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ORIGINAL PAPER

Cooling island effect of urban lakes in hot waves under foehn and climate change

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Abstract

The central region of Vietnam has a tropical monsoon climate but often undergoes heat waves due to uncontrolled urbanization, foehn winds, and climate change. Water bodies are considered effective candidates for heat mitigation in cities through the water cooling island (WCI) effect. Quantifying the WCI capacity of water areas and related factors is necessary for sites with advantages of surface water. The current attempt used the WCI effect range (L_{max}), temperature drop amplitude (ΔT_{max}), and temperature gradient (*G*temp) to investigate the cooling effect of 20 lakes in the Thanh Noi region, Hue City. Data derived from high-resolution Google Earth, Landsat-8 Satellite Imagery Data, and ground truth. The results show that the average water temperature of the 20 studied lakes was about 36.61 °C, lower than the average temperature in the area with an urban heat island (UHI) of about 2.82 °C. The mean L_{max} was 150 m, ΔT_{max} was 1.52 °C, and *G*temp was 10.16 °C /km or 0.01 °C/m. Climate characteristics and human impacts had reduced the ability of the lakes to create WCI during the period when the lake water level was low. The factors that influenced the WCI significantly were the landscape shape index (LSI), the proportion of green (PG), and the percentage of impervious surfaces (PI). Most lakes with relatively simple LSI, high PG, and low PI obtained high WCI, suggesting that structural and landscape characteristics played a critical role in urban cooling.

1 Introduction

The increase in extreme weather events, including hot weather due to climate change (IPCC 2007), has been a great challenge for humanity in terms of human health, energy consumption demand, and a host of other environmental problems. Because land cover often has a high permeability rate in urban areas, it is easy to create an urban heat island (UHI). In urban areas with tropical climates with intense hot seasons and little rain, the UHI situation will undoubtedly be severe and extreme. In contrast to UHI, there are areas in urban that can create urban cooling island effects, such as green space and water bodies (Rosenzweig et al. 2007), (Chang et al. 2007).

Water bodies absorb latent heat through evaporation (Oke 1992), (Amani-Beni et al. 2018), and convection (Spronken-Smith et al. 2000), thereby significantly reducing the temperature and cooling the air around the water bodies. The

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ability of water to reduce surface temperature due to continuous evaporation is powerful, especially on sunny days when the air can absorb more water. Each gram of water that evaporates will absorb 2500 J and reduce the surface temperature very effectively (Grinzato et al 2002). The cooling effect of water bodies, such as lakes, rivers, or fountains, has been studied by many authors such as Xu et al. (2010) and Sun and Chen (2012). Using the observational method, Xu et al. (2010) studied the effect of water bodies on thermal comfort during sweltering days with air temperatures above 35 °C and found that water bodies with a large surface area larger than 2104 m^2 can significantly cool the riverside areas. Moreover, the cooling water island (WCI) effect of the water surface has been detected and confirmed by Chang et al. (2007), Cao et al. (2010b, a), and Du et al. (2016).

Several investigations were carried out to quantify the cooling of water bodies. Murakawa et al. (1991) reported that the Ota River (Hiroshima, Japan) increased wind cooling by at least a few hundred meters in the region. Similarly, Coutts et al. (2013) confirmed that the air temperature around the river (270 m wide) was about 3–5 °C cooler than the surrounding areas, between 12 and 5 pm on days. The range of rivers cooling will further increase if the surrounding areas are sparsely built and the wider street. Hathway and Sharples (2012) detected a cooling effect of a large pond in Fukuoka, which attained a reduction of 3 °C and the cooled extent extended horizontally to 400 m. Yang et al. (2020) provided evidence of the WCI effect in 58 ha—Daming Lake (Jinan, China) with an average cooling around the lake was ~ 1 °C in the hot season (July–August). Until now, the research on the WCI effect has often focused on large rivers and lakes in urban areas—from a few hectares to several tens of hectares, while the impact of small lakes and ponds has not received much attention.

The WCI effect is related to the UHI effect. Surface temperature (LST) has an indirect but significant effect on the near-surface air temperature. The change of LST is mainly due to the energetic interaction between the atmosphere and the Earth's surface (Dousset & Gourmelon 2003). However, the air temperature usually varies less than the surface temperature over an area. In general, the air temperature in densely built-up areas (urban areas) will be higher than the air temperature in areas with lots of trees and water surface (rural areas, suburbs), leading to atmospheric urban heat islands in the atmosphere. Therefore, Ridd (1995) suggested that UHI characteristics and identification are based on land surface temperature (LST). Besides direct observations, remote sensing technology is being applied in WCI research with reasonable accuracy (Sun et al 2012). Many studies of UHI based on thermal remote sensing data from different satellites have been performed (Anielo et al. 1995, Streutker 2002; Dousset & Gourmelon 2003, Mathew et al. 2017). The data retrieved from satellite images help to clarify the trend of temperature changes and determines the extent and distribution of the effects of the WCI effect in a specific region. Using remote sensing to study UHI in Europe by Olah (2012) in Budapest, Schwarz et al. (2012) in Leipzig showed that water bodies can reduce urban air temperatures by 1 to 10 °C. Also, Du et al. (2016) relied on high-resolution Google Earth and Landsat-8 Satellite Imagery Data to quantify the WCI of lakes and rivers in Shanghai.

Moreover, Gupta et al. (2019) used Landsat 5 Thematic Mapper (TM) (2009, 2010 and 2011) of 30-m resolution to process. They created LST maps using the ERDAS Imagine and ArcGIS 10.1 software packages of Chandigarh City, India, Asia. There have been few studies on the WCI effect by remote sensing technology in areas with a humid tropical monsoon climate and extreme hot seasons due to the foehn effect.

The central region of Vietnam, including Hue City, is considered one of the areas with fierce foehn activities causing disadvantages in human thermal comfort in the hot season (Vu et al. 2007, 2008). The hot weather strengthened by climate change and the UHI effect tends to increase in the Thanh Noi, Hue City, where it holds many lakes and ponds of small size. Surface water areas should be considered a tool to reduce urban heat. The assessment of WCI effects of lakes will provide convincing evidence in landscape protection planning city in the direction of ecology, minimizing UHI, and increasing the convenience of the destination for tourism development in the region.

This work aimed to (1) elucidate the effect and extent of WCI during the day of the lake and pond system in the Thanh Noi, Hue City, Vietnam; (2) quantify the impact of influenced factors to WCI of lakes and ponds in the region; and (3) discuss the WCI lifetime of the lakes during the hot season. The high-resolution Google Earth, Landsat-8 satellite imagery data, and ground truth were used in this study.

2 Study area and method

2.1 Study area and data source

Thanh Noi is an urban area of 520 ha surrounding Imperial City—Hue Citadel, Hue City, central of Vietnam, located at 16° 29′–16° 27′ N and 107° 33′ 107° 35′ E (Fig. 1). This region has a humid tropical monsoon climate. The rainy season has a cold, wet northeast monsoon, while the dry season with little rain, is hot, with southwesterly winds; this is also the season often with dry, hot foehn winds. This wind, appearing in waves from February to September, peaks in June, July, and August. On average, each wave lasts from 3 to 5 days; in some years, it lasts up to 41 days, such as May 25–July 4 in 1977 and June 9–23 in 1993. In foehn days, the maximum air temperature in Hue reached 39.2 °C (average

