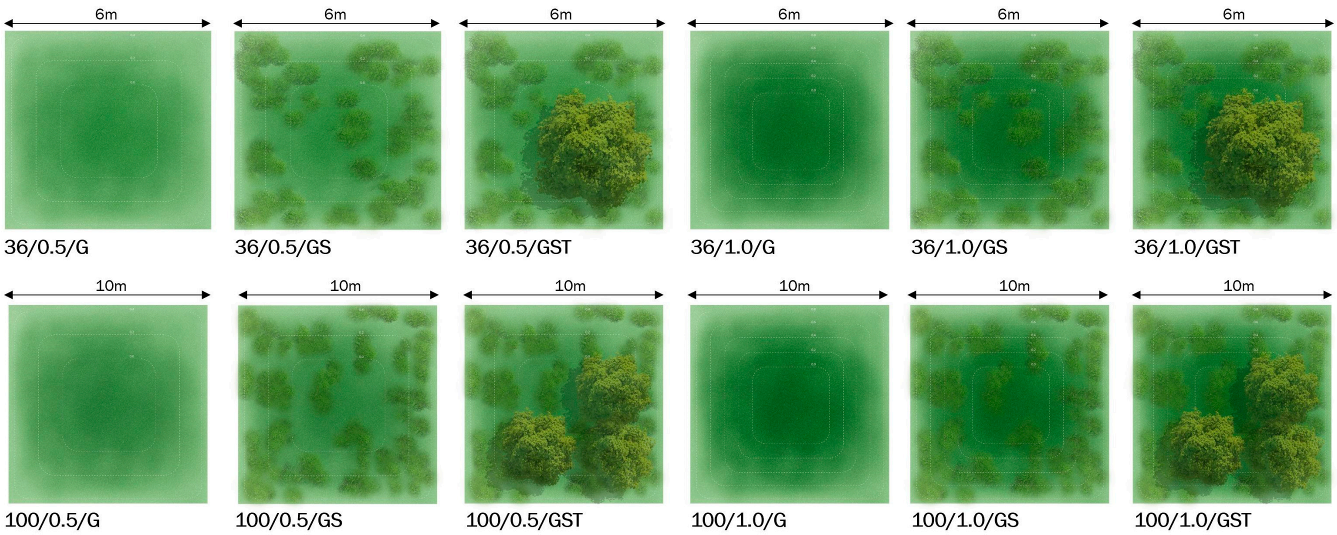

Figure 3. Twelve rain garden design scenarios generated by the combination of study variables.

3.2. Microclimate Impacts Analysis

By combining these factors, 12 types of rain garden design scenarios can be generated. Based on the 12 rain garden design scenarios, important microclimate impacts, including the potential air temperature, relative humidity, and wind direction/speed for each rain garden design option, are simulated and analyzed. The 3D test models for all the rain garden options are made using Rhino, which allows researchers to check the overall view and feasibility of the options. ENVI-met is a climate simulation and analysis software that has been used in many environmental studies [33–36]; it is reliable and efficient for simulating the built environment at multiple scales. In this research, all the rain garden design options are modeled in ENVI-met, according to the Rhino testing model. Then, the microclimate impacts, mentioned above, are simulated and analyzed through ENVI-met. Moreover, the related data are exported from ENVI-met to Photoshop for color proportion analysis, and to SPSS for statistical analysis.

Various microclimate impacts have the potential to affect daily human activities and the quality of the urban living environment [15]. Among them, the potential air temperature, relative humidity, and wind speed/direction are typical and fundamental components [15–17]. Regarding the relationship between these microclimate impacts and the studied variables, existing research has shown that the land scale, topography, and vegetation can either significantly or subtly affect the pattern of the potential temperature and relative humidity [19–21]. Therefore, analyzing the potential temperature, relative humidity, and wind speed/direction of the 12 rain garden design options is necessary, feasible, and reasonable given the goal and design of this research.

To conduct the microclimate impacts analysis, some environmental information needs to be preset based on the context of the study site. This research focuses on exploring the general relationship between different rain garden design factors, the microclimate pattern, and people's spatial perception. Therefore, a specific date (4 January 2023) is randomly selected, and the related climate data is adopted as pre-settings for the ENVI-met analysis. Because most people tend to better perceive design during the day, this research only includes microclimate analysis during the daytime. Based on the historical sunrise and sunset time in Virginia [37], researchers measured the air temperature on site at 6:00 a.m. (one hour before the predicted sunrise time), 12:00 p.m., and 9:00 p.m. (an hour after the predicted sunset time). In this way, the approximate minimum (17 °C) and maximum air temperature (27 °C) of the site can be learned. The relative humidity was measured on site at 6:00 a.m., 9:00 a.m., 12:00 p.m., 15:00 p.m., 18:00 p.m., and 21:00 p.m. Among the results, the minimum humidity was around 45% and the maximum humidity was around 75%. The wind speed and direction were measured at 12:00 p.m. The wind speed was around 2 m/s and the wind direction at inflow was approximately 90°. These measurements may have errors, but for this research, obtaining reasonable climate data from the site is more important. In summary, all the data mentioned above are used as pre-settings in ENVI-met for the following microclimate analysis.

3.3. Microclimate Comfort and Perception Analysis

Besides the microclimate impacts analysis, the microclimate comfort and related spatial perception analysis is equally important, given the goal of examining the microclimate impacts of GSI on the living environment. People's subjective feelings and perceptions of a rain garden design is a crucial complement to the objective software-based simulations explained in the previous sections [38]. To study the microclimate comfort and people's perceptions for all rain garden design scenarios, 3D modeling, real-time digital rendering, and virtual reality (VR) technology were adopted. The 12 rain garden design options and surrounding site contexts were modelled using Rhino, which is a widely used 3D modeling software in the field of architecture, landscape architecture, urban planning, product design, and civil engineering [39–41]. Twinmotion, a real-time rendering engine has been applied in various environmental research, visual communication research, and practical design projects [42,43]. In this study, Twinmotion was adopted to generate realistic renders of the different rain garden design options using the 3D models made in Rhino. The VR HMD used in this study involved two sets of HP Windows Mixed Reality, which were connected to Twinmotion to provide people with immersive visualizations of the digital renderings. Two standing points were selected by the researchers for participants to view the rain garden design. One standing point was located near the street and provided an overall view of the rain garden, the other standing point was located in the rain garden where people could have a more immersive experience (Figure 4).

