河流降温效应在一个具有复杂地形的超大城市——以重庆为例

## Abstract

## Introduction

### UHI~150 words【up2023\_1207 10:33】

* With population explosion and economic development, the urban population has witnessed significant expansion globally.
* According to the prediction from the United Nations, this trend will continue in the following decades and the urbanization rate is estimated to be up to 68 % by 2050 (United Nations. 2019).
* As has been observed in many cities over the world, urbanization has caused multiple adverse effects on local environment, such as water and air pollution, ecosystem degradation and urban heat island (Wang et al., 2020; Ahmad et al., 2021).
* Urban heat island is a phenomenon by which temperatures in urban areas tend to be higher compared to those in the surrounding rural areas.
* Elevated temperatures have been found to increase the intensities and durations of heatwaves and they will inevitably enhance energy consumption and pose threats to public health of urban residents in summer (Guan et al., 2017; Nieuwenhuijsen et al., 2018).
* Therefore, certain measures are necessary to address the associated negative effects.

### 水体降温效应机理~150 words【up2023\_1208 09:53】

* Primary measures to address excessive heat in urban areas include altering surface materials, optimizing spatial layout of land cover, and promoting ventilation (Azhdari et al., 2018; Taleghani，2018; He, 2020).
* In terms of land cover, the roles of blue and green spaces have received much attention.
* Blue spaces refer to urban surfaces that are dominated by water (Ampatzidis et al., 2020).
* Compared to impermeable surfaces, the lower thermal conductivity and higher specific heat capacity of water make blue spaces absorb less heat during the day.
* In addition, evaporation from water surfaces can reduce release of sensible heat.
* Consequently, blue spaces can be considered to be cooling sources and they play important roles in lowering temperatures of surrounding areas.
* According to a research in Chengdu, the contrast of surface temperature between lakeside and inland areas can be more than 8 °C (Du et al., 2016).
* Researches have also demonstrated that the cooling ability of water bodies can be stronger than green spaces (Dugord et al., 2014; Tan et al., 2017).
  + 【参考Water as an urban heat sink: Blue infrastructure alleviates urban heat island effect in mega-city agglomeration】

### 1.3 水体降温效应的影响因素（强调缺乏对地形影响的研究）~250 words

* According to the analyses from previous studies, there are large diversities in the cooling effects of blue spaces and the dominant influencing factors vary with space and time.
* Morphological characteristics of water bodies are mostly found to be important factors.
* Specifically, stronger cooling effects tend to appear near larger water bodies (Theeuwes et al., 2013).
* As for the relationship between shape regularity and cooling effect, the conclusions are contradictory. For example, observations in Shanghai and Beijing show that water cooling effect is strengthened with improved shape regularity, while the corresponding relation is insignificant in Chengdu. (Du et al., 2016; Sun et al., 2012; Wu et al., 2021)
* In addition to the characteristics of blue spaces, the roles of land use pattern and urban geometry of surrounding urban areas have also been explored.
* According to previous researches, proportion of vegetation cover, street width, average building height, floor area ratio, the ratio of building area potentially take effects.
* It is worth noting that topographic features might be irregular in some cities with uneven surfaces.
* Primarily because of the mechanical forcing effect, wind directions and intensities of urban areas are found to be affected by local topographic variations, such as hills, ridges, and cliffs.
* Therefore, it can be speculated that terrain can be a potential impact factor of water cooling effect.
* However, most of the previous studies on cooling effects of blue spaces were performed in plain cities.
* There is still lack of understanding regarding the relationship between topography and water cooling.

### 1.4 河流与其它水体类型的区别 ~100 words

* Rivers and lakes are major types of water bodies with different characteristics.
* A large proportion of lakes are polygonal or circular in shapes and located dispersedly within a city, while rivers have a narrow and linear layout, mostly traversing the entire urban area.
* In the northeastern Chinese cities of Changchun and Jilin City, the cooling effects of rivers on the surrounding environment are found to be stronger than those of lakes and green spaces (Xue et al., 2019).