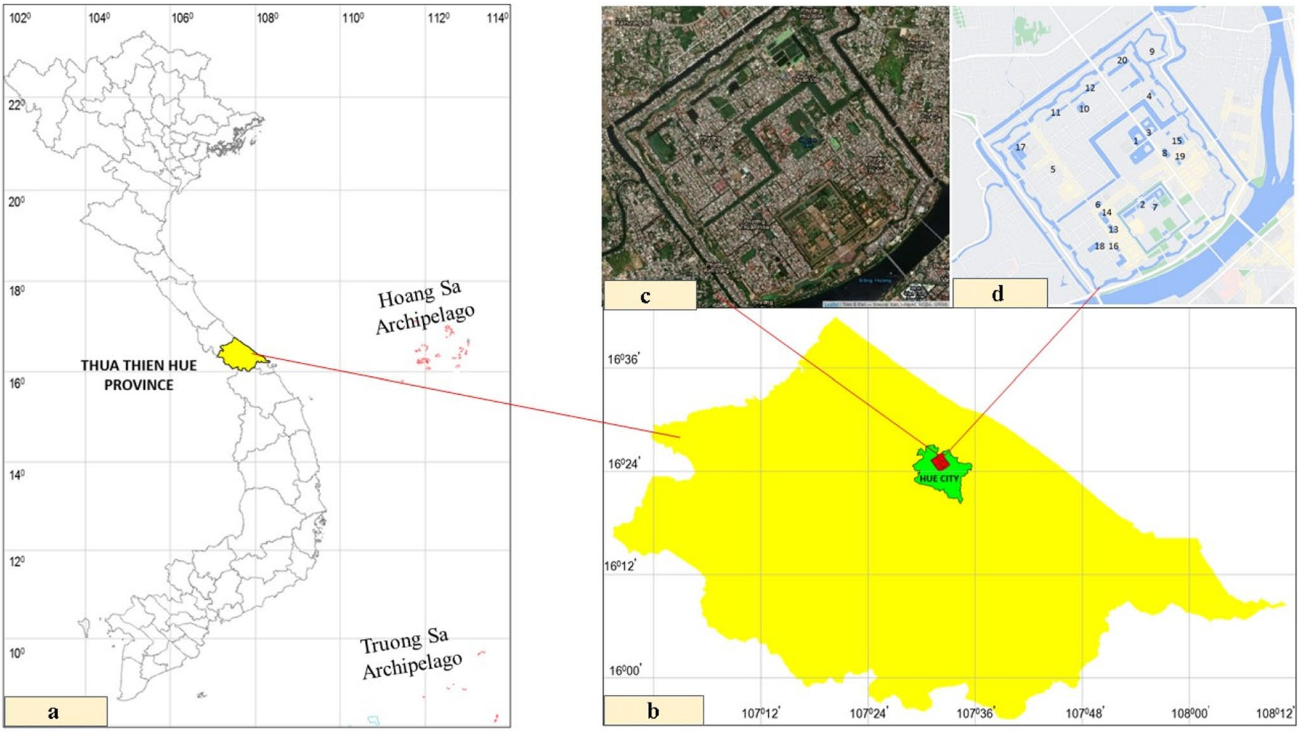


Fig. 1 Research locations: Vietnam (**a**) and Thua Thien Hue Province (**b**). Satellite image of lakes and ponds (**c**). and Map of lakes and ponds in the Thanh Noi (**d**) (edited from Google Map)

32 °C); the lowest humidity was only 38% (mean 60%). Due to the impact of climate change, the frequency and intensity of heatwaves are forecasted to be increased. Monitoring data updated from the Thua Thien Hue Department of Science and Technology show that the heat waves resulted in a recorded maximum temperature of 47 °C on May 19 and 39.9 °C on June 29 in 2019, with the humidity of only 40%.

There are 38 lakes in the Thanh Noi, Hue city with about 431,858 m^2, accounting for 8.3% of Thanh Noi's area. Most of the lakes are small, only from 3000 to 23,000 m^2. The largest one is Tinh Tam lake, with 103,376 m^2. These lakes typically have simple geometry (square, rectangular) and an average depth from 2 to 3 m. Urban sprawl has disappeared 695,749 m^2 of lakes and ponds between 2003 and 2008, accompanied by an increase in impermeable soil around the lakes and the change in lake shape. In climate change, the risk of increasing heat waves and urban heat island in the region is very high, adversely affecting daily life and production activities. Currently, these lakes are being used mainly for urban drainage and economic purposes such as fish farming and lotus cultivation. The function of regulating microclimate, minimizing urban heat islands of lakes and ponds, has not been studied, evaluated, and used.

Twenty lakes in Thanh Noi were selected based on diversity in terms of area, structure, and landscape. The differentiation of lakes in this work reflects the rules and causes affecting WCI values. The Landsat 8 image on June 28, 2019, from the United States Geological Survey (USGS) was selected to measure the LST and the extent of the WCI effect of some representation lakes in the region. The resolution of the image is 30 m. A temperature profile was observed at Provincial Hydrometeorological Center (Hue station) during heat waves in 2019. Land use data of Thanh Noi Hue and LST dataset were derived from sensor images.

2.2 Method

2.2.1 Retrieve LST

The LST values were retrieved from the Landsat 8 image by the single-channel method. In this method, a 01 thermal infrared channel of Landsat image (channel 10 or channel 11) was used to calculate brightness temperature according to formula (1) (Sobrino et al. 2004; NASA 2016).

$$\mathrm{T_B} = \frac{\mathrm{K_2}}{\ln \frac{\mathrm{K_1}}{\mathrm{L_\lambda}} + 1} \tag{1}$$

where K_1 and K_2 are the conversion coefficients provided in the Landsat satellite image metadata file.

L_λ, a spectral radiance value, was calculated according to formula (2) (NASA 2016).

$$L_\lambda = M_L.Q_{cal} + A_L \tag{2}$$

The ML and AL (conversion coefficients) are also provided in the metadata file of the Landsat 8 image.

Ordinal	Channel	K_1 (M/m^2 sr \ μ m)	K_2 (kelvin)
1	10	774,89	1321.08
2	11	480,89	1201.14

LST was calculated according to formula (3) (Wan and Dozier 1989; Sobrino et al 2004; Van and Lan 2009; Vlassova et al. 2014).

$$LST = \frac{T_B}{1 + \frac{\lambda . T_B}{\rho} . \ln \varepsilon} \tag{3}$$

where T_B is the radiant temperature; λ is the center wavelength value of the thermal infrared channel; ε is the surface emissivity; and ρ is a constant (1.438.10^{-2} m K).

By applying the above procedure, the LST of study area on June 28 in 2019 was obtained and is shown in Fig. 2. The land surface temperature of the areas located in the study area is in the range of 29.4 to 40.9 °C depending on the characteristics of the mantle.

2.2.2 Calculation and classification of land use cover

Based on the value of spectral reflectance in the red channel (channel 4) and near-infrared channel (channel 5), NDVI was computed according to formula (4) (Rouse et al. 1974).

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \tag{4}$$

where ρ_{NIR} and ρ_{RED} are the spectral reflectance value at the near-infrared and red channels, respectively.

The NDVI is a function of change in the range [−1, +1], but negative values correspond to water, i.e., values near zero. Positive values correspond to soil and range from 0.2 to 0.6, indicating the presence of vegetated surfaces (Giannini et al 2015).

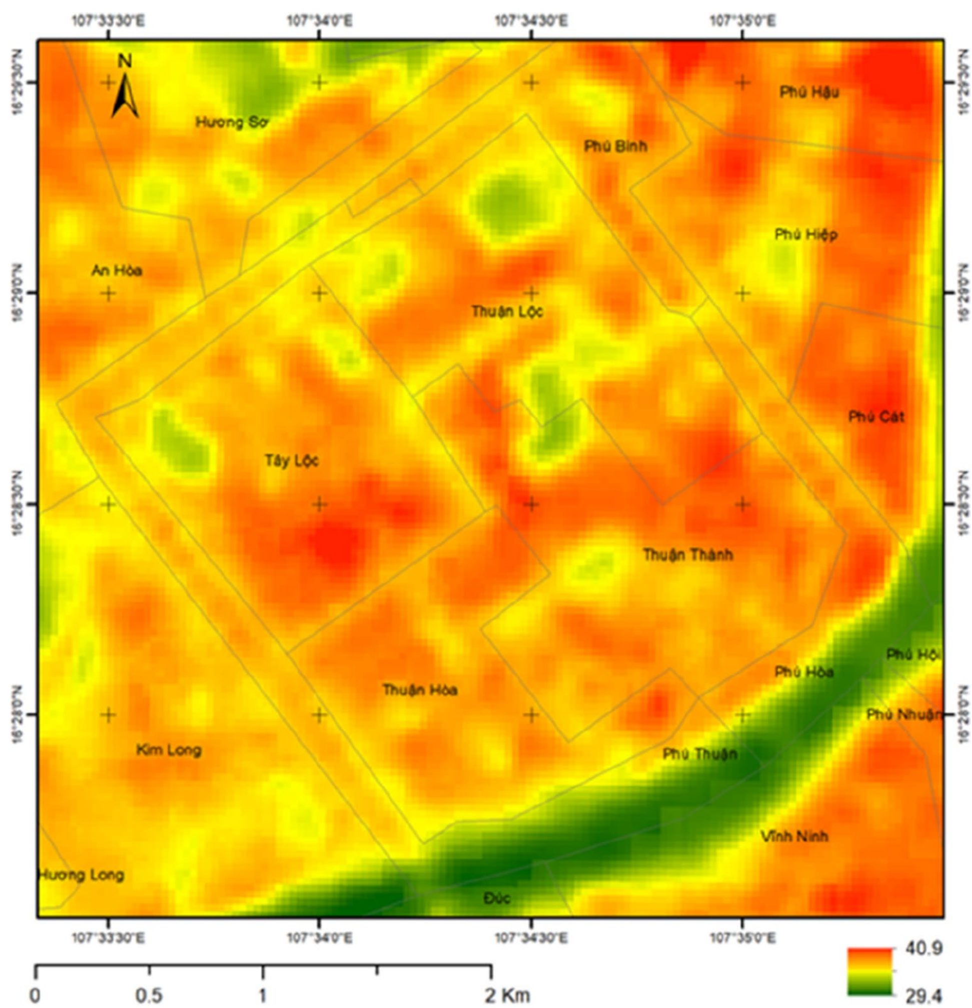


Fig. 2 Land surface temperature map of the Thanh Noi region and surrounding areas on June 28 in 2019

