An Analysis of Urban Cooling Island (UCI) Effects by Water Spaces Applying UCI Indices

D. Lee, K. Oh, and J. Seo

***Abstract*—An urban cooling island (UCI) involves an area that has a lower temperature compared with its surroundings. The UCI effect is created from shading effects by urban trees or evapotranspiration effects by green space and water spaces.**

Water spaces such as stream and lakes in particular play an important role in creating urban cool islands because water spaces have higher evapotranspiration rates than green spaces.

The objective of this study is to present planning and management information on water spaces to mitigate urban heat islands (UHI), by analyzing their effects on air temperature due to water space characteristics.

To achieve this, the UCI effects of urban water spaces were analyzed by applying UCI indices such as UCI scale, temperature difference, and UCI intensity. Next, considerations for composing and managing water spaces to mitigate urban heat islands were identified through analysis of the relationship between UCI indices and characteristics of water spaces such as area, perimeter, shape, and width.

The results show that larger water spaces are more useful in reducing urban heat. In addition, more complex water spaces were found to be more efficient than simple ones. The results of this study can be applied to analyze priority areas for the creation or restoration of new water spaces. It can be also utilized as a planning guideline for designing water spaces.

***Index Terms*—Air temperature, GIS (geographic information systems), temperature reduction, UCI (urban cooling island), urban water spaces.**

I. Introduction

With rapid urbanization and population growth, urban heat island (UHI) effects are occurring frequently due to increases of impervious areas and decreases of green spaces and water spaces. Because this phenomenon can bring about harmful effects to humans that include exhaustion symptoms and even death, international efforts to mitigate UHI are being rendered in the form of stream restoration and green infrastructure expansion, as examples. Green spaces and streams in particular, can provide comfortable environments for citizens while also serving as means to control urban temperature [1]. Contrary to the urban heat island, areas that have low temperatures compared with their surroundings are known as urban cooling islands (UCI) [2]. The UCI effect is created by shading effects of urban trees or evapotranspiration effects by green space and water space [3].

In UCI, water spaces such as streams and lakes are relatively more efficient than green spaces due to the higher rate of evapotranspiration. Water spaces thus function as cooling islands in urban areas due to the temperature difference of their nearby environment [4]-[6].

The aim of this study is to present planning and management information on water spaces to mitigate UHI, by analyzing the effects on air temperature due to the characteristics of water spaces. The study area is administrative units of the Seoul Metropolitan Area (SMA) in Korea, whereby over half of them consist of built up areas and their total area is 3,514km^2. Temperature data were extracted from the most suitable Lands at images to analyze temperatures in the summer period (11:00 a.m. on June 1, 2009).

II. The Study Methods

Fig. 1 shows the study flow. First, land surface temperature was analyzed using Lands at TM images, and an air temperature correction formula was identified through regression analysis between AWS (Automatic Weather System) temperature and land surface temperature. The analysis unit is a 30m×30m grid considering Lands at image resolution. Second, water spaces were selected using land cover and digital maps. Third, UCI indices (UCI scale, temperature difference, UCI intensity) of water spaces were calculated using GIS spatial analysis, and dependent variables (water spaces characteristics, surrounding areas characteristics) were prepared. Finally, design and management recommendations for UCI were suggested based on the OLS regression model (Fig. 1).

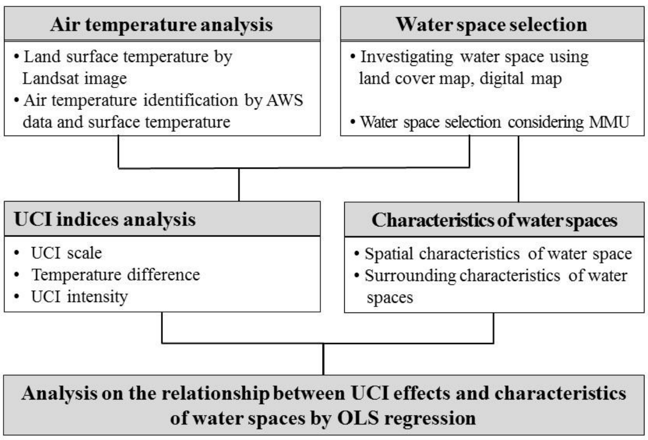

Fig. 1. Study flow.

A. Air Temperature Analysis

Land surface temperature data were extracted from Lands at images taken at 11:00 a.m. on June 1, 2009. The land

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surface temperature was calculated using a conversion formula developed by NASA. Because the surface temperature is different from the actual experienced air temperature by humans, air temperature was prepared using regression analysis between AWS temperature and land surface temperature. Among the regression models, the model that had the highest R^2 was selected for the air temperature correction formula.

