Analysis of Thermal Environment of Waterfront Space in Summer in Mountain City: A case study in Chongqing, China

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Abstract. A crucial component of the urban ecology, waterfront space plays a key role in mitigating the urban heat island effect. However, waterfront spaces in mountain cities differ greatly from those in plain cities in terms of spatial form and environmental factors. Accordingly, it is urgent to study and improve the thermal environment of waterfront spaces in mountain cities. According to the spatial morphological characteristics and shading means of the waterfront space in Chongqing, a typical mountain city in China, the summer thermal environment of the waterfront space has been studied through field measurements. The outdoor thermal environment factors assessed include air temperature, relative humidity, wind speed, and mean radiation temperature. The results showed that the cooling effect was more significant at 1 m from the water's edge and decreased as the elevation increased. Air temperature and humidity showed a clear stratification characteristic with increasing elevation. At the same time, viaduct-shading was the most effective way of reducing heat stress, followed by the combined shading of sun sails with building-shading, while tree-shading was the least. This study offers basic data for further study and optimization of shading strategies for waterfront spaces in mountain communities.

1 Introduction

As linear open spaces, urban waterfront spaces reflect the image and character of the city and are significant gateways to attract residents and foreign visitors [1,2]. With the high workload and intense pressure of modern cities, waterfront spaces with a pleasant climate can be extremely beneficial to one's physical and mental well-being. Thus, the waterfront has become the focus of urban planning in the era of neoliberal urbanisation [3]. In recent years, urban waterfront development has shown that it can enhance or restore urban vitality [4]. However, as the global climate warms, the urban heat island effect and heat wave disasters are intensifying [5]. In addition to increasing the incidence of cardiovascular, respiratory, and digestive diseases, extreme heat events also trigger natural disasters that directly lead to a large number of deaths, including the 1995 Chicago heat wave [6], the 2003 European heat wave [7] and the 2020 English heat wave [8]. The creation of thermally comfortable waterfront spaces in the existing built environment has become an increasingly pressing issue. Chongqing is one of the hottest cities in China, with maximum summer temperatures reaching over 40 °C [9]. The thermal environment of waterfronts is particularly problematic.

Some progress has been made in research on the thermal environment of waterfront spaces, but there are some limitations. In terms of cooling mechanisms in water bodies, Van Hove et al. [10] found that water can remove heat through turbulent mixing if the depth of the water exceeds 0.5 m. Hathway et al. [11] found that the cooling effect of urban water bodies is influenced by the geometry of the city. In addition to water bodies and urban forms, the synergistic cooling effect of water bodies and greenery is also the focus of research. Xu et al. [12] reported that greenery can improve thermal comfort along the Huangpu River in Shanghai in areas 10-20 m from the water's edge. Jiang et al. [13] showed that in Shanghai, green corridors oriented along the summer monsoon had a greater cooling effect. Despite previous studies investigating the cooling effect of urban water bodies, most of these studies have been conducted in plain cities. However, relatively few studies have been conducted in mountainous areas. The waterfront public space in Chongqing is characterized by a height difference of 25~30 m. This leads to a spatial form of its waterfront area that is quite different from other cities. In addition, Chongqing is a hot summer and cold winter zone, where extreme hot weather poses a significant obstacle to waterfront activities. Therefore, it is urgent to study and improve the thermal environment of waterfronts in Chongqing.

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Through field tests, the current state of the waterfront thermal environment is analysed in terms of both spatial patterns and environmental factors. The results of the study can provide basic data for further investigation and the optimal design of the thermal environment of mountainous waterfronts.

2 Methodology

2.1 An analysis of the status quo of Open Communities

Chongqing, located in southwest China, is a typical representative of a mountainous city, ranging from 105°11′E to 110°11′E and from 28°10′N to 32°13′N. It has a humid subtropical monsoonal climate with an average annual temperature of 16–18 °C and a maximum temperature of 42 °C in summer[14]. The flood protection elevation of Water body side Road in the main urban area of Chongqing is 194 m (50-year maximum water level as the base). Influenced by the winter storage and summer discharge of the Three Gorges Reservoir, the year-round water level is 145–174 m, with the lowest water level in summer. We examined 35.61 km of water-friendly spaces in the main urban area of Chongqing and summarized their morphology and characteristics, with five typical forms shown in Fig.1. In this paper, a composite type is selected for the study.