Based on the NDVI to calculate the proportion of vegetation in 1 pixel of the P_v image, P_v was determined by formula (5) (Vlassova et al. 2014; Guha et al. 2018).

$$P_v = \left(\frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}\right)^2 \quad (5)$$

$NDVI_{veg}$ and $NDVI_{soil}$ are the NDVI values for plants and homogenous soils, respectively (Vlassova et al. 2014). P_v takes on a value of 0 for bare soil and 1.0 for vegetated overcover soil. Then, the P_v value was used to determine the surface emissivity according to formula (6) (Wan.J.,1989; Valor and Caselles 1996).

$$\varepsilon = \epsilon_v . P_v + \varepsilon_s (1 - P_v) \quad (6)$$

where ε_v and ε_s are the surface emissivity of plants and bare soil, respectively.

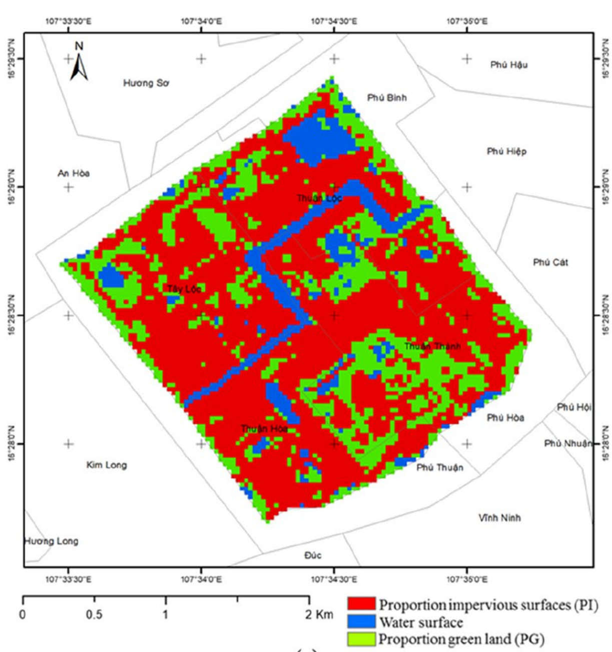
Land use cover was deduced from Landsat 8 image (same date as an image used to calculate LST). The processed data has been interpreted on the Google Earth Engine platform. Three land cover types were mapped, including impermeable soil (houses, commercial centers, industrial zones, roads), green soils (trees, grasses, shrubs, and other vegetation other than 10%), and water surface (Fig. 3). Calculation of WA, PI, and PG of 20 lakes selected to quantify WCI consist of Tinh Tam, Noi Kim Thuy, Hoc Hai, Giam Thanh, Moc Duc, Phong Trach, Ngoc Dich, Nhan Hau, Tran Binh Dai, Chua, Tien Bao, Ta Bao, Vo Sanh, Tan Mieu, Mung, Hau Ve, Kham, Xa Tac, Phu Van, and Hau Bao.

2.2.3 Calculation of UHI

To better determine the influence of urban on temperature, it is necessary to subtract the average temperature of the non-urban areas around the Hue City center. To make this thing, the following must be obtained: The data required for the implementation are data on the vegetational cover of Hue City; SNAP image processing software version 8.0 has integrated the CCI Land Cover-2015 global database.

Land Cover CCI data is built from multiple sensors to make the most of existing satellite data. Land Cover (LC) data CCI is built based on many years of data from many sensors to make the most of existing satellite data. All Envisat Meris (Medium Resolution Imaging Spectrometer) satellite images (2003–2012) were applied as input data for the 2003 to 2012 land cover map. This land cover (LC) product was further processed to produce land cover maps for 2000, 2005, 2010, and 2015 by technical backdating, using a series of SPOT Vegetation images. Besides, higher-resolution image sources have also been employed as input datasets for the classification process, including Sentinel-2, Sentinel-3, SPOT-4, SPOT-5, MODIS (Moderate Resolution Imaging Spectroradiometers) Terra, and Landsat 8 OLI. Land Cover CCI products have made many significant improvements: supervised machine learning algorithms have been thoroughly applied. Land Cover CCI products must go through 5 steps: pre-processing, classification by machine learning algorithms, untested sort, merging of classification results, and post-classification editing.

To better identify the effect of urban area on temperature, we subtract the average temperature of non-urban areas close



Object	Acreage (ha)	Ratio (%)
Proportion impervious surfaces (PI)	360.9	63.2
Water surface	60.6	10.7
Proportion green land (PG)	149.5	26,1

(b)

Fig. 3 Land cover map of the Thanh Noi area (**a**) and scale of each type (**b**) to Thanh Noi area. In order to do that, we first add a land cover band to identify different land covers, that is, the synchronization of LST data with Land Cover CCI data (Fig. 4).

Once the land cover band is added, the next step is to derive the mean temperature in the surroundings of the Thanh Noi area using specific pixel values identified using the Pin tool of SNAP software. We determined 15 points around the Thanh Noi area which were included in the calculation of the temperature. From these temperature values, SNAP software was used to calculate the average temperature, then put into the Band Math tool to determine the influence of the urban on the land surface temperature. The mean temperature of 15 points around the central area was 33.43 °C (Fig. 5).

2.2.4 Calculation of related WCI indexes

The differences in the LST of the water bodies and their surroundings influenced the WCI. Three aspects of WCI include L_{max}—the distance between the edge of the water body and the first point on the temperature curve (km); temperature drop amplitude (ΔT_{max}) which is the temperature drop of the first transition point relative to the water temperature (°C); and WCI intensity (*G*temp) which is the temperature gradient in L_{max} (°C/km). These indexes were inherited from Du et al. (2016) which assessed the WCI in Shanghai, China.

The factors representing the characteristics of lakes and ponds used to quantify the WCI effect include water surface area (WA); proportion impervious surfaces (PI); and proportion green land (PG). The geometric shape of the LSI water mass was calculated as follows (7) (McGarigal & Marks 1995):

$$\mathrm{LSI} = \mathrm{D}/2\sqrt{\pi}\mathrm{xWA} \tag{7}$$

where *D* is the total circumference of an area of water.

Ideally, the LSI equals 1.00 for circles and 1.13 for squares. It increases with the rising of irregularity of the landscape shape. The WA, PI, PG, and LSI of the 20 lakes were extracted from the land use cover map used for the WCI quantitative analysis.

2.2.5 Buffers and extract data

The buffer represents an area around a particular feature at a specific distance. A buffer was created to measure the extent of the cooling effect of the lake as the distance from the boundary of the water space increases. The "Buffer" option of the "Geo Processing Tool" in ArcGIS 10.1 (ESRI 2014), the flat of end type, and the border (left or right) _type was used to draw the buffers. Also, the temperature of each buffer was extracted using the "Extract by Mask" command of the spatial analysis tool in ArcGIS 10.1. First, a buffer of 240 m was created for the water surface objects and these buffers were divided into segments at equal intervals of 30 m (to coincide with the 1-pixel size of the Landsat image). Then