This study recruited 75 people between 18 and 50 years old as participants, 39 of whom were females and 36 of whom were males. The research team recruited participants from

Virginia Tech, Qingdao Agriculture University, and commercial firms that have collaborated with the research team before. The occupations of the participants were diverse, including students, faculties, and researchers with various backgrounds, engineers, designers, consultants, and social workers. Although the occupation, age, and gender of the participants were not analyzed in this perception study, their diversity was guaranteed to make the survey results more reliable. After obtaining the consent of every participant, the researchers asked the participants to use a VR HMD to view the 12 simulated rain garden designs from both standing points (point A first and then point B). The order of appearance of the designs viewed by each participant was randomized, which to a certain extent prevented the validity threat caused by participants' visual fatigue and selection difficulties.

Figure 4. Examples of the rain garden design simulation (100/1.0/GST) from the two selected viewpoints.

For the assessment, a survey was used to investigate the participants' spatial perceptions of various rain garden design options. According to relevant environmental perception and environmental phycology studies [43–45], the Likert scale with brief survey questions is one of the most efficient and easily accessed approaches to investigate landscape users' subjective feelings. This spatial perception study was supplementary to the overall research, so using the Likert scale and simple survey questions was more feasible. According to the survey design using the Likert scale in existing research [45,46], visual comfort (feelings of being relaxed, safe, and harmony) and visual beauty (feelings of interest, fascination, and vividness) are two important aspects related to people's spatial perception of a landscape space. The Likert scale between 5 to 7 points is commonly adopted. Therefore, an appropriate survey was designed for this research. Table 2 shows the design of the survey and the important contents of the evaluation. The general feelings of visual comfort, the landscape's visual beauty, and the overall favorite are three dimensions included in the contents of the evaluation. The Likert scale from 1 to 5 points (from bad to excellent), based on the Richter scale [46], was used for the participants to evaluate the dimensions of a rain garden design option. In this research, using VR simulation could not provide any realistic feelings on the thermal or humidity aspects, so the comfort and beauty perceptions of the landscape were investigated based on the participants' visual experience.

Table 2. Study variables related to the rain garden design in this research (source: authors).

Evaluation Matrix	Visual Comforts	Landscape Visual Beauty	Overall Favorite
Grading criteria	Very uncomfortable: 1 A little bit uncomfortable: 2 Neutral and indifferent: 3 Fair comfortable: 4 Very comfortable: 5	Very bad visual beauty:1 Relatively bad visual beauty: 2 Neutral and indifferent: 3 Good visual beauty: 4 Excellent visual beauty: 5	Very bad: 1 Bad: 2 Fair: 3 Good: 4 Excellent: 5

4. Results

4.1. Microclimate Patterns for Different Rain Garden Design Options

By conducting microclimate analysis for 12 rain garden design options, the microclimate patterns, including the potential air temperature, relative humidity, and wind speed/direction for each design option, were assessed as follows.

4.1.1. Potential Air Temperature

The potential air temperature distribution for all rain garden design options is shown in Figure 5. Before conducting any in-depth analysis, it can be roughly learned from Figure 5 that, for the rain garden design options with the same scale and depth, the potential temperature patterns look very similar, which might indicate that the planting design does not significantly affect rain gardens' potential temperature distribution. However, for the rain garden design options with a different scale and depth, the difference in potential temperature patterns is apparent. Further analysis is necessary to examine these differences and will be detailed in the following sections. It is worth noting that because of the wind direction, the distribution of the lower temperature is downwind in all 12 design options, which is not affected by all the study factors. However, the temperature distribution in the central area of a rain garden can be different due to the impacts of scale and depth.