### 1.5 研究目的~100 words

* In summary, previous researches on the cooling effects of blue spaces have the following limitations.
* Firstly, compared to cooling effects generated by lakes and ponds, much less studies focus on the effects of rivers on surrounding thermal environment.
* Secondly, most relevant studies are restricted to cities with relatively flat topography, and there is a lack of researches in cities with complex terrain.
* Additionally, there is insufficient understanding of water cooling effects during extremely hot summer days which has important implications on heatwave mitigation and public benefit.
* Therefore, we aim to address the following research questions:
* (1) What is the intensity and spatial pattern of river cooling effect in a city with complex terrain?
* (2) What are the main environmental factors that influence river cooling effect ? What’s the role of terrain factor in affecting river cooling?
* (3) What’s the difference of river cooling and the corresponding factors between a normal summer day and a extremely hot day.

## 2. Data and Methods

* The analytical procedures of this study can be divided into 3 steps.
* Firstly, land surface temperature of the study area is calculated based on Landsat-8 images.
* Then we divide the riverbank into segments and calculate indexes of river cooling for individual segments.
* Finally, random forest is utilized to evaluate the non-linear impacts of environmental factors on river cooling.
* The flow chart is shown in Fig. xxx.

### 2.1. Study area~180 words【up2023\_1208 16:45】

* Chongqing is a metropolitan city located in the upper reach of the Yangtze River.
* The Yangtze River flows through this city, and its major tributary, the Jialing River, converges with it in the urban area.
* The urban area of Chongqing is primarily composed of hills and mountains and it is therefore characterized by significantly undulating terrain with elevation ranging from 170 meters to more than 400 meters.
* The urban area of Chongqing is located in a subtropical monsoon climate zone.
* Summer periods normally last from June to September, which are characterized by high temperatures and high humidities.
* On average, there can be more than 40 heatwave days with maximum air temperatures being larger than 35 °C in a year , mostly distributed in July and August. The highest air temperature can reach up to 43 °C.
* In last decades, Chongqing has experienced a process of urbanization with urban population surging from 6 million in 2000 to 10 million in 2020. With a huge influx of population, urban construction accelerates, and the built-up area expands rapidly.

### 2.2. Data

* For the analysis of the river cooling effect, satellite images from Landsat-8 OLI/TIRS surface reflectance products are utilized to calculate land surface temperature in Chongqing.
* These data are obtained from United States Geological Survey (http://earthexplorer.usgs.gov).
* Two days with cloud-free Landsat images are selected to as representatives of normal summer day and extremely hot summer day, respectively.
* In our study, we select 26th, Sep, 2021 to represent normal summer day and the maximum air temperature is xxx °C on this day.
* For the extremely hot summer day, 12th, Aug, 2022 is selected as the representative and the maximum air temperature is on this day.
* In addition, near-infrared and shortwave infrared 1 bands of Landsat images are employed to extract water bodies.
* Shuttle Radar Topography Mission 3.0 (SRTM-V3) product with the spatial resolution of 30 meters serves as a tool for terrain analysis of the riverside area. It can be downloaded from USGS Earth Explorer.
* Land cover data are sourced from the CLCD 2021 land cover dataset of China with a spatial resolution of 30 meters and temporal resolution of one year (Yang et al., 2021).
* This dataset is computed from Landsat data based on the Google Earth Engine platform.
* It covers the spatial distribution of land cover in China from 1985 to 2021, categorizing land cover types into nine classes.
* Currently, this dataset has been applied in various research areas, such as ecosystem service and land use change analysis (Deng et al., 2023; Liu et al., 2023).