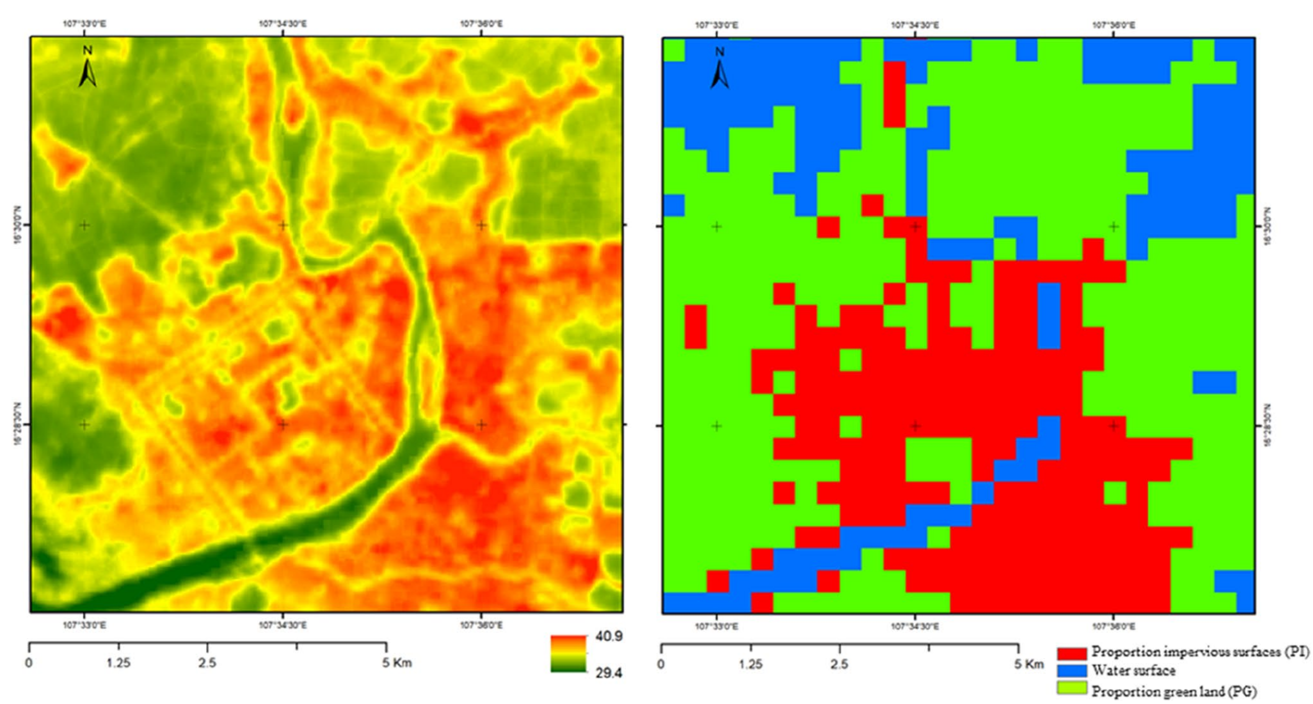


Fig. 4 Land surface temperature data synchronized with Land Cover CCI data

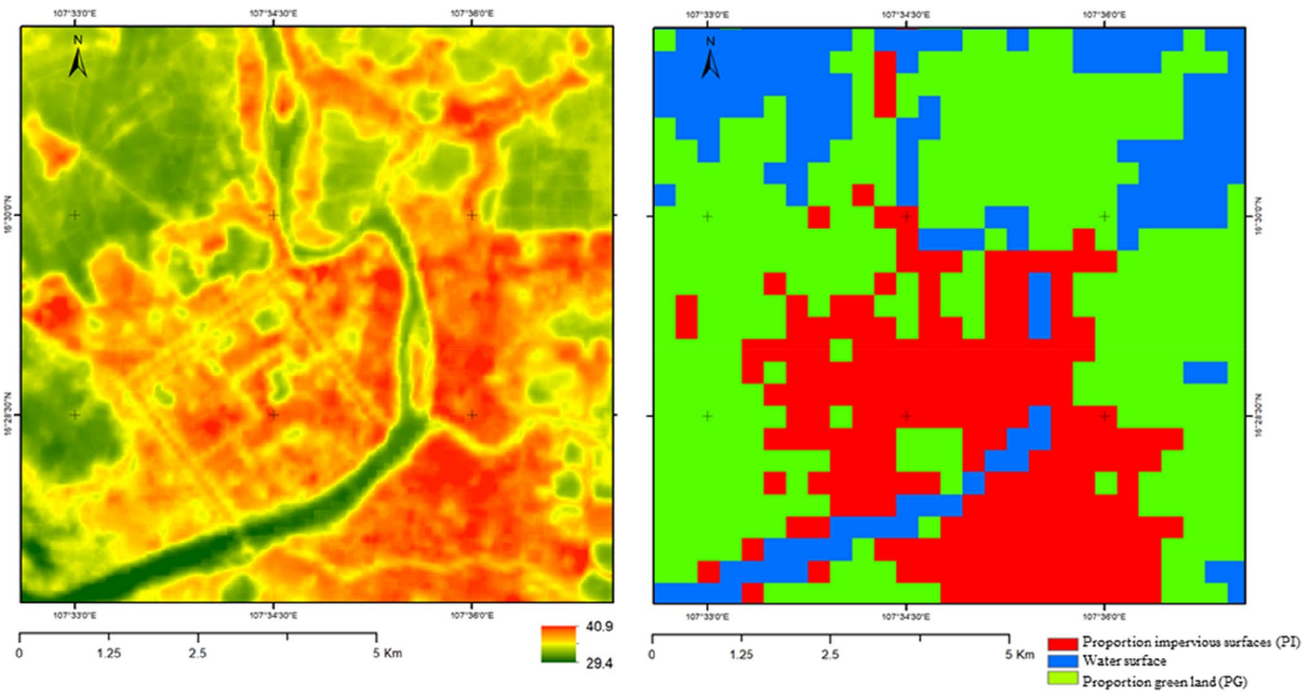


Fig. 5 Selected neighbourhood points in the Thanh Noi area

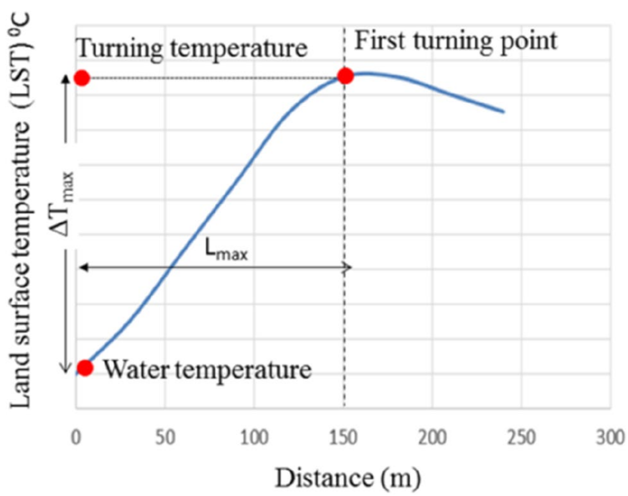


Fig. 6 Quantitative graph of the WCI effect derived from the Landsat image

the temperature values at each pixel in the distance from the lakes were extracted, as shown in Fig. 6.

L_{max} was determined by the first turning point of the LST curve (Fig. 6), as subsequent turning points may be due to other cooling factors (Sun et al 2012). The turning points of the LST curve were selected manually when the slope of the LST curve changes sharply or reaches a relative level. Statistical analysis was performed using SPSS 19.0 software. The Spearman rank correlation coefficient was used to quantify the relationship between the properties of the water bodies and the WCI effect.

3 Research results and discussion

3.1 Land surface temperature

Between the hottest area of Thanh Noi and the extra-urban space around this area, there is a rather significant temperature difference at a particular time. Thanh Noi's areas with many houses and a low ratio of tree cover had about 6 °C higher than neighboring regions with a low ratio of soil impermeability, increasing the tree cover ratio (Fig. 7). The hottest area has a maximum surface temperature of 40.9 °C; these places have a high building density, from 60 to 70%. This extreme temperature value results from the urban effect and the impact of hot, dry foehn winds in the area.