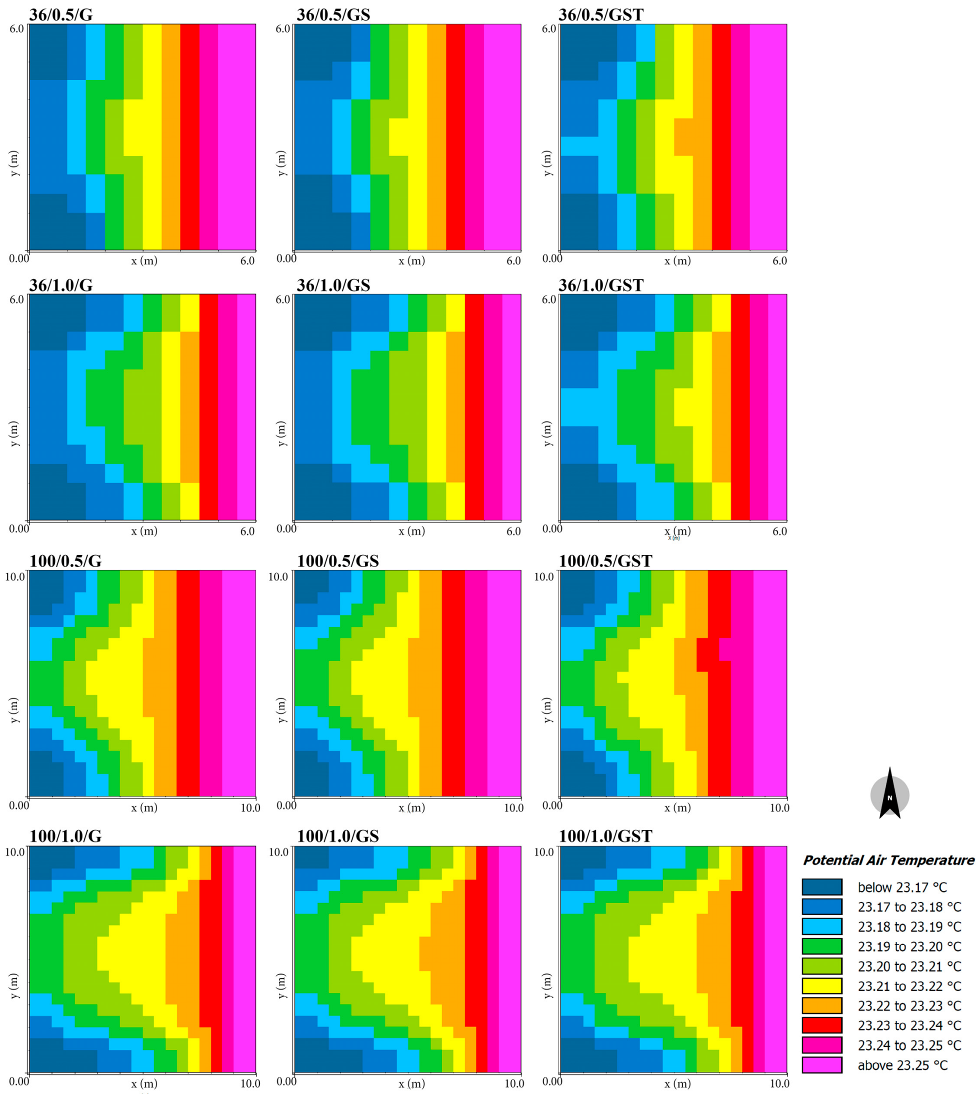

Figure 5. Potential temperature distribution.

4.1.2. Relative Humidity

By roughly reading the results from the relative humidity analysis (Figure 6), it can be seen that the distribution patterns for relative humidity are not obviously affected by planting design, which is similar to the potential temperature. Meanwhile, different depths do not apparently affect the relative humidity distribution, though its impact is more visible than the planting design. Scale seems to be the factor that has the greatest impact on relative humidity. As shown in Figure 6, the larger the scale of the rain garden makes the distribution of relative humidity more fragmented and diverse, which to some extent makes the relative humidity in the same area more uniform and balanced. In-depth analysis will be detailed and discussed in the following sections.

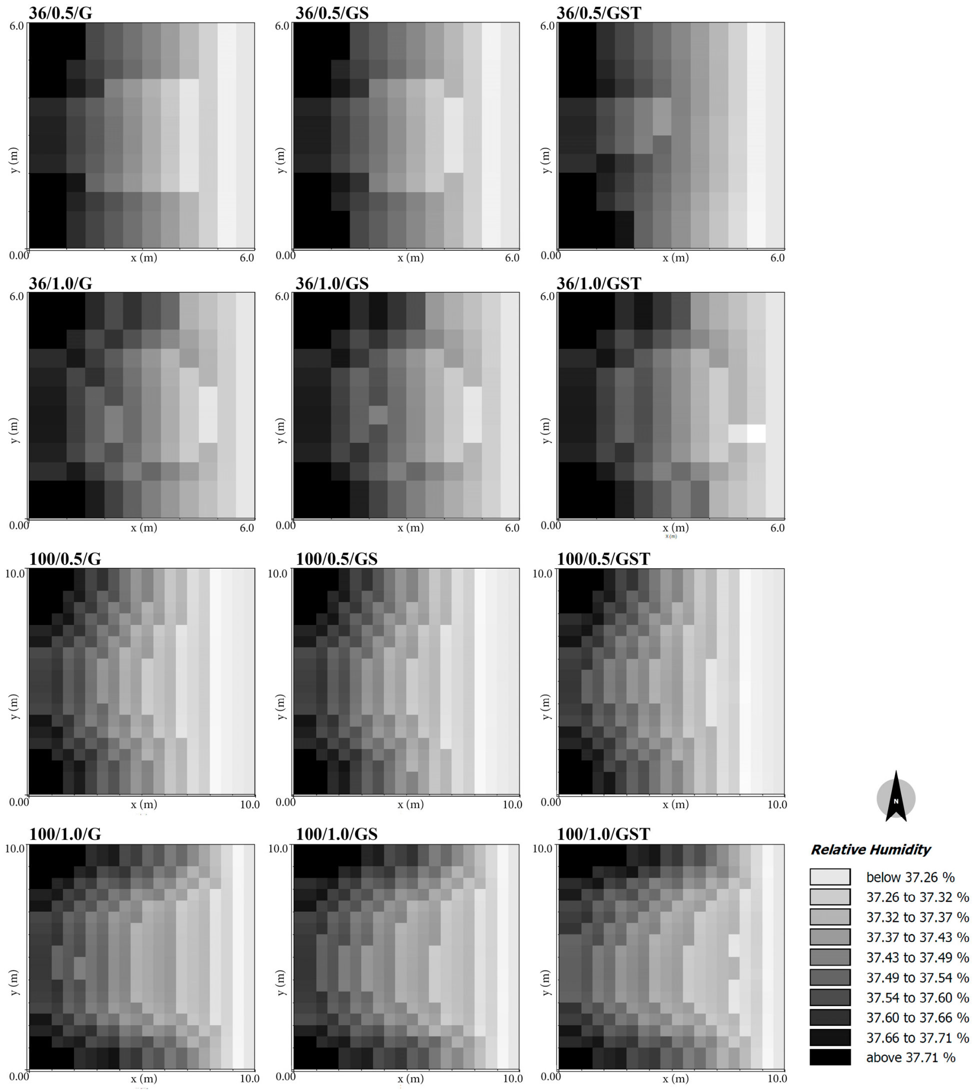

Figure 6. Relative humidity distribution.