B. Definition of Water Spaces in This Study

Water spaces in this study are defined as natural and artificial spaces that have significant accumulations of water. The green spaces that abut with water space were also included in the category of water space. Otherwise, artificial areas that adjoin water space were not included. Moreover, bodies of moving water such as rivers and/or small river spaces were classified as streams, and areas for storing water surrounded by land such as ponds or reservoirs were classified as lakes. The water spaces were extracted from land cover, stream, and reservoir maps by the Korean Ministry of Environment.

C. UCI Indices

Considering the Korea situation, UCI indices in this study were redefined based on Sun *et al*. (2012) [7]. The redefined indices in this study are UCI scale, temperature difference, and UCI intensity. UCI scale is the distance from the boundary of water spaces to a buffer zone which has the maximum temperature on first inflection point. Temperature difference is the difference value between the average temperature of water spaces and the average temperature on the UCI scale. UCI intensity is the water temperature difference per distance unit, therefore gradient increases mean that the temperature difference value increases. Meanwhile, UCI scale in this study was determined as the averaged same distance in order to compare UCI intensity under equal conditions. Therefore, the distance for calculating UCI intensity was investigated using the UCI scale mean value of twenty one streams and ninety five lakes, and the distance is defined as mean UCI scale (Fig. 2).

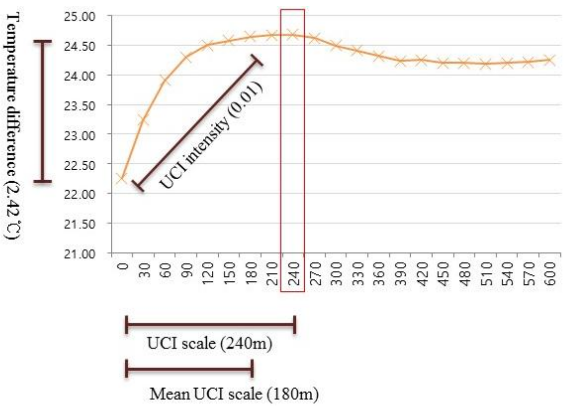


Fig. 2. The definition of UCI indices.

To identify UCI indices, twenty buffers around each water space were created at 30m intervals. The average temperature of each buffer zone was estimated, and the buffer zone had a maximum average temperature selected as the UCI scale. Furthermore, temperature differences were estimated using the difference values between the average temperature on the UCI scale and the average temperature of the water spaces. Finally, the mean UCI scale for identifying UCI intensity was calculated. The mean UCI scale of streams was calculated as 222.86m, while the mean UCI scale of lakes turned out to be 189.63m. Because the buffer interval is 30m, the UCI scale was determined as 240m, of which 180m was close to the mean value.

D. Water Spaces and Surrounding Area Characteristics

Two kinds of characteristics of water spaces were investigated. The first involves structural indices of water spaces, and the other is for the surrounding characteristics. The average temperature of water spaces, area, perimeter, and shape were determined as structural characteristics. In addition, the average width was included in the case of the stream analysis. On the other hand, impervious surface ratio, building stories, coverage ratio, and floor area ratio were selected as surrounding characteristics indices. The average temperature was calculated using Lands at images. The shapes of water spaces were estimated using shape index (SI). SI means that in case a perfect circle is 1, a square is 1.13. That is, the more complex the value, the higher the increase to infinity [8].

$$SI = \frac{Peri}{2\sqrt{Area \times \pi}} \tag{1}$$

Peri = Perimeter of water space,
Area = area of water space

The surrounding characteristics were investigated within the UCI scale except for water space (Fig. 3). The impervious surface ratios were calculated using land cover maps (2009) from the Korean Ministry of Environment. Other indices such as building stories, coverage ratio, and floor area ratio were investigated using GIS census data of the study area from the Korean Ministry of Land, Infrastructure and Transport.

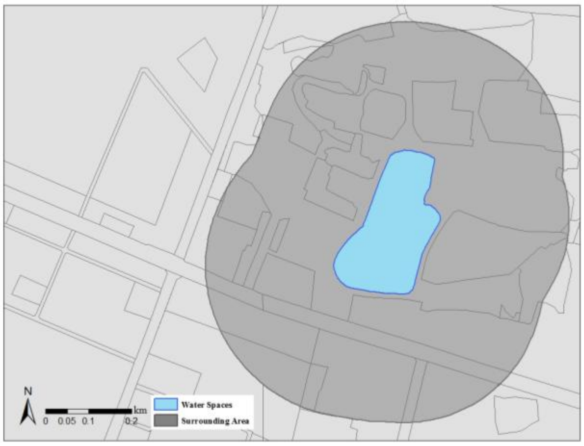


Fig. 3. The definition of surrounding area.

III. RESULTS

A. Air Temperature of the Study Area

To investigate the land surface temperature, the Quadratic Regression model was applied as the conversion formula. Equation 2 shows the regression analysis results between AWS temperature and land surface temperature by Lands at.