3.2 Characteristics of the lake and the WCI effect

LST retrieval data and statistical analysis show that the average water temperature of the 20 lakes was about 36.6 °C, which was lower than that of the UHI area (39.4 °C) — extracted from the surface temperature map, equivalent to 2.8 °C reduction. In that situation, the air temperature from 12 pm to 3.0 pm at Hue weather station

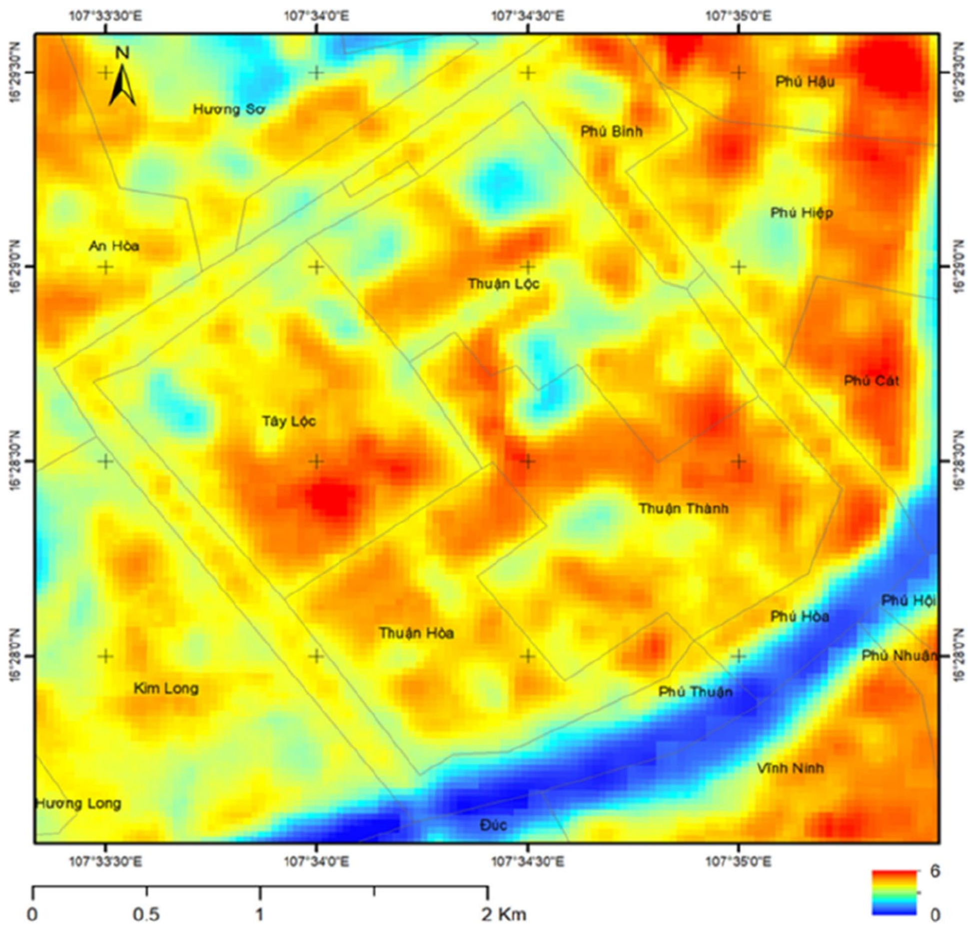


Fig. 7 Calculation results of land surface temperature in the Thanh Noi region

reached over 40 °C. This confirmed the WCI effect of the lakes, but there were differences among the lakes (Table 1).

Table 1 shows that their shape index (LSI) ranged from 1.10 to 2.28. The area of the studied lakes is not large, ranging from 0.9 to 10.3 ha, and the difference in area between the largest and smallest lakes is more than nine times. L_{max} was from 90 to 210 m (Fig. 8), with an average of 150 m, indicating a difference in cooling scale, while ΔT_{max} was from 0.33 to 2.47 °C (mean 1.52 °C). Gtemp covered from 2.4 °C/km to 16.67 °C/km, with an average of 10.16 °C/km or 0.01 °C/m.

Figure 8 shows that the LST of the lakes varies widely. Most lakes with low LST have L_{max} and ΔT_{max} of large type, for example, Tinh Tam lake, Tan Mieu, Kham, and Xa Tac. In contrast, lakes with high LST have small L_{max} and ΔT_{max}, such as Phong Trach lake and Nhan Hau lake. The turning temperature between lakes is also different; the difference between the highest value of 40.65 °C in Phu Van Lake and the lowest value of 36.36 °C in Hau Bao Lake is up to 4.29 °C. Therefore, the thermal comfort for residents that the lakes provide will be to different degrees.

3.3 Correlation of lakes and the WCI effect

The relationship among WA, PG, PI, and LSI with WCI effect of 20 lakes in Thanh Noi is shown in Fig. 9(a)–(c). It demonstrates that the WA value was positively correlated with the ΔT_{max} and *G*temp values ($r = 0.14$ and $r = 0.13$, respectively), and negatively correlated with L_{max} ($r = -0.0077$). However, these correlations are not significant. The LSI values in Fig. 9(d)–(f) were negatively correlated with L_{max} ($r = -0.51$), ΔT_{max} ($r = -0.42$), and *G*temp ($r = -0.31$). It means that water features with more complex shapes led to small L_{max} and ΔT_{max}, while water objects with a simple shape (round or square) resulted in large L_{max} and ΔT_{max} values. This is because the more extensive the LSI value (compared to the ideal index of 1 for circles and 1.3 for squares), the larger the irregularity and complexity of the landscape shape, and the higher the L_{max} value and the smaller the ΔT_{max}; conversely, the smaller the LSI value due to the simple landscape shape (circle or square), the larger the L_{max} and ΔT_{max}. The variable of the LSI was used to describe the complexity of the landscape patterns by calculating the degree of deviation between the shape

Table 1 Structural, landscape characteristics, and WCI of 20 studied lakes in the Thanh Noi area

Lake's name	Perimeter	Acreage	LSI	PI	PG	Water*T* (°C)	Turning*T* (°C)	L_{max} (m)	ΔT_{max} (°C)	G_{temp} (°C/km)
Tinh Tam	1527	103,376	1.34	0.66	0.32	35.1	37	150	1.9	12.67
Kim Thuy Trong	1433	37,861	2.08	0.87	0.13	37.3	37.63	90	0.33	3.67
Hoc Hai	730	31,690	1.16	0.38	0.6	35	38.5	210	3.5	16.67
Giam Thanh	274	4052	1.21	0.76	0.2	37.41	37.77	150	0.36	2.40
Moc Duc	276	4816	1.12	0.68	0.32	37.85	39.28	120	1.43	11.92
Phong Trach	260	4073	1.15	0.67	0.32	38.84	39.4	180	0.56	3.11
Ngoc Dich	368	8893	1.10	0.54	0.34	36.46	38.3	180	1.84	10.22
Nhan Hau	399	8635	1.21	0.76	0.23	38.54	39.45	100	0.91	9.10
Tran Binh Dai	239	3630	1.12	0.61	0.39	35.03	37.5	210	2.47	11.76
Chua	396	8978	1.18	0.78	0.2	36.63	38.3	120	1.67	13.92
Tien Bao	770	12,643	1.93	0.75	0.22	35.82	37.17	120	1.35	11.25
Ta Bao	988	14,982	2.23	0.76	0.22	36.82	37.47	90	0.65	7.22
Vo Sanh	501	13,369	1.22	0.65	0.33	35.5	36.84	120	1.34	11.17
Tan Mieu	348	6617	1.20	0.59	0.4	35.5	38.1	210	2.6	12.38
Mung	373	8925	1.12	0.81	0.19	37	38.4	150	1.4	9.33
Hau Ve	418	8136	1.31	0.79	0.2	37	38.2	90	1.2	13.33
Kham	695	23,722	1.27	0.68	0.31	36.5	38.2	210	1.7	8.10
Xa Tac	462	10,811	1.25	0.6	0.4	36	38.27	180	2.27	12.61
Phu Van	326	5327	1.26	0.74	0.25	39.22	40.65	120	1.43	11.92
Hau Bao	803	19,148	1.64	0.65	0.34	34.78	36.36	150	1.58	10.53

of a plaque and its square of the same area. The simulation results show that the simpler the shape, the higher the influence on the cooling effect. The PG positively correlated with L_{max} ($r = 0.75$), ΔT_{max} ($r = 0.84$), and *G*temp ($r = 0.53$) (Fig. 9(j)–(l)). In contrast to PG, the PI had a negative correlation with L_{max} ($r = -0.74$) and ΔT_{max} ($r = -0.81$) and *G*temp ($r = -0.49$) (Fig. 9(g)–(i)).

The correlation analysis of factors affecting the WCI of 20 lakes indicates that the high PI ratio reduced the cooling effect of the water area. In contrast, with the PG ratio, the lake's size increased to the simple of the lake. Also, the cooling effect expanded in size, intensity, and temperature reduction.