4.1.3. Wind Speed and Direction

Figure 7 does not show any obvious difference in wind speed and direction among the different planting designs. Subtle wind speed changes can be roughly detected between the different depths. Scale might be the most important factor affecting the wind speed. Overall, the pattern of the wind direction does not change significantly due to the different rain garden design factors. In the section on data analysis and discussion, further analysis of the wind speed is conducted to draw more reliable findings.

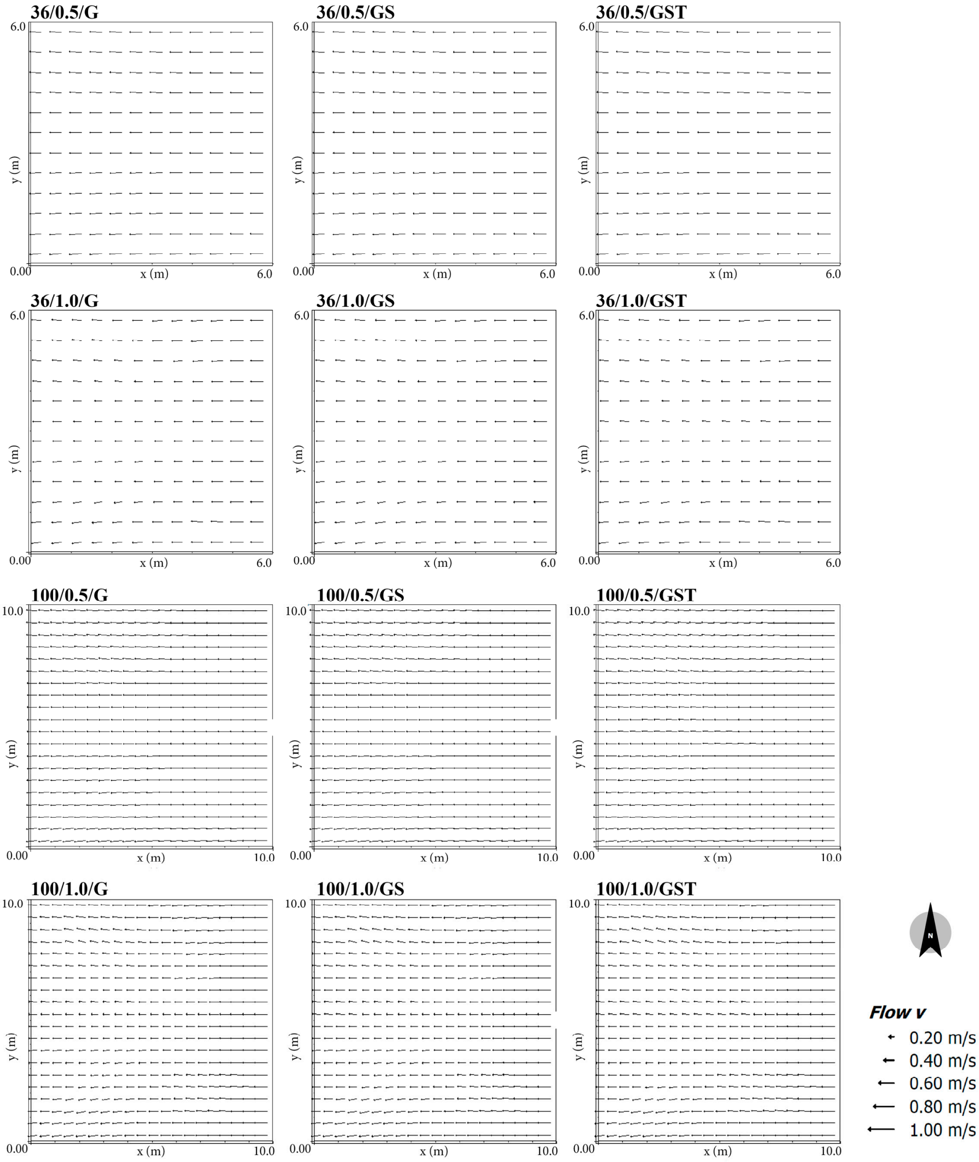

Figure 7. Wind speed and direction pattern.

4.2. Results of the Spatial Perception Study

The overall survey results from the microclimate comfort and perception study can be seen in Figure 8 and Tables 3–5. These results initially show that a larger scale could generally improve people's satisfaction across all the evaluation index adopted in this study (feelings of comfort, the landscape's visual beauty, and the overall favorite). Similarly, the results may imply an obvious impact caused by the different planting designs on all the evaluation index. The use of trees can apparently increase participants' rating of a rain garden design, especially the landscape's visual beauty. However, the depth of the rain garden fails to show a significant influence on the feelings of comfort and the landscape's visual beauty, and more depth can slightly decrease people's rating on the overall favorite rain garden option. Although these descriptive statistics can tentatively implicate these findings, further and detailed statistical analysis is necessary and will be detailed in the discussion section.