2.2 Site description, measurement instruments and method

The study site was selected in the Yuzhong District of Chongqing, as shown in Fig.2. As a typical waterfront space in Chongqing, it has a large difference in section elevation as well as a rich spatial morphology. The study of the thermal environment of the waterfront space is carried out from two perspectives, namely spatial morphology, and environmental factors, with five groups A, B, C, D, and E, as shown in Table 1. Groups A and B investigate the thermal environment from the perspective of spatial morphology, with all measurement points in a no-shading environment. Groups C, D, and E explore the effects of environmental factors on the thermal environment. Each group has its own no-shading measurement point for comparison, with the elevation and land surface material consistent across all measurement points within each group. The comparative analysis of the groups is shown in Table 2.

The thermal environment of the waterfront space was measured at 09:00~18:00 on 24 July 2020. The data were recorded using both automatic and manual methods, and all instruments were calibrated before the experiment. The names, accuracy, collection frequency, and measurement items of the experimental instruments are shown in Table 2. TES-1369, Testo-480, and HOBO are automatic collection instruments with a frequency of 1 min, and the height of the sensing element is controlled between 1.1~1.5 m. To shield the air temperature and humidity measurements from the instrument's own radiation, the instrument needs to be radiation-proofed. We place the HOBO into a paper cup with a diameter of 8 cm and wrap the cup in aluminium foil. Small holes around the cups are drilled to facilitate air circulation inside and outside to reduce the effect of the heat generated by the cups on the air temperature and humidity. The surface temperature around the measurement point was
Table 1. Description of different project groups.

<table>
<thead>
<tr>
<th>Projects</th>
<th>Groups</th>
<th>Measurement points</th>
<th>Content</th>
<th>Thermal environment parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial form</td>
<td>A</td>
<td>1-2-4-11</td>
<td>Same section, different positions</td>
<td>Temperature, Relative Humidity, Wind velocity</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>1-8-10-11</td>
<td>Same horizontal distance, different elevation</td>
<td>Temperature, Relative Humidity</td>
</tr>
<tr>
<td>Environmental factors</td>
<td>C</td>
<td>3-4-5</td>
<td>Point 3: shading by tree and building; Point 5: Shading by sun-sail and building; Point 4: no-shading (Comparison points).</td>
<td>Temperature, Relative Humidity, Globe Temperature, Land Surface temperature</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>7-11</td>
<td>Point 7: Tree shading; Point 11: no-shading (Comparison points).</td>
<td>Temperature, Relative Humidity, Land Surface temperature</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>9-10</td>
<td>Point 9: Viaduct shading; Point 10: no-shading (Comparison points).</td>
<td>Temperature, Relative Humidity, Land Surface temperature</td>
</tr>
</tbody>
</table>

Table 2. Performance parameters of main instruments.

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Measurement Items</th>
<th>Accuracy</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>TES-1369</td>
<td>Globe Temperature</td>
<td>±0.5 ℃</td>
<td>1 min</td>
</tr>
<tr>
<td>Testo-480</td>
<td>Wind velocity</td>
<td>±(0.2 m/s)</td>
<td>1 min</td>
</tr>
<tr>
<td>HOBO</td>
<td>Temperature, Relative Humidity</td>
<td>±0.1 ℃, ±1 %RH</td>
<td>1 min</td>
</tr>
<tr>
<td>FLIR-C5</td>
<td>Surface temperature</td>
<td>±2 ℃</td>
<td>30 min</td>
</tr>
</tbody>
</table>

photographed every 30 minutes using a FLIR-C5 infrared thermal imager. After post-correcting the images, land surface temperatures were extracted for comparison. In addition, we selected the average temperature within 30 minutes for the analysis, i.e. the temperature at 12:00 is the average of the temperature between 11:45 and 12:15.

