Although urban rivers are considered to have a mitigating effect on the extreme heat stress, the influences of topographical characteristics still remain poorly understood, particularly under extremely hot weather conditions. Taking the mountainous city of Chongqing as an example, this research focuses on the river cooling effects on the surrounding urban environment during normal and extreme summer days based on 3 indices: River Cooling Intensity (RCI), River Cooling Distance (RCD) and Cumulative River Cooling Intensity (CRCI). Employing the Boosted Regression Tree (BRT) model, the impacts of environmental variables on river cooling effects have been explored. The findings underscore a pronounced intensification of river cooling effects on the extremely hot day, with the River Cooling Index (RCI) not only rising from an average of 5.5°C on the normal summer day to 6.4°C but also exhibiting a broader range of variability, as reflected by an increase in the standard deviation from 2.4°C to 3.1°C. Topographical characteristics exhibited strong impacts on river cooling effects, with the relative importance for RCI being 27.6% and 31.5% on the normal summer day and the extremely hot day, respectively. Moreover, average elevation and slope exhibited ascent and descent patterns in their influences on river cooling, while the impacts of patch density and river width were relatively fluctuating, showing descent and ascent patterns as a whole. These findings can provide a foundation for urban planners and managers to develop strategies aimed at improving the thermal environment of riverside areas.

## Introduction

Across numerous cities worldwide, the process of urbanization has been associated with various detrimental impacts on the local environment, encompassing issues such as water and air pollution, ecosystem degradation, and urban heat island[1,2]. Urban heat island manifests as elevated temperatures within urban areas relative to their rural surroundings. Elevated temperature is the contributor to heightened intensities and prolonged durations of heatwaves, resulting in increased energy consumption and posing potential threats to the public health of urban residents, particularly during the summer months [3,4]. Consequently, it is imperative to implement strategic measures to mitigate the adverse consequences associated with urban heat. Strategies for mitigating the heat in urban environment encompass modification to surface materials, optimization of land cover patterns, and enhancement of ventilation [5-7]. Notably, blue and green spaces have garnered significant attention. Blue spaces are urban surfaces predominantly characterized by water features [8]. In comparison to impervious surfaces, augmented specific heat capacity of water contributes to decreased temperatures during daylight hours. Furthermore, water surfaces facilitate evaporation, thereby curbing the release of sensible heat to the overlying air. A study conducted in Chengdu revealed a temperature contrast exceeding 8 °C between lakeside and inland areas [9]. Observations have also suggested that water bodies can exhibit stronger cooling capability than green spaces. For instance, during the summer daytime in Berlin, water surfaces exhibited an average temperature being approximately 2 °C cooler than green spaces [10].

The cooling effects of blue spaces exhibit significant spatiotemporal variations. The cooling intensity is higher in the summer compared to the winter [11]. Throughout a day, the daytime water cooling intensity typically exceeds that of nighttime [12]. Some studies have also suggested that waterfront areas might be warmer than the surrounding inland areas during the night. For instance, a measurement conducted in central Pennsylvania revealed that the average temperature decreased with the distance from the riverbank during 22:00 – 05:00 [13]. In addition, observations have found noteworthy spatial heterogeneities in water cooling effects within same cities [14]. Accordingly, the interaction between water bodies and environmental variables has become a crucial aspect in the understanding of urban heat mitigation [15]. The morphological characteristics of water bodies are important factors affecting their cooling effects, with stronger cooling frequently observed near larger water bodies [16]. However, conclusions on the relationship between shape regularity and cooling effects are often contradictory. Studies in Shanghai and Beijing suggested that water cooling effects were strengthened with improved shape regularity, while an investigation in the northeastern China indicated that wetlands with more complex shapes had better cooling effects [17-19]. The roles of land cover patterns and 3D building characteristics in waterfront areas have also been explored, showing varied impacts. Several studies showed that higher and denser buildings may reduce water cooling, while a study in the Pearl River Delta suggested that better cooling effects tended to appear at wetlands near densely built areas [20,21]. Furthermore, factors such as proportion of vegetation cover, mean building height, and building coverage ratio, also potentially take effects [22,23].

Despite numerous studies, the understanding of water cooling effects still faces certain limitations. Firstly, wind plays a crucial role in transporting cool air and expelling excess heat from specific areas. As mechanical forces resulting from local topographic variations such as hills and mountains can alter urban wind patterns, it can be speculated that topographical features could significantly impact water cooling [24,25]. Previous researches on water cooling effects were primarily conducted in cities with flat terrains, resulting in a gap in understanding how various topographic indicators influence water cooling of urban areas with more complex terrains [8]. Secondly, there are differences of morphological characteristics between rivers and lakes. Lakes commonly assume polygonal or circular shapes and are dispersed throughout a city, while rivers follow a narrow and linear layout, predominantly traversing or flowing around urban areas. Consequently, the cooling effects of rivers on their surroundings differ from those of lakes or ponds. According to a study in the northeastern Chinese cities of Changchun and Jilin City, river cooling effects were found to surpass those of lakes and green spaces [19]. However, prior studies on water cooling primarily centered around ponds, lakes, and wetlands [26,27]. Rivers, as crucial water bodies in cities, have received comparatively less attention. Finally, existing relevant studies mostly focused on normal summer days, typically characterized by days with maximum air temperatures below 35 °C. The understanding of water cooling on extremely hot days is insufficient. However, the practical significance of studying water cooling lies in enabling targeted measures to alleviate the negative impacts of extreme heat. As differences in urban climate characteristics have been found between normal summer days and extremely hot days, it is essential to pay more attention to water cooling on extremely hot days [28-31].