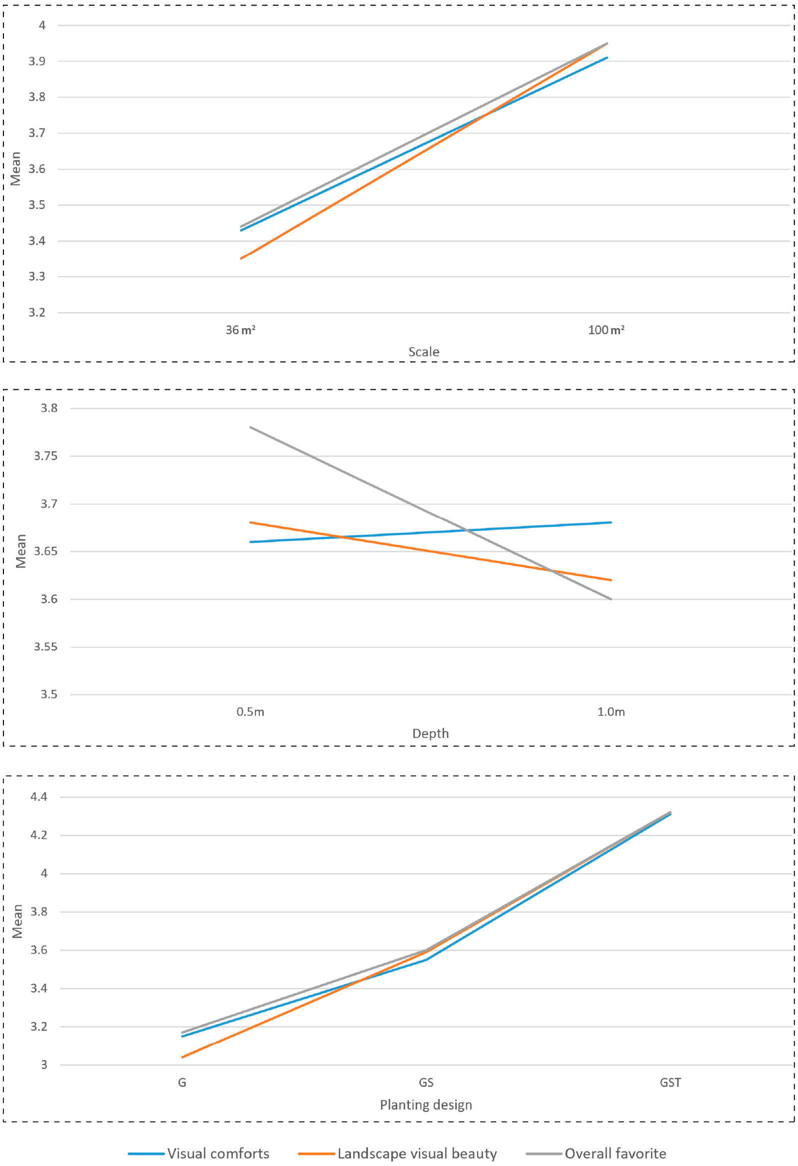

Figure 8. Mean comparisons among different study factors and the evaluation index.

Table 3. Descriptive statistics on the scale (m^2) and the different evaluation index.

Scale		Visual Comfort	Landscape Visual Beauty	Overall Favorite
36 m^2	Mean	3.43	3.35	3.44
	Std. Deviation	0.839	0.840	0.782
100 m^2	Mean	3.91	3.95	3.95
	Std. Deviation	0.743	0.776	0.743

Table 4. Descriptive statistics on the depth (m) and the different evaluation index.

Depth		Feelings of Comfort	Landscape Visual Beauty	Overall Favorite
0.5 m	Mean	3.66	3.68	3.78
	Std. Deviation	0.812	0.831	0.761
1.0 m	Mean	3.68	3.62	3.60
	Std. Deviation	0.845	0.891	0.834

Table 5. Descriptive statistics on the planning design and the different evaluation index.

Planting Design		Feelings of Comfort	Landscape Visual Beauty	Overall Favorite
G	Mean	3.15	3.04	3.17
	Std. Deviation	0.725	0.746	0.677
GS	Mean	3.55	3.59	3.60
	Std. Deviation	0.650	0.651	0.654
GST	Mean	4.31	4.32	4.32
	Std. Deviation	0.650	0.657	0.625

Notes: ground cover (G); ground cover + shrub (GS); ground cover + shrub + tree (GST).

5. Data Analysis

5.1. Potential Air Temperature and Rain Garden Design

According to the results from the potential air temperature analysis, the change in temperature is relatively subtle. Therefore, in order to more straightforwardly analyze the differences in temperature distribution in 12 rain garden design options, this study divided the temperature into three intervals, including low temperature (low-tem), medium temperature (medium-tem), and high temperature (high-tem), and then performed data analysis on the proportion of different ranges. Based on the temperature range used in the ENVI-met analysis (Figure 5), the range for the low temperature was set to be below 23.19 °C, the range for the medium temperature was set to be from 23.19 °C to 23.23 °C, and the range for the high temperature was set above 23.23 °C. Figure 9 shows the results of the analysis.