3 Results

3.1 Impact of spatial patterns on the thermal environment

To investigate the influence of the spatial morphology of the waterfront space on the thermal environment, two scenarios were considered: different locations within the same section and different elevation values at the same horizontal distance. The relative positions of the measured points in Group A and Group B in the section are shown in Fig.3.

Fig.4(a-d) show the comparison of air temperature, relative humidity, wind speed and global temperature for Group A respectively. We can see that the overall trend of the measurement points is relatively similar. In terms of the order of air temperature, point 11 > point 4 > point 2 > point 1, the average values of measurement time are 39.2 ℃, 38.4 ℃, 36.6 ℃ and 35.0 ℃ respectively, showing a trend of increasing air temperature as the distance to the waterbody increases. The mean difference between point 1 and point 11 is 4.2 ℃, and the largest difference between 14:30 and 16:00 is 5.7~6.1 ℃. This indicates that the cooling benefit of the waterfront is obvious and varies greatly with the distance from the waterbody, with the maximum temperature difference in this experiment being up to 6.1 ℃ within a range of 25 m horizontally and 15 m vertically from the waterbody. The relative humidity is the opposite of the air temperature: point 1 > point 2 > point 4 > point 11, with mean values of 58.8%, 55%, 50.5% and 47.8% respectively. As the distance from the water body decreases, the relative humidity increases. The most pronounced difference in relative humidity was at 14:30 ~16:00, with values ranging from 13 to 15.7%.

Fig.4(c) shows the wind speed at the closest (point 1) and farthest (point 11) from the waterbody, respectively. In terms of wind speed, the mean wind speeds throughout the day at the two measurement points were 0.76 m/s and 0.69 m/s respectively, indicating a small difference in wind speed. At point 1, the wind speed fluctuated more sharply, and the variance was significantly wider than at point 11. Natural winds
generally have a gradient distribution, with relatively high wind speeds at higher elevations, but this phenomenon does not appear to be evident in this exploratory measurement. This may be due to the fact that the wind speed environment close to the water (point 1) is more complex, being influenced not only by the dominant wind speed and direction, but also by the air temperature difference[15].

In terms of global temperature, the two points show a consistent trend in Fig.4(d). The mean global temperatures at points 1 and 11 were 41 °C and 46.7 °C respectively, which were 5.7 °C and 7.5 °C higher than the air temperature. This indicates that thermal radiation strongly influences the thermal environment of the waterfront. The mean value of the global temperature at point 11 is about 5.7 °C higher than that at point 1. Consequently, the water body can mitigate the thermal radiation of the surrounding environment to some extent.

Measurement points 10 and 11 are at the same horizontal distance from the waterbody, with an elevation difference of 10 m. The air temperature and relative humidity at points 11 and 1 were subtracted and noted as ΔTa and ΔRH, respectively, as shown in Figure 5, and the same was done for points 10 and 8. The mean values for High-elevation and Low-elevation were 4.2 °C and 1.7 °C, respectively. The results of this study demonstrate that, in addition to horizontal distance, vertical height also affects the cooling effect of water. When the horizontal distance from the water body is the same, the air temperature increases significantly as the elevation increases. In this experiment, the difference in height between the comparison measurement points is about 10 m, and the difference in the cooling benefit of the water body is about 2.5 °C.

3.2 Environmental configuration impact on the thermal environment

To compare the influence of environmental factors on the thermal environment, the shaded measurement points in groups C, D, and E were subtracted from the unshaded measurement points. The difference in air temperature, relative humidity and ground surface temperature was noted as ΔTa, ΔRH and ΔLST respectively, as shown in Fig.6.