Given the above-mentioned shortcomings, this study aims to explore the quantitative effects of river cooling and examine their influencing factors on a normal summer day and an extremely hot day by the Boosted Regression Tree model, taking the mountainous city of Chongqing as an example. The purpose is to answer the following questions: (1) What are the spatial patterns of river cooling effects under different weather conditions? (2) What are the contributions of individual environmental variables on river cooling effects? (3) How do key influencing factors affect river cooling effects? The findings of this research are expected to provide valuable insights into mitigating urban heat and offer guidance for the heat-resilient planning and design of urban riverside areas.

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[21] F. Guo, J. Zhao, H. Zhang, J. Dong, P. Zhu, S. S. Y. Lau, Effects of urban form on sea cooling capacity under the heatwave, Sustain. Cities Soc. 88 (2023) 104271.

[22] N. I. Syafii, M. Ichinose, E. Kumakura, S. K. Jusuf, K. Chigusa, N. H. Wong, Thermal environment assessment around bodies of water in urban canyons: A scale model study, Sustain. Cities Soc. 34 (2017) 79-89.

[23] X. Zhou, S. Zhang, Y. Liu, Q. Zhou, B. Wu, Y. Gao, T. Zhang, Impact of urban morphology on the microclimatic regulation of water bodies on waterfront in summer: A case study of Wuhan, Build. Environ. 226 (2022) 109720.

[24] X. Chen, Z. Wang, Y. Bao, Cool island effects of urban remnant natural mountains for cooling communities: A case study of Guiyang, China, Sustain. Cities Soc. 71 (2021) 102983.

[25] Z. Zhou, Z. Zhang, X. Zou, K. Zhang, W. Zhang, Quantifying wind erosion at landscape scale in a temperate grassland: Nonignorable influence of topography, Geomorphology 370 (2020) 107401.

[26] S. Cheval, A.-M. Popa, I. Șandric, I.-C. Iojă, Exploratory analysis of cooling effect of urban lakes on land surface temperature in Bucharest (Romania) using Landsat imagery, Urban Clim. 34 (2020) 100696.

[27] L. Yao, D. J. Sailor, X. Yang, G. Xu, L. Zhao, Are water bodies effective for urban heat mitigation? Evidence from field studies of urban lakes in two humid subtropical cities, Build. Environ. 245 (2023) 110860.

[28] D. Li, T. Sun, M. Liu, L. Yang, L. Wang, Z. Gao, Contrasting responses of urban and rural surface energy budgets to heat waves explain synergies between urban heat islands and heat waves, Environ. Res. Lett. 10(5) (2015) 054009.

[29] P. Ramamurthy, J. González, L. Ortiz, M. Arend, F. Moshary, Impact of heatwave on a megacity: an observational analysis of New York City during July 2016, Environ. Res. Lett. 12(5) (2017) 054011.

[30] Z. Gao, Y. Hou, W. Chen, Enhanced sensitivity of the urban heat island effect to summer temperatures induced by urban expansion, Environ. Res. Lett. 14(9) (2019) 094005.

[31] N. An, J. Dou, J. E. González-Cruz, R. D. Bornstein, S. Miao, L. Li, An observational case study of synergies between an intense heat wave and the urban heat island in Beijing, J. Appl. Meteorol. Climatol. 59(4) (2020) 605-620.

[32] H. Liu, P. Gong, J. Wang, N. Clinton, Y. Bai, S. Liang, Annual dynamics of global land cover and its long-term changes from 1982 to 2015, Earth Syst. Sci. Data 12(2) (2020) 1217-1243.

[33] J. Ma, J. C. Cheng, F. Jiang, W. Chen, J. Zhang, Analyzing driving factors of land values in urban scale based on big data and non-linear machine learning techniques, Land Use Policy 94 (2020) 104537.

[34] J. Elith, J. R. Leathwick, T. Hastie, A working guide to boosted regression trees, J. Anim. Ecol. 77(4) (2008) 802-813.

[35] G. Manteghi, H. bin Limit, D. Remaz, Water bodies an urban microclimate: A review, Mod. Appl. Sci. 9(6) (2015) 1.

[36] T. R. Oke, G. Mills, A. Christen, J. A. Voogt, Urban climates, Cambridge University Press, 2017.

[37] S. Liao, H. Cai, P. Tian, B. Zhang, Y. Li, Combined impacts of the abnormal and urban heat island effect in Guiyang, a typical Karst Mountain City in China, Urban Clim. 41 (2022) 101014.

[38] N. Mo, J. Han, Y. Yin, Y. Zhang, Seasonal analysis of land surface temperature using local climate zones in peak forest basin topography: A case study of Guilin, Build. Environ. 247 (2024) 111042.

1. Method

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