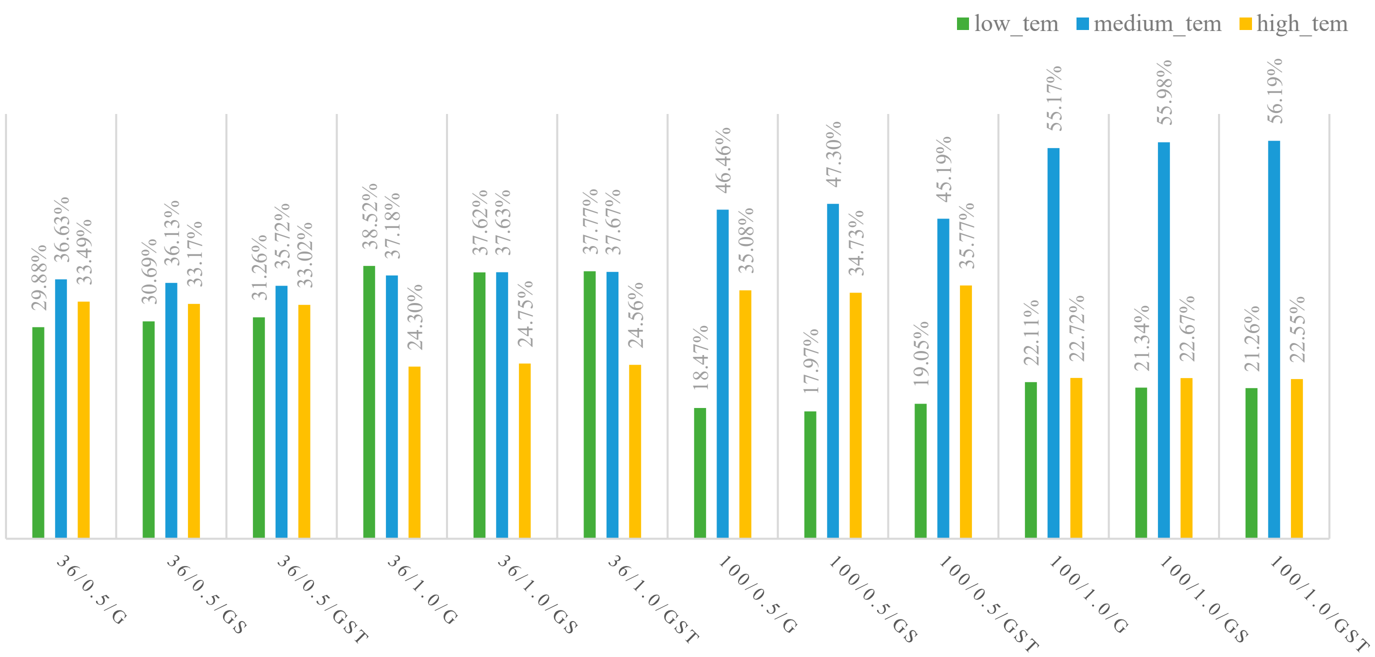

Figure 9. Proportion of different temperature ranges among the 12 design options.

It can be learned from the analysis that a larger scale and more depth might create more areas with medium air temperature. When the depth stays the same, a smaller rain garden scale might provide more areas with low temperature. Moreover, according to the analysis, the vegetation does not significantly affect the distribution of the air temperature among the 12 rain garden design options. However, a more diverse planting design will slightly reduce the areas with a higher temperature and add more space with a medium temperature. Although the changes in the temperature distribution pattern for the different rain garden design options are examined in this research, these changes are quite subtle and difficult to be felt by people in real-world situations. The discussion on the temperature distribution pattern here focuses more on exploring the potential impacts of the different rain garden design factors. On the other hand, the analysis only deals with one single rain garden, if there are many bioretention cells in existence in the urban GSI system, this temperature change pattern might be magnified to a perceivable level.

5.2. Relative Humidity and Rain Garden Design

Unlike the potential air temperature, which has obvious clusters of low, medium, and high temperature, the results from the overall relative humidity analysis discussed in the previous section show a relatively even and fragmented distribution. Therefore, the approach of setting multiple humidity ranges is not useful. A comparison map was adopted for the detailed relative humidity analysis. As mentioned in Section 4.1.2, the overall relative humidity patterns for the 12 rain garden design options show the possible impacts of landform depth and scale. Thus, a comparison map and overlay map were conducted to explore their impacts extensively (Figure 10).

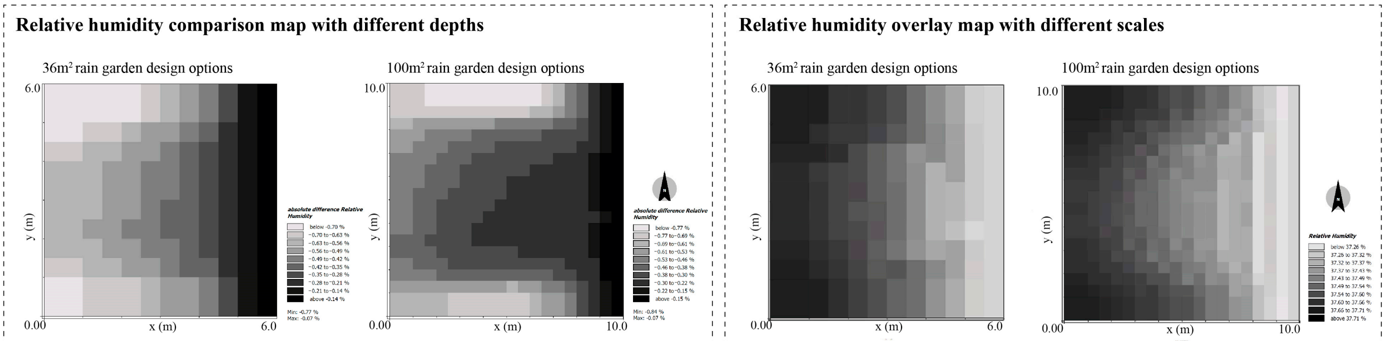

Figure 10. Comparison map and overlay map analysis of the relative humidity.

Based on the comparison map analysis for the relative humidity among the 12 rain garden design options, several findings can be summarized. The depth can subtly affect the primary pattern of relative humidity when the scale of the rain garden and planting design are the same. Given the overall environmental settings in this research, for a smaller scale rain garden, the relative humidity in the bottom of the rain garden is obviously low. However, for a larger scale, the relative humidity change across the site is relatively even and the relative humidity in the bottom of the rain garden does not show an obvious decrease. However, again, as mentioned in Section 4.1.2, the factor of scale does not significantly change the overall pattern of relative humidity distribution. In terms of planting design, different vegetation does not obviously affect the distribution of relative humidity, according to Figure 6. However, when we examine both the overall humidity distribution and the comparison map, we can learn that a more complex planting design (ground cover + shrub + tree, in this research) might increase the areas with higher relative humidity, this might be because more abundant vegetation results in stronger transpiration and evapotranspiration processes [32].