Fig.6(a) shows the comparison of the mean difference in air temperature by different shadings, viaduct > building and sun-sail > building and tree > tree, which are 4.9°C, 4.7°C, 4.2°C, and 2.5°C, respectively. During the period 9:00~10:00, measurement point 5 in group C was affected by tree shading at the same time, thus making
the temperature difference closer to that of measurement point 3. Fig. 6(b) shows the comparison of the mean difference in relative humidity, compared to the measurement points without shading, the mean differences in relative humidity for the shading by viaduct, building with sun-sail, building with tree and tree were: 14.5%, 12.7%, 8.4% and 6.1%, respectively. Fig. 6(c) shows the comparison of the mean difference in land surface temperature, by different shadings, viaduct > building and tree > building and sun-sail > tree, at 16.03 °C, 6.99 °C, 6.93 °C and 2.51 °C respectively. As the surface temperature is mainly influenced by solar radiation, the surface temperatures of tree shading and sun-sail shading in group C are essentially similar. The combined building and tree shading effect was significantly higher than the combined building and sun-sail shading effect before 13:00. This indicates that the cooling effect of plant shading on the surface temperature should be better than the solar sail shading effect.

**Fig. 6.** Environmental factors impacting on the thermal environment

### 4 Discussion

In our study, we found that the closer the waterbody, the greater the cooling effect, similar to the findings of Fei et al. [15] and Xu et al. [12]. However, somewhat differently, the cooling effect of the water bodies in this study was more pronounced and more extensive. Within a range of 25 m horizontally and 15 m vertically from the water body, the average differences in air temperature, relative humidity and global temperature between the near-water and far-water measurement points were 4.2 °C, 11% and 5.7 °C, respectively, with maximum differences of 6.3 °C, 15.7% and 8.1 °C, respectively. The reason for the difference is that the cooling and humidifying effect is more pronounced due to the approximately 400 m width of the waterbody in this study[16]. Therefore, the thermal environment of the large waterfront differs significantly from that of the small river. In the wind speed comparison, no significant gradient winds were found within the 14 m height difference. This may be due to the thermal pressure caused by the air temperature difference, indicating that the wind environment is more complex in mountainous waterfront spaces than in the plains.

It is somewhat surprising that, not only horizontal distances, vertical topography also affects the cooling and humidifying effect of water bodies. At the same horizontal distance from the water body, the air temperature increases and the relative humidity decreases as the elevation increases. In this study, the difference in elevation at the comparison measurement sites was approximately 12 m, the difference in cooling benefit was approximately 2.5 °C, and the difference in humidification benefit was approximately 8.3%. According to Fig.1, the spatial morphology of mountain waterfronts is variable. Thus, systematic quantitative studies could guide future waterfront spatial morphology design in order to enhance summer thermal comfort.

In terms of the cooling effect of the different environmental factors, viaduct > building and sun-sail > building and tree > tree. There are numerous viaducts along Chongqing's waterfront space in Fig.1. These spaces are under-appreciated and under-utilised, and most of them are abandoned, becoming urban lost space. The findings of this study suggest that urban planners can rationalize the space under viaducts to reduce waste of urban resources and increase outdoor comfort. Furthermore, waterfront should be shaded by a combination of different shading factors based on convenience and landscape needs, rather than just trees.

### 5 Conclusions

Through surveys and measurements, we investigated the characteristics of the summer thermal environment of the mountainous waterfront space in Chongqing. The main conclusions are as follows:

1. We have summarized and mapped the typical waterfront forms in Chongqing into five categories: sloping, terraced, retaining walls, composite and stepped.
2. From a spatial morphological perspective, it was found that the closer to the water body, the more pronounced the cooling and humidifying effect. The spatial gradient wind along the mountainous
waterfront was not significant. At the same horizontal distance from the water body, the air temperature increases and the relative humidity decreases as the elevation increases.

3. Viaduct shading is the most effective way of reducing heat stress, followed by combined solar sail and building shading, while tree shading is the least effective.

6 Declarations

Competing interests:
The authors declare no competing interests.

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Authors’ contributions:
Jinhui Ma: Data curation; Formal analysis; Investigation; Software; Formal analysis; Visualization; Writing - original draft.
Haijing Huang: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing - review & editing.

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