### 2.3. Land surface temperature

* Before the calculation of land surface temperature, preprocessing steps are required for original Landat-8 images. They include radiometric calibration and atmospheric correction.
* Then, radiative transfer equation (RTE) method is adopted. The equation can be expressed as:
* where *Lλ* is the radiation intensity of thermal infrared band obtained by the sensor, represents the downward atmospheric radiance, represents the upward atmospheric radiance, *ε*stands for surface emissivity,*τ* is the atmospheric transmissivity and B(Ts) is the black body radiance.
* The above equation can be converted to:
* In this study, and *τ* are obtained by NASA Atmospheric Correction Parameter Calculator.
* *ε* is calculated by the following formula:
* In this formula, represents surface emissivity of vegetation cover, represents surface emissivity of soil and *Pv* is the percentage of vegetation cover calculated by:
* where *NDVI* is the normalized difference vegetation index, *NDVIveg* is the NDVI value of area fully covered by vegetation, *NDVIsoil* is the NDVI value of area fully covered by soil.
* Once black body radiance is calculated, land surface temperature (LST) is obtained by the following equation:
* All the above steps are performed in ENVI software.

### 2.4. Quantification of river cooling effect

* In order to accurately quantify the cooling effects of rivers, the riverbanks are partitioned at the interval of 1 kilometer.
* As a result, a total of 185 riverbank segments are generated along the Yangtze River and the Jialing River, with 97 segments along the Yangtze River, and 88 segments along the Jialing River.
* For each riverbank segment, buffer zones are established from the riverbank to the inland area, spaced at 20-meter intervals.
* The average surface temperature within each buffer zone is then calculated for the following analysis of river cooling effect.
* As a cooling source, a river has a cooling effect on the surrounding area and this effect is highly related to the distance from the riverbank.
* Specifically, the temperature gradually rises from the riverbank to the inland area until a certain point where the trend of temperature rise stops, as shown in Fig. xxx.
* In this study, it is defined as the first turning point.
* The area represented by the non-linear curve from the original point to the first turning point is considered to be cooled by river and is employed to calculate relevant indexes of river cooling effect.
* Specifically, River Cooling Intensity (RCI) is defined as the temperature contrast between the riverbank and the first turning point, as shown in the following equation:

(1)

* where Ttp is the surface temperature at the first turning point, while Trb is the temperature at the corresponding riverbank.
* The index of RCI has the disadvantage that it only reveals the maximum temperature reduction within the waterfront area, while the non-linear variation of surface temperature are not embodied.
* In order to get a better understanding of the river cooling effect during its inland penetration process, the index of Cumulative River Cooing Intensity (CRCI) is adopted in this study.
* It is defined as the accumulated difference between turning temperature and the temperature curve from riverbank to the first turning point, which is illustrated in Fig. xxx. The equation is given by:

(2)

* where *Ti* is the averaged temperature of the *i*th buffer zone from the riverbank and n is the total number of buffer zones along non-linear temperature curve.

### 2.5. Calculation of impact factors

* The potential influencing factors of river cooling effect can primarily be classified into the following types: river characteristics, land cover properties, urban geometry and topography.
* In terms of river characteristics, curvature of riverbank and river width are considered.
* Curvature of riverbank is adopted here to characterize the shape features of segments along individual riverbanks.
* River width of each segment is calculated as the distance from the central point of the riverbank to the opposite riverbank.
* As for land cover, percentage of green space (PLAND\_GS), percentage of impervious surface (PLAND\_IS), mean aggregation index of green space (AI\_GS) and mean aggregation index of impervious surface (AI\_IS) are chosen. The calculation of aggregation index for a certain land cover is as follows:
* In this study, the above landscape metrics are calculated using R-landscapemetrics packages.
* Urban geometry indicates 3-dimensional characteristics shaped by spatial layout of buildings with different heights.
* According to findings in previous studies and our data availability, mean building height, floor area ratio, building density are chosen for the analysis of river cooling effect.
* In addition, topography variables utilized in this study include averaged elevation and averaged slope of individual buffer zones. They are calculated based on DEM data in ArcMap 10.7.
* Variables of geographical location consist of latitude, longitude and the angle between riverbank and the prevailing wind direction in summer. It’s worth noting that the direction of riverbank for each segment is calculated based on the central point.
* Topography is considered as the urban area is marked by moderate fluctuations in elevation. The selected topography variables in this study consist of averaged slope, averaged elevation and standard error of elevation.
* The effects of indexes related to spatial patterns on urban thermal environment have been widely reported (Estoque et al., 2017; Shen et al., 2022).
* Here we propose to select indicators those are closely related to urban climate and are capable of reflecting typical morphological characteristics of individual segments.
* Mean aggregation index represents the degree of agglomeration for particular patch types.
  + 【参考Quantifying spatial morphology and connectivity of urban heat islands in a megacity: A radius approach】