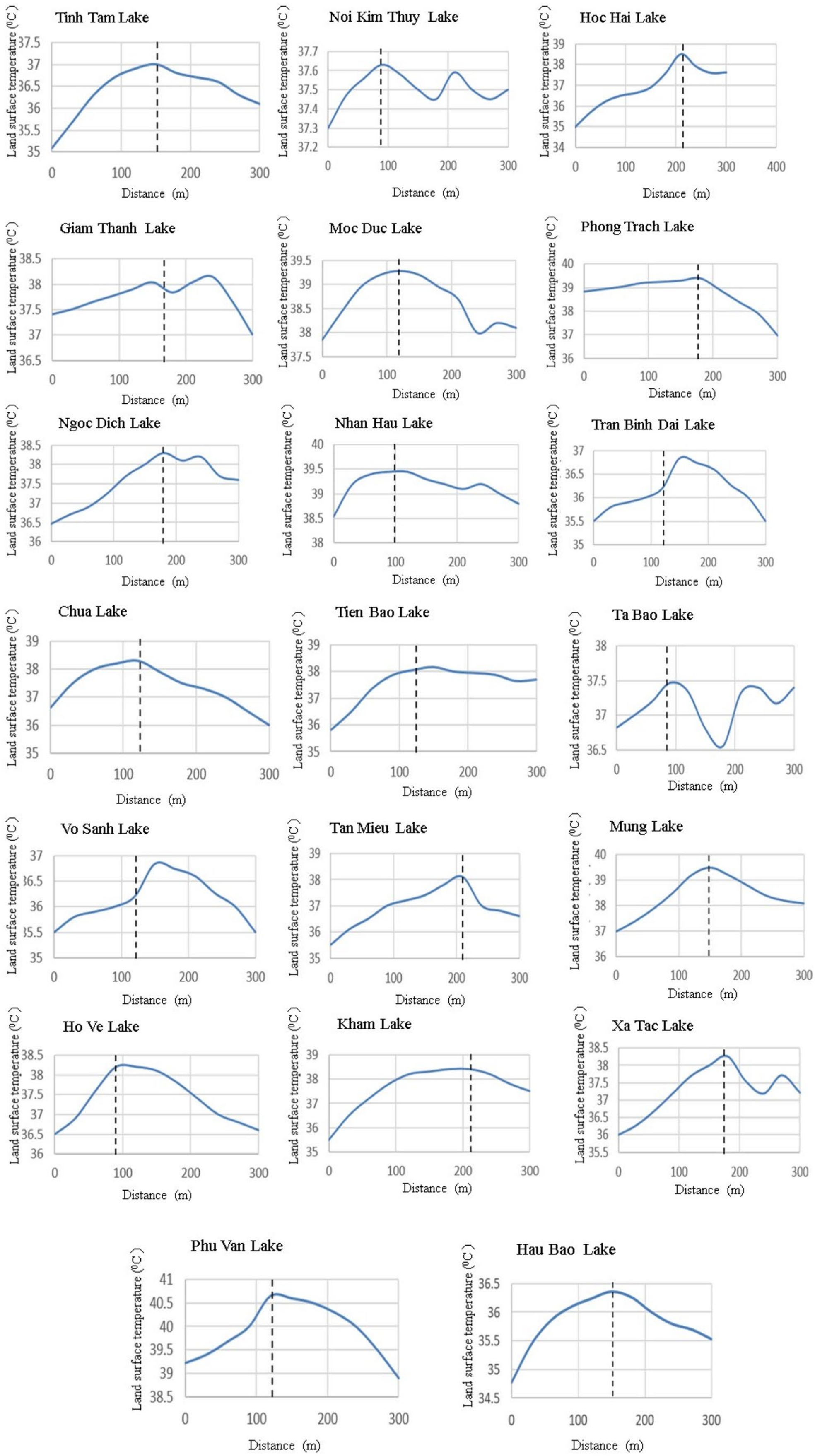
3.4 Duration of WCI effect

In the hot season, heatwaves were mainly caused by intense foehn activity and enhanced the UHI effect due to an insignificant amount of rainfall; thus, some lakes in Thanh Noi and Hue City often shrink in water surface area (the year was still dry and inert like the drought in July 1978). The lake water level was lower with only 0.5–1.0 m in depth — positions closed to the lakeshore exposed the lake bottom, which changed the lake's LSI. Then, the exposed bottom places thrived easy plants such as Wedelia Chinensis (Osb) Merr, Eleusine indica (L.) Gaertn, and Cynodon dactylon Pers, covering to 80–90%. This situation occurs robustly in July and August, which are also the hottest months of the hot season. From mathematical models, Zeng et al. (2017) suggested that when the water depth is more significant than 0.5 m, a cooling effect occurs because shallow waters have a warming effect due to reflectivity. Besides, Ishii et al. (1991) stated that the cooling effect around a drained large pond (127,000 m^2) dropped two times compared to full water.

Therefore, we confirm that the WCI effect of lakes in Thanh Noi and Hue City is still there. The replacement of water cover by vegetation cover in some parts of the lake bottom during dry times should be able to maintain the WCI effect of the lake. A field analysis using the EXTECH 445,703 temperature and humidity measuring device (from 1 to 3 pm; August 12 to August 14, 2021) found that less wind and cloudy weather and drained lake resulted in a lower temperature from 0.8 to 1.35 °C than that of the Hue hydro-meteorological station.

4 Discussion

The study confirmed that the WCI effect of the lakes in Thanh Noi happened during the daytime. The cooling effect varied among lakes depending on the structural features (WA, LSI) and the surrounding water features (PI, PG). The influence of the WA index was not the main differentiating factor on WCI of the studied lakes. This is because the


Tinh Tam Lake
Noi Kim Thuy Lake
Hoc Hai Lake
Giam Thanh Lake
Moc Duc Lake
Phong Trach Lake
Ngoc Dich Lake
Nhan Hau Lake
Tran Binh Dai Lake
Chua Lake
Tien Bao Lake
Ta Bao Lake
Vo Sanh Lake
Tan Mieu Lake
Mung Lake
Ho Ve Lake
Kham Lake
Xa Tac Lake
Phu Van Lake
Hau Bao Lake
Land surface temperature (ºC)
Distance (m)

◂**Fig. 8** WCI effect of investigated lakes in the Thanh Noi

Ve, Ta Bao, and Noi Kim Thuy reservoirs had only 90 m in L_{max} while the areas of these lakes are not the smallest lakes of the 20 investigated lakes. In addition, small lakes (e.g., Tran Binh Dai) had a high WCI with 210 m in L_{max} and 2.47 °C in ΔT_{max}. This result is different from several previous studies. Sun and Chen (2012) and Theeuwes et al. (2013) reported that enormous lakes had a more significant cooling effect. Zeng et al. (2017) demonstrated that the water area of 400 m^2 reduced 0.2 °C, while 1600 m^2 dropped 0.39 °C. However, there were few exceptions; for example, large and medium lakes such as Tinh Tam, Kham, Tan Mieu, and Hoc Hai obtained the most considerable WCI effect (210 m in L_{max}, ΔT_{max} from 1.6 to 3.5 °C). This find agrees with previous authors. Zeng et al. (2017), and Syafii et al. (2016) have not confirmed the increase in WCI due to the rise in the water area.

LST retrieval data manifest an "urban hot tub" effect in some lakes in the study area. Specifically, areas of Phu Van, Nhan Hau, Phong Trach, and Moc Duc lakes were not the smallest types but had an ideal LSI of about 1.2. Still, the water surface temperature of these lakes was much higher than that of other lakes in the study area. This has greatly reduced their cooling water island effect (Table 1).

The actual survey had shed more light on the cause of this problem: Because the area around these lakes has high construction density and poor ventilation, lake water is polluted by untreated domestic wastewater. This is consistent with the findings of Brans et al. (2018) and Mai et al. (2007). Brans et al. (2018) reported that the impact of urbanization within a radius of 50 m on lake water temperature was much larger than the impact of urbanization in the vicinity of 3200 m.

The expected points of the lakes obtaining the highest WCI effect in the study area accounted for an LSI from 1.1 to 1.3, a reasonably high PG of 0.3 to 0.6, and a relatively low water temperature of ~ 35 °C. The actual survey shows that most of these lakes, such as Tinh Tam, Hoc Hai, Tran Binh Dai, Tan Mieu, Vo Sanh, Hau Bao, and Xa Tac, had high ventilation and were not surrounded by residential areas. This raises the question whether openness of lakes is linked or not to the WCI effect. Murakawa et al. (1991) suggested that the density of buildings and the width of the street influenced the horizontal cooling distance of the water body to the microclimate. Specifically, a road with a width of 100 m next to a water body had a cooling distance three times higher than that with only 10 m wide. Zhang et al. (2018) also confirmed that small and scattered urban architecture helped form efficient urban ventilation corridors, thereby expanding the cooling range.

The complicated interaction among the above factors for heat reduction of lakes still needs to be explored. Other factors such as lake location, design, density of constructions, and width of streets around the lakes should also be considered when quantifying the WCI of lakes.