5.3. Wind Speed/Direction and Rain Garden Design

The wind speed and direction analysis results, shown in Section 4.1.3, do not show any obvious differences between the options with different planting designs and scales. At the same time, the results indicate the potential impacts of depth on wind speed. By conducting a comparison map on wind speed (Figure 11), these inferences are supported. According to Figure 11, regardless of scale, the planting design has almost no effect on the wind speed. Different depths primarily affect the wind speed in the middle area of a rain garden. The depth change from 0.5 m to 1.0 m will reduce the wind speed by about 30% to 35%. Meanwhile, the overall patterns in the wind speed comparison maps between the different scales are very similar, which indicates that scale might not be an important factor affecting the wind speed within rain gardens.

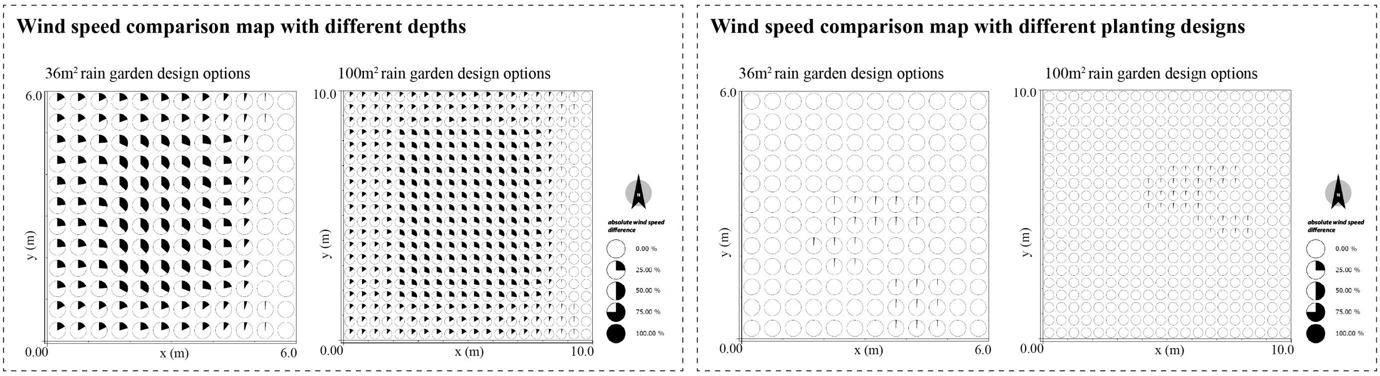

Figure 11. Comparison map analysis of wind speed.

5.4. Public Perception of the Rain Garden Design

Based on the survey results and descriptive statistics from the perception study, ANOVA analysis was conducted to explore the impacts of different study factors on people's visual comfort, the landscape's visual beauty, and the overall favorite rain garden. The Levene test does not show a significant variance difference in people's ratings between each rain garden design option, therefore the assumption of homogeneity of variance is met. Meanwhile, participants' rating scores were basically normally distributed, and every participant's answers were independent of each other.

The statistical analysis (Tables 6–8) indicates that the planting design has significant impacts on all the aspects of the evaluation index (visual comfort, the landscape's visual beauty, and the overall favorite rain garden design). The survey results show that a more complex planting design, especially adding trees, can obviously increase people's rating of a rain garden design. Different from the factor of planting design, the depth of a rain garden does not really affect people's perception of comfort or the landscape's visual beauty, but it can affect people's overall favorite rain garden design. Although depth fails to significantly affect the visual comfort and the landscape's visual beauty, its interaction impacts with the planting design are significant, which shows that depth can become a crucial factor in rain garden design if combined with a specific planting design strategy. From the detailed survey results, we know that a relatively flatter landform with a complex planting design receives the highest rating. Moreover, for the factor of scale, the statistical analysis implies that it has significant impacts on all the aspects of the evaluation index. According to the detailed survey results, it can be learned that, compared with a small-scale rain garden, a large-scale rain garden tends to receive a higher rating for both feelings of comfort, the landscape's visual beauty, and the overall favorite to some extent.

Table 6. ANOVA test for the different study factors' impacts on visual comfort.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	274.370 [a]	11	24.943	63.805	0.000
Intercept	12,385.548	1	12,385.548	31,683.072	0.000
Scale	54.052	1	54.052	138.268	0.000
Depth	0.044	1	0.044	0.113	0.736
Planting design	214.935	2	107.468	274.909	0.000
Scale × Depth	1.450	1	1.450	3.710	0.054
Scale × Planting design	1.622	2	0.811	2.075	0.126
Depth × Planting design	7.920	2	3.960	10.130	0.000
Scale × Depth × Planting design	0.732	2	0.366	0.937	0.392

[a]: R Squared = 0.435 (Adjusted R Squared = 0.428).

Table 7. ANOVA test for the different study factors' impacts on the landscape's visual beauty.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	271.742 [a]	11	24.704	63.603	0.000
Intercept	12,129.351	1	12,129.351	31,228.343	0.000
Scale	52.804	1	52.804	135.951	0.000
Depth	0.040	1	0.040	0.103	0.748
Planting design	207.282	2	103.641	266.835	0.000
Scale × Depth	1.440	1	1.440	3.707	0.054
Scale × Planting design	1.602	2	0.801	2.063	0.128
Depth × Planting design	7.887	2	3.943	10.153	0.000
Scale × Depth × Planting design	0.687	2	0.343	0.884	0.414

[a]: R Squared = 0.441 (Adjusted R Squared = 0.434).

Table 8. ANOVA test for the different study factors' impacts on the overall favorite.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	338.489 [a]	11	30.772	83.167	0.000
Intercept	11,982.951	1	11,982.951	32,386.354	0.000
Scale	79.804	1	79.804	215.688	0.000
Depth	0.871	1	0.871	2.354	0.125
Planting design	244.949	2	122.474	331.012	0.000
Scale × Depth	3.484	1	3.484	9.417	0.002
Scale × Planting design	1.069	2	0.534	1.444	0.236
Depth × Planting design	6.616	2	3.308	8.940	0.000
Scale × Depth × Planting design	1.696	2	0.848	2.291	0.102

[a]: R Squared = 0.507 (Adjusted R Squared = 0.501).

