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# Thermal environment effects and interactions of reservoirs and forests as urban blue-green infrastructures

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## ABSTRACT

Blue-green infrastructures, including reservoirs, lakes, forests and green spaces, play important roles in the microclimate environment. This study investigated the effects of blue-green infrastructures on the surface temperature adjacent to 12 reservoirs in the Pearl River Delta area, China. The temperature of each reservoir and its surrounding environment was retrieved by Landsat Thematic Mapper (TM) remote sensing imagery. The relationship between the temperature fields around the reservoir and the influencing factors was analyzed with statistical analysis. The results showed that distance (D), underlying surface type, and reservoir capacity (V) had significant effects on the temperature fields around the reservoirs. The temperatures across distances of 0–100 m and 0–200 m away from the reservoir boundary had a linear relationship with distance. The effect of the reservoir on temperature gradually declined when the distance exceeded 200 m. In the 0–300 m range, a quadratic equation with an intercept best fitted the relationship between temperature and distance. Four types of underlying surfaces, including built-up land, bare land, sparse forest land and forest land, were quantified by the normalized difference vegetation index (NDVI). Subsequently, a quadratic model expressing the correlation between temperature and the NDVI was obtained. Moreover, the surface temperature at the reservoir edge was negatively correlated to V. Finally, a multiple nonlinear regression equation was found to effectively describe the influence of D, NDVI and V on temperature fields around reservoirs. The influence of reservoir and vegetation (i.e., NDVI) on the field and their contributions were calculated by mathematical methods. The effects of the reservoir and vegetation on the peripheral temperature interacted with each other; the influence of the reservoir and the vegetation on temperature declined and increased, respectively, as distance increased. By addressing the influence of reservoirs and forests on temperature fields and cooling contribution rates, this study provides more insight into the role of blue-green infrastructure in the urban thermal environment.

## 1. Introduction

With rapid urbanization, a large number of artificial heat sources and low-reflectivity materials have been widely used in building and road construction, in many cases leading to urban heat islands. At the same time, the lack of natural elements in urban areas aggravates the negative impacts of heat sources on urban thermal environments.

The concept of "blue-green infrastructure" was proposed in the United States during the 1990s to be used in urban planning, which suggested that blue-green infrastructure could be planned and arranged as part of the urban planning (Ghofrani et al., 2016). The concept also considered ecological safety and health in urban construction (Dreiseit, 2015). Blue-green infrastructures have the same importance as building infrastructures in the city. "Blue" infrastructure includes lakes, reservoirs, rivers and other water bodies, and "Green" infrastructure includes forests, lawns, parks, green roofs, and other areas. Because the heat capacity of water is much greater than that of air, vegetation directly absorbs light and heat, and heat is dissipated by evaporation and transpiration. Blue-green infrastructures have become "cold sourced" in cities. Currently, the urban heat island effect is becoming more prominent (Xiao et al., 2015; Shou and Zhang, 2012), and its mitigation by blue-green infrastructures have attracted worldwide attention (Jia and Qiu, 2017; Azmy et al., 2016). Many studies have shown that blue-green infrastructures have direct impacts on the urban thermal environment. Gao et al. (2016) showed that green communities around city streets and squares have substantial microclimate cooling effects, and these effects vary with community structure. Liu et al. (2017) found that a rational allocation and layout of urban green space can improve

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the microclimate of urban environments. Liang et al. (2015) found that urban green space and water in Guilin have cooling effects on the surrounding environment.

At present, urban parks, green spaces and rivers are the main focuses in studies investigating the impacts of blue-green infrastructure on the urban thermal environment. For example, Suomi and Käyhkö (2012) analyzed the influence of green spaces and river surfaces on the surrounding temperature with a large number of microclimatic data. Zhou et al. (2005) explored the influencing factors of cooling effects on the surrounding environment by studying the geometry and other important characteristics of different green spaces. Lin et al. (2006) addressed various indices for evaluating the ecological effects of urban green space. Using a geographic information system, Li et al. (2015) quantitatively analyzed the thermal effects of a river. In addition, by studying the cooling effect of 61 parks in Taipei, Chang et al. (2007) found that the larger a park area was, the higher its cooling effect. Feng and Shi (2012) reported a logarithmic relationship between the distance from the urban parks and the surrounding surface temperature and revealed that the larger the water area of a park is, the farther the cooling effect can reach. Choi et al. (2012) reported that the cooling buffer radius of a park is generally less than 500 m. At distances greater than 500 m, other interferences had a stronger effect on temperature than the park.

The cooling effect is an important ecosystem service of urban reservoirs and forests. Han et al. (2008), Jin et al. (2005) and Zhang et al. (2012) investigated this ecosystem service and function of urban reservoirs and forests by using different approaches and data. When two cold sources were adjacent, their cooling effects could interact with each other, which could occur between reservoirs, forests, parks and lakes. However, insufficient attention has been paid to such interactions. Reservoirs are an important urban landscape and climatic adjustment factor. Especially in southern Chinese cities, reservoirs are usually surrounded by forests, which constitute a typical blue-green infrastructure area. The synergistic role of these blue-green infrastructure areas is of importance in the regulation of the urban thermal environment. However, determining how to identify and quantify the interactions between reservoirs and forests and their synergy is a question worth exploring. Exploring this question can provide a theoretical basis for the construction of urban blue-green infrastructure and the improvement of the living quality of urban residents.