The results of this work for the WCI effect further prove the enhancement effect of the cooling if showing the combination of water bodies and vegetation. Also, the reduction of the cooling effect is due to the increase in the proportion of land impermeability. Furthermore, different landscape surfaces resulted in various UHI mitigation capacities, partly found in previous investigations (Du et al. 2016; Neha Gupta et al. 2019; Yang et al. 2020). These suggest that urban planners should pay attention to the landscape features around lakes and ponds to utilize the benefits of water surfaces in the region.

Maintaining the WCI effect of lakes was strongly dependent on their drying status. The water in the lakes was directly related to the rainfall and the additional water source from the Huong River through the sewer system, connecting the lakes with Ngu Ha and Huong rivers. However, barrier nets in the drains to avoid the loss of fish raised in the lakes have caused sedimentation at the sluice gate. Thus, the addition of lake water from Huong and Ngu Ha rivers in the hot season and flood drainage in the rainy season encounters many obstacles, even interruptions. The encroachment of the lake and the lake's sedimentation due to domestic and production waste also changed the indicators of WA, LSI, PI, and PG.

The study analyzed and elucidated the aspects related to the WCI effect of the studied lakes, which is helpful for urban management. However, some limitations, such as the limited number of lakes and short air data series, suggest to be improved in the future. Also, concretizing PG and PI to increase accuracy when analyzing the influence of these factors on WCI is recommended.

5 Conclusions

This work assessed the WCI cooling effect of 20 lakes in Thanh Noi, Hue City, Vietnam. The average water temperature of the 20 lakes was about 36.61 °C, lower than the area's average temperature with a UHI of about 2.82 °C. The main results of the WCI aspects obtained a mean 150 m of L_{max}, 1.52 °C of ΔT_{max}, and 10.16 °C/km of *G*temp. The PG was positively correlated with L_{max}, ΔT_{max}, and *G*temp, while PI tended to be negatively correlated with L_{max}, ΔT_{max}, and *G*temp. LSI was negatively correlated with L_{max}, ΔT_{max}, and *G*temp. This means that the more complex the shaped water features, the smaller the L_{max} and ΔT_{max} values, and the simpler shaped (e.g., round or square) the water features, the larger L_{max} and ΔT_{max} values. A high WCI effect happened with lakes featuring a relatively simple shape, a high percentage of vegetation, a low percentage of impermeable soil, and maintaining of water surface area stability.

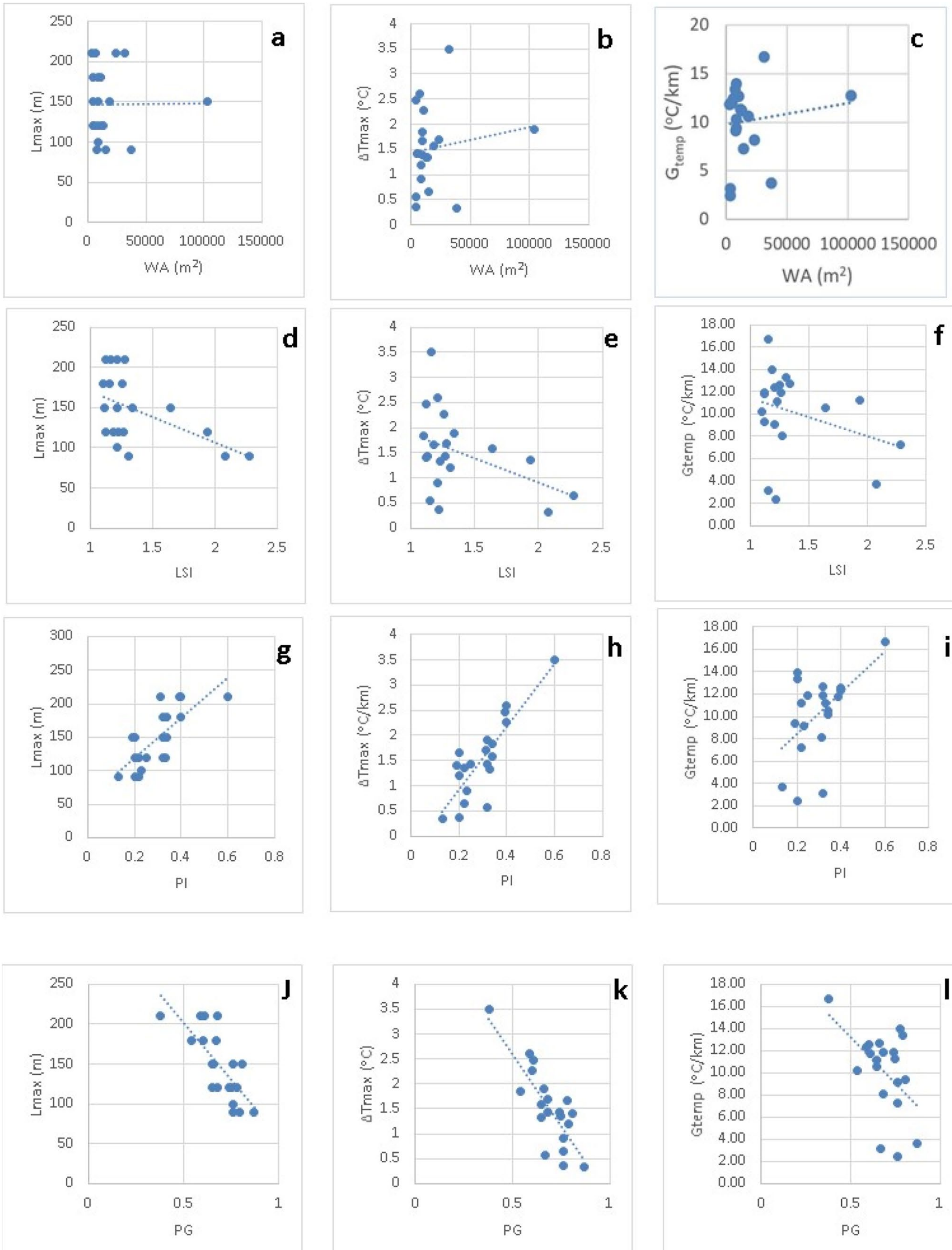


Fig. 9 Relationship between values of WA, PG, PI, LSI with WCI effect of 20 lakes

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Author contribution Chi Lang Le Phuc, Hoang Son Nguyen: conceptualization, writing—original draft, software, formal analysis, visualization; Cham Dao Dinh, Ngoc Bay Tran: data acquisition, analysis, writing, review; Xuan Cuong Nguyen: data preparation, writing, review, supervision, Quoc Bao Pham: supervision, conceptualization, writing, review.

Data availability The data that support the findings of this study are available from the corresponding authors, upon reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Amani-Beni M, Zhang B, Xie G, Xu J (2018) Impact of urban park's tree, grass and waterbody on microclimate in hot summer days: a case study of Olympic Park in Beijing, China. Urban For Urban Green 32:1–6

Anielo C, Morgan K, Busbay A, Newland L (1995) Mapping micro urban heat island using Landsat TM and a GIS. Comput Geosci 21(8):965–969

Brans KI, Engelen J, Meester L (2018) Urban hot-tubs: Local ubanization has profound effects on average and extreme temperatures in ponds. Environ Sci Landsc Urban Plan. https://doi.org/10.1016/j.landurbplan.2018.03.013

Cao X, Onishi A, Imura H (2010) Quantifying the cool island intensity of urbanparks using ASTER and IKONOS data. Landsc Urban Plan 96:224–231

Cao X, Onishi A, Chen J, Imura H (2010b) Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. Landsc Urban Plan 96(4):224–231. https://doi.org/10.1016/j.landurbplan.2010.03.008

Chang C, Li M, Chang S (2007) A preliminary study on the local cool-island inten-sity of Taipei city parks. Landsc Urban Plan 80:386–395

Chen A, Yao XA, Sun R, Chen L (2014) Effect of urban green patterns on surface urban cool islands and its seasonal variations. Urban For Urban Green 13(4):646–654. https://doi.org/10.1016/j.ufug.2014.07.006

Coutts AM, Tapper NJ, Beringer J, Loughnan M, Demuzere M (2013) Watering our cities: the capacity for water sensitive urban design to support urban cooling and improve human thermal comfort in the Australian context. Prog Phys Geogr 37(1):2–28

Dousset B, Gourmelon F (2003) Satellite multi-sensor data analysis of urban surface temperatures and landcover. ISPRS J Photogramm Remote Sens 58(1–2):43–54

Du H, Song X, Jiang H, Kan Z, Wang Z, Cai Y (2016) Research on the cooling island effects of water body: a case study of Shanghai, China. Ecol Ind 67:31–38. https://doi.org/10.1016/j.ecolind.2016.02.040