### 2.6. Random forest algorithm

* Urban climate is formed by comprehensive effects of multiple factors with non-linear processes.
* However, the relationships between urban thermal environment and environmental factors are investigated using simple linear regression or stepwise regression in most previous researches.
* In this study, random forest is adopted for investigating the comprehensive effects of potential impact factors on river cooling.
* The random forest model is an ensemble learning method for classification and regression. It builds multiple decision trees to form a random forest and combines the computed results of each tree through weighted regression, providing strong robustness and accuracy.
* Compared to traditional regression methods, the random forest model can handle complex nonlinear effects.
* In our analysis, we firstly use variance inflation factor(VIF) to assess the covariance of the independent variables and select variables with VIF values being less than 10.
* This step is performed to remove factors with high collinearity.
* Then, the random forest algorithm is performed by “randomForest” package in R.
* By exploring the relative importances and marginal effects of independent variables, a more detailed understanding of river cooling effect and its influencing factors can be revealed.
* R2 and root-mean-square error (RMSE) are applied to validate the prediction from random forest model.

## Results

### 3.1 River cooling effect in the normal summer day and the extremely hot day

* The spatial patterns of river cooling intensities on a typical normal summer day (8, May, 2022) and an extremely hot day (12,Aug, 2022) are demonstrated in Fig. xxx.
* On the normal summer day, the maximum and average values of river cooling intensities are 16.9°C and 6.8°C, respectively.
* On the extremely hot day, the magnitudes of river cooling intensities are evidently higher, with the maximum and average values being 23.3°C and 7.9°C, respectively.
* It should be noted that there are also larger diversities in river cooling intensities across riverbanks. Specifically, the standard deviation is 2.7 °C on the normal summer day, while the corresponding value is 3.8 °C in the extremely hot day.
* It can be observed that the spatial patterns of river cooling intensities are similar on both reference days.
* For riverbanks along the Jialing River, the river cooling intensities are relatively lower compared to the Yangtze River.
* Specifically, the average river cooling intensity along the Jialing River is 6.3 °C and 7.4 °C on the normal summer day and the extremely hot day, respectively.
* For the Yangtze River, the corresponding values are 7.4°C and 8.5°C, both being 1.1 °C higher than the Jialing River.
* The wider width of the Yangtze River is speculated to cause this difference.
* Simultaneously, for riverbanks near the Tongluo Mountain in the eastern suburb of Chongqing, the river cooling intensities are significantly lower than the surrounding areas.
* It can be inferred that higher mountainous terrain plays a significantly obstructive role in the river cooling effect.
* Furthermore, river cooling intensities are relatively higher in the suburb, while they are lower in the city center where most high-rise buildings are located.
* The blocking effect of dense buildings is believed to explain this phenomenon.
* The spatial patterns of cumulative cooling intensities of rivers on the normal summer day and the extremely hot day are shown in Fig. xxx.
* On the normal summer day, the average cumulative cooling intensity is 56.6°C. The maximum value and standard deviation are 442.7°C and 60.0°C, respectively.
* While on the extremely hot day, both the average and standard deviation are higher, being 48.4°C and 44.5°C, respectively.
* The spatial patterns of cumulative river cooling intensities are similar on the 2 example days.

3.2

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