Although many studies have discussed the ecosystem services of urban blue-green infrastructures (Park et al., 2017; Jeanjean et al., 2017; Yang et al., 2017), the current quantitative research is far from adequate. Most of these works were primarily based on traditional field measurements and model simulations. However, information on the investigated area or target can be limited by these approaches. Currently, this knowledge gap can be addressed by using remote sensing technology (Zhu and Zhang, 2011). With the combination of remote sensing technology and traditional approaches, geological and microclimatic information can be comprehensively obtained and analyzed (Oliveira et al., 2011; Rogan et al., 2013; Cao et al, 2010). By now, remote sensing imagery has been applied as a well-developed geographic information system method (Hu et al., 2015; Song et al., 2015; Chen et al., 2012). This approach can be potentially used in the field to investigate the environmental effects of blue-green infrastructure in cities.

In this paper, 12 reservoirs in the Pearl River Delta of southern China were investigated. The temperature fields of each reservoir and their surrounding environment were retrieved by remote sensing imagery. Here, we addressed the temperature variations and changes within these temperature fields and explored the relationship between reservoirs and forests in terms of their thermal environmental effects by using remote sensing imagery. With the area and water storage capacity gradients for different reservoirs, the interactions between the blue-green infrastructures and their contributions the regulation of microclimates could be comprehensively investigated.

**Table 1**
Characteristics and landscape indices of the 12 reservoirs.

| Reservoir | Area $hm^2$ | Perimeter km | Capacity $10^6\,m^3$ | Ratio of perimeter to area | Shape index $\frac{perimeter}{2\sqrt{\pi * \text{area}}}$ | Ratio of length to width |
|---|---|---|---|---|---|---|
| Damali | 45 | 4.971 | 1.20 | 11.044 | 2.087 | 1.475 |
| Dashanbei | 47 | 2.935 | 4.81 | 6.234 | 1.205 | 2.252 |
| Guanjingtou | 55 | 4.027 | 11.85 | 7.309 | 1.529 | 2.295 |
| Jingxin | 68 | 5.070 | 14.93 | 7.455 | 1.734 | 3.073 |
| Chi'ao | 78 | 4.073 | 18.11 | 5.217 | 1.298 | 2.477 |
| Fengtian | 114 | 8.013 | 25.43 | 7.017 | 2.114 | 4.390 |
| Qiyeshi | 154 | 5.875 | 11.55 | 3.811 | 1.334 | 1.448 |
| Wulipai | 181 | 8.961 | 18.64 | 4.950 | 1.879 | 2.841 |
| Songzikeng | 218 | 6.368 | 26.59 | 2.917 | 1.215 | 3.791 |
| Yantian | 242 | 7.466 | 48.67 | 3.082 | 1.352 | 3.282 |
| Qingnian | 296 | 10.892 | 59.64 | 3.679 | 1.786 | 3.627 |
| Guandong | 336 | 15.649 | 62.41 | 4.654 | 2.407 | 4.934 |

## 2. Study areas and methods

### 2.1. Study areas

Twelve reservoirs located in the Pearl River Delta of southern China were selected according to gradients of reservoir area and reservoir capacity. The reservoir areas ranged from 44 to 336 $hm^2$, and the reservoir capacities ranged from 1.20 to 62.41 million $m^3$. Basic information for the reservoirs and several landscape indices are listed in Table 1.

### 2.2. Temperature field inversion

The most complete and clean Landsat 8 Thematic Mapper (TM) remote sensing imagery with clear ground features and without cloud obstruction was obtained on July 4th, 2015. Hence, the image from that day was used in this paper. ENVI 5.1 and ArcGIS 10.2 software were used to process the images, and the 10th bands were used for temperature inversion. The ground features were captured by Google Earth images and registered with TM images. Referring to the methods of Artis and Carnahan (1982), Qin et al. (2003, 2001) and Meng et al. (2012), the actual surface temperature field value of each reservoir was calculated.

By comparing the inversed surface temperature with the ground features, we found that the maximum range of the reservoir's cooling effect was approximately 300 m, which was in accordance with the reports of previous studies (Liang et al., 2015; Li et al., 2015). Thus, 300 m buffer areas were generated for each reservoir outside the water body, and equidistant temperature measurement points were selected along the vertical direction of the reservoir boundary. The correlation models between temperature and different factors were established, while the variations in the surrounding temperature of the field reservoirs and forests and their interaction effects were investigated.

## 3. Results

### 3.1. Inversion results of temperature field

Interpreting the TM and Google image overlays and object registration, the temperature fields of each reservoir and surroundings were retrieved. The local temperature field and the corresponding ground map of certain reservoirs showed that the temperature distribution was in line with the shape of the ground objects.

It can be seen in Fig. 1 that the cooling effect produced by the reservoir water was obvious. The paired Student's t-test was run using the boundary temperature of the reservoir and the surface temperature at 300 m away from the boundary. The results showed that the temperature difference was significant ($p = 0.0248$). This finding reveals that

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