ESRI (2014) ArcGIS desktop, release 10.1. Environmental Systems Research Institute, Redlands

Giannini MB, Belfiore OR, Parente C, Santamaria R, (2015) Land Surface Temperature from Landsat 5 TM images: comparison of different methods using airborne thermal data. J. Eng. Sci. Technol. ISSN 1791–2377. Google Scholar

Grinzato E, Bison PG, Marinetti S (2002) Monitoring of ancient buildings by the thermal method. J Cult Herit 3:21–29. https://doi.org/10.1016/S1296-2074(02)01159-7

Guha S, Govil H, Dey A, Gill N (2018) Analytical study of land surface temperature with NDVI and NDBI using Landsat 8 OLI and TIRS data in Florence and Naples city. Italy Eur J Remote Sens 51(1):667–678

Gupta N, Mathew A, Khandelwal S (2019) Analysis of cooling effect of water bodies on land surface temperature in nearby region: a case study of Ahmedabad and Chandigarh cities in India. Egypt J Remote Sens Space Sci 22:81–93. https://doi.org/10.1016/j.ejrs.2018.03.007

Hathway EA, Sharples S (2012) The interaction of rivers and urban form in mitigating the Urban Heat Island effect: a UK case study. Build Environ 58:14–22. https://doi.org/10.1016/j.buildenv.2012.06.013

IPCC (2007) Fourth assessment report. Cambridge, Retrieved from https://www.ipcc.ch/publications_and_data/ publications_and_data_reports.shtml

Ishii A, Iwamoto S, Katayama T, Hayashi T, Shiotsuki Y, Kitayama H, Nishida M (1991) A comparison of field surveys on the thermal environment in urban areas surroundings a large pond: when filled and when drained. Energy Build 16(3):965–971

Lee D, Oh K, Seo J (2016) An analysis of urban cooling island (UCI) effects by water spaces applying UCI indices. Int J Environ Sci Dev 7(11):810–815. https://doi.org/10.18178/ijesd.2016.7.11.886

Mai TTT, Lang LPC (2008) The ability to improve the microclimate of lakes and ponds in Hue city. Sci Educ J Univ Educ Hue Univ 02(06):26–34

Mai TTT, Do ND, Son NH, Lang LPC (2007) Declining function of the lake and pond system in the Thanh Noi, Hue City. Sci Educ J Univ Educ Hue Univ 03(07):40–56

Mathew A, Khan delwal S, Kau N (2017) Analysis of diurnal surface temperature variations for assessment of surface urban heat island effect over Indian cities. Energy Build 159:271–295

McGarigal K, Marks BJ (1995) FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure. USDA For. Serv. Gen. Tech. Rep. PNW-351, Corvallis.

Murakawa S, Sekine T, Narita K, Nishina D (1991) Study of the effects of a river on the thermal environment in an urban area. Energy Build 16(3):993–1001

National Aeronautics and Space Administration (NASA) (2016) LANDSAT Science data user's Handbook. NASA, Washington DC

O'Malleya C, Piroozfarbb PAE, Farrc ERP, Gatesb J (2014) An investigation into minimizing urban heat island (UHI) effects: a UK perspective. Energy Procedia 62(2014):72–80

Oke TR (1992) Boundary layer climates: Psychology Press.

Olah A (2012) The possibilities of decreasing the urban heat island. Appl Ecol Environ

Ridd MK (1995) Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. Int J Remote Sens 16:2165–2185. https://doi.org/10.1080/01431169508954549

Rinner C, Hussain M (2011) Toronto's urban heat island-exploring the relationship between land use and surface temperature. Remote Sens 3(6):1251–1265

Rinner C, Hussain M (2011) Toronto's urban heat island-exploring the relationship between land use and surface temperature. Remote Sens 3:1251–1265. https://doi.org/10.3390/rs3061251

Robitu M, Musy M, Inard C, Groleau D (2003) Thermal radiative modelling of water pond and its influences on microclimate. ICUC'5 Fifth International conference on urban climate. Lodz, Poland.

Rosenzweig C, Solecki W, Slosberg R (2007) Mitigating New York City's heat island with urban forestry, living roofs and light surfaces. New York State Energy Research and Development Authority, New York

Rouse JWRH, Haas JA, Schell DW, Deering (1974) Monitoring vegetation systems in the Great Plains with ERTS, Proc. ERTS-1 Symposium 3rd, Greenbelt, NASA, Washington DC.

Schwarz N, Schlink U, Franck U, Großmann K (2012) Relationship of land surface and air temperatures and its implications for quantifying urban heat island indicators-an application for the city of Leipzig (Germany). Ecol Ind 2012(18):693–704. https://doi.org/10.1016/j.ecolind.2012.01.001

Sobrino JA, Jimenez-Munoz JC, Paolini L (2004) Land surface temperature retrieval from Landsat TM 5. Remote Sens Environ 90:434

Spronken-Smith RA, Oke TR, Lowry WP (2000) Advection and the surface energy balance across an irrigated urban park. Int J Climatol 20(9):1033–1047

Steeneveld GJ, Koopmans S, Heusinkveld BG, Theeuwes NE (2014) Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. Landsc Urban Plan 121:92–96. https://doi.org/10.1016/j.landurbplan.2013.09.001

Streutker DR (2002) A remote sensing study of the urban heat island of Houston Texsas. Int J Remote Sens 23(13):2595–2608

Sun R, Chen L (2012) How can urban water bodies be designed for climate adaptation? Landsc Urban Plan 105(1–2):27–33. https://doi.org/10.1016/j.landurbplan.2011.11.018

Sun R, Chen A, Chen L, Lü Y (2012) Cooling effects of wetlands in an urban region: the case of Beijing. Ecol Ind 20:57–64

Syafii NI, Ichinose M, Wong NH, Kumakura E, Jusuf SK, Chigusa K (2016) Experimental study on the influence of urban water body on thermal environment at outdoor scale model. Procedia Eng 169:191–198. https://doi.org/10.1016/j.proeng.2016.10.023

Theeuwes NE, Solcerová A, Steeneveld GJ (2013) Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. J Geophys Res 118(16):8881–8896

Thua Thien Hue Department of Science and Technology (2004) Hydroclimate characteristics of Thua Thien Hue Hue province. Thuan Hoa Publishing House.

Valor E, Caselles V (1996) Mapping land surface emissivity from NDVI: application to European, African, and South American areas. Remote Sens Environ 57(3):167–184

Van TT, Lan H.n.T.i (2009) Thermal remote sensing method in studying urban surface temperature distribution. Vietnam J Earth Sci 31(2) 168-177

Vlassova L, Perez-Cabello F, Nieto H, Martín P, Riaño D, De La Riva J (2014) Assessment of methods for land surface temperature retrieval from Landsat-5 TM images applicable to multiscale treegrass ecosystem modeling. Remote Sens 6(5):4345–4368

Vu ND, Son NH (2008) Influence of hot and dry Westerly winds on drought in the north-central part. Proceedings of the 3rd national science conference on geography, Ha Noi, 16 December 2008. Publishing house of Scientific and Technical (pp 185–188)

Vu ND, Xuan NH (2007) The formation and impact of the South West Wind in Northern Central Vietnam, J Res Dev 4(63) (07):42–48

Wan Z, Dozier J (1989) 'Land-surface temperature measurement from space: physical principles and inverse modeling. IEEE Trans Geosci Remote Sens 27:268

Xu J, Wei Q, Huang X, Zhu X, Li G (2010) Evaluation of human thermal comfort near urban waterbody during summer. Build Environ 45(4):1072–1080

Xu X, Liu S, Sun S, Zhang W, Liu Y, Lao Z, Zhu J (2019) Evaluation of energy saving potential of an urban green space and its water bodies. Energy Build 188–189:58–70

Yang SJ, Ran GP, Zhang W, Wang ZH (2020) The cooling effect of an urban lake landscape on the urban heat island: a case study in Jinan, China. Appl Ecol Environ Res 18(2):2197–2211

Zeng Z, Zhou X, Li L (2017) The impact of water on microclimate in Lingnan area. Procedia Eng 205:2034–2040. https://doi.org/10.1016/j.proeng.2017.10.082

Zhang Q, Wen Y, Wu Z, Chen Y (2018) Seasonal variations of the cooling effect of water landscape in high-density urban built-up area: a case study of the center urban district of Guangzhou. Ecol. Environ. Sci. 2018, 27, 1323–1334. [Google Scholar] [CrossRef]