6. Discussion

As one of the most important goals of this study, the research findings above can potentially suggest optimized guidelines for rain garden design in future GSI systems. First, according to the study, planting design is the core among three study factors in rain garden design. The implementation of multilayer planting design can increase the areas with higher relative humidity and moderate temperature. Existing studies have found advantages of increasing green coverage in regulating regional temperature and humidity [15,16]; this study focuses on intra-scale GSI [17] and the findings align with other regional-scale research. Meanwhile, including trees and shrubs can significantly improve the public perception of a rain garden from the perspectives of visual comfort, the landscape's visual beauty, and the overall favorite. Existing studies have clarified the positive impacts of vegetation on the users' comfort and the landscape's visual beauty [19,38,45], but related research specifically focusing on GSI, such as rain gardens, is limited [11,17]. This study validates the rationality of these conclusions using rain gardens as a case study. Based on the research findings above, this research suggests that landscape designers and civil engineers should pay more attention to planting design when designing and constructing a rain garden. The use of more diverse plant species and multilayers of vegetation should be the first choice.

The effects of scale and depth on a rain garden's microclimate patterns and the related public perception are not as significant as the planting design, but they should also be considered in practical rain garden design [10,32]. According to the research findings, we know that a larger scale can make the distribution of potential air temperature and relative humidity more even. It also increases the proportion of moderate temperature areas. On the other hand, in terms of people's subjective perception of a rain garden, a larger scale can bring more visual comfort and improve the visual beauty of the rain garden. Therefore, if conditions permit, designing a rain garden with a larger area and various functions is a better choice [6]. In some cases, a larger-scale rain garden itself can become an independent urban green space or part of a park, which increases the green coverage of a region and enhances the local green infrastructure system. Existing studies have pointed out the potential of integrating the stormwater management landscape into the recreational landscape [8,9], and this research provides more scientific evidence and innovative design guidelines to support this finding. Regarding the analysis, the impacts of depth on a rain garden's microclimate pattern are subtle. Existing studies have clarified the importance of depth and topography change on landscape design [27,31,32], but microclimate and public perception analysis of rain gardens taking depth as one study factor is seldomly conducted. This research finds that a shallower landform can increase the wind speed in the center of a rain garden. However, the factor of depth cannot really affect people's perception of a rain garden unless it is combined with planting design. A relatively flatter landform with a complex planting design can achieve a better feeling of comfort and visual beauty, which might be because this type of rain garden looks more like a recreational landscape rather than a stormwater management infrastructure. This result is slightly different from some related studies which claim that more elevation changes may bring more visual comfort (when people are standing or sitting on the lower level) [32,47]. Inspired by this finding, researchers believe that when designing and constructing a rain garden the features of GSI should be weaker, while the signatures of a recreational landscape, such as lush vegetation, a stretched terrain, and an open field of vision, should be emphasized.

On the limitations and future scope of this research, some critical issues should be addressed and explored further. First, although the data has been collected, the change in the selected microclimate impacts during a day needs to be analyzed better. This will make up for the problem of using data at one specific time [34]. Meanwhile, the current study only focuses on the microclimate pattern of the rain garden itself, its impacts on the surrounding areas need further research. The rain garden design contexts in this study are based on a random and normal urban area, but various types of design contexts, such as a residential community, CBD zone, urban infrastructure, and industrial area, can be used to reach more comprehensive research findings [10]. In addition, in this study, only the most basic factors of rain garden design are involved and only a few levels of one factor are used for analysis. In future studies, more rain garden design factors, such as the height of plants and the border shape of the rain garden should be considered. For each factor, more detailed levels and types should be included. In terms of the perception study, the sample size can be increased to achieve better validity. Meanwhile, the evaluation index for the perception study only included three fundamental aspects, and other useful indicators on how people perceive a rain garden design should be included. Moreover, viewing a rain garden design through a VR HMD only focuses on the visual experience. For perception studies related to microclimate comforts, involving simulation tools that can achieve a multisensory experience is important in future research.

7. Conclusions

Overall, this research aims to examine the microclimate impacts of rain garden design in an urban GSI system by studying three design factors (scale, depth, and planting design). Both microclimate simulation and a perception study involving people were conducted to explore how different factors affect the distribution of air temperature, relative humidity, wind speed/direction, people's perception of comfort, the landscape's visual beauty, and the overall favorite rain garden. This research finds that multilayer and complex planting design can increase the areas with higher relative humidity and add more areas with a moderate temperature. It can improve people's subjective perception of a rain garden. Therefore, using more diverse plant species and multilayers of vegetation could benefit future rain garden design. The effects of scale and depth on a rain garden's microclimate impacts and the related human perceptions are not as significant as the planting design. However, a larger scale can make people feel more comfortable and improve the visual beauty of the rain garden, which indicates the necessity of designing a larger rain garden in urban GSI systems. For the factor of depth, the research shows that a relatively flatter rain garden with complex planting design can achieve a better feeling of comfort and visual beauty. In summary, the research findings suggest that designing a rain garden with more features of a recreational landscape could be an effective way to optimize the microclimate impacts and the related human perceptions for future GSI and related landscape design.

Overall, this research innovatively combines the methods of objective computational simulation of the microclimate and a subjective human perception study to explore the microclimate pattern and related spatial perception of rain gardens. It suggests feasible rain garden design guidelines for landscape designers, environmental designers, and civil engineers. By examining the microclimate patterns and related perception of rain gardens, this study provides insight into better rain garden design strategies for urban GSI. It explores the potential of rain garden design in urban GSI, regional environmental restoration, and the response to climate change.

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