The p-value is 0.000 and t of the constant is 13.143.

$$Y = 12.174 + 0.371X, R^2 = 0.681 \quad (2)$$

Y = Air temperature

X = land surface temperature

Fig. 4 presents the air temperature of the study area on June, 1, 2009 by equation 2. The maximum and minimum gap of the air temperature was approximately 16°C, and the temperature difference between urban area and suburbs was determined to be 5°C.

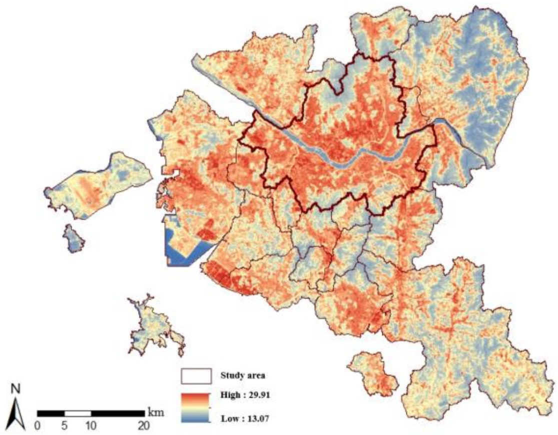


Fig. 4. Air temperature in the study area (June, 1, 2009).

B. Water Spaces in the Study Area

The total area of water spaces is about 103.9km^2 and it accounted for 2.95% of study area. Among them, the average width of the streams was less than 60m, while for lakes, the average areas less than 3,600m^2 were excluded considering MMU (Minimum Mapping Unit). As a result, 21 streams and 84 lakes were selected for analysis of the water spaces, and the total area was about 75.9km^2, accounting for 75.9% of the total water space (Fig. 5).

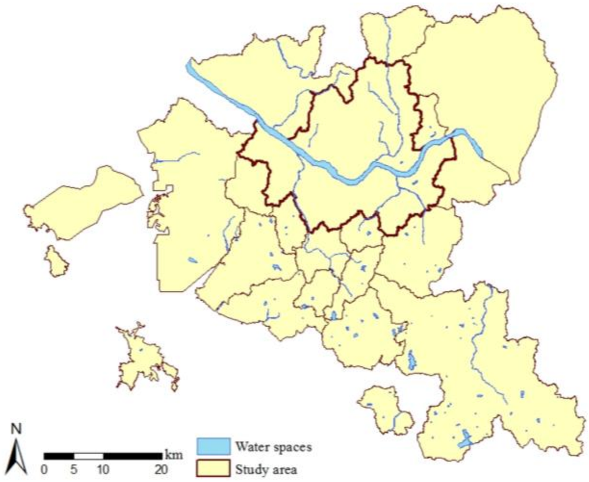


Fig. 5. Water spaces for analysis.

C. UCI Indices

The UCI scale of streams varied from 150m to 390m, with an average value of 222.86m. The temperature differences ranged from 0.07°C to 2.77°C, with the average value of 0.88°C. The UCI intensity of the streams ranged from ranged from 0.07°C to 2.77°C, with the average value of 0.001°C /m to 0.011°C /m with 0.003°C /m in Table I and Table II.

The UCI scale of the lakes varied from 60m to 450m, with an average value of 188.53m. The temperature differences ranged from 0.07°C to 2.76°C, with an average value of 1.11°C. The UCI intensity of lakes ranged from -0.001°C /m to 0.015°C /m with 0.005°C /m in Table I and Table II. Because the differences in values between temperature on the mean UCI scale and the average temperature of the water spaces were negative, the minimum UCI intensity had a negative value.

These results were identified when the UCI scale was less than 180m, and were determined to be due to the existence of heat reduction elements such as green spaces and water spaces in the 180m buffer zone, or artificial composition of water space causing urban heat islands.

TABLE I: DESCRIPTIVE STATISTICS OF UCI INDICES

	(a) Streams			(b) Lakes		
	UCI scale (m)	Temperature difference (°C)	UCI intensity (°C/m)	UCI scale (m)	Temperature difference (°C)	UCI intensity (°C/m)
Max.	390.00	2.77	0.011	450.00	2.76	0.015
Min.	150.00	0.07	0.001	60.00	0.07	-0.001
Avg.	222.86	0.88	0.003	188.53	1.11	0.005
SD	60	0.73	0.003	97.52	0.72	0.004

D. Water Spaces and Surrounding Area Characteristics

Table III and Table IV show the descriptive statistics of water spaces and the surrounding characteristics. The Standard Deviation of streams on the average temperature is greater than for lakes. This means that the performance of the streams had a wide range, more so than the lakes. Meanwhile, the area, shape index, perimeter, and width are indices that correlate with streams and the average temperature is greater than for lakes. This means that the performance of the streams had wide landscape design descriptors. It turned out that the streams were more complicated than the lakes from the structural characteristics indices. Otherwise, the surrounding characteristics such as impervious surface ratio, building stories, coverage ratio, and floor area ratio are expected indices that cause increasing temperature differences and UCI intensity. The results show that urbanization has taken place around the streams rather than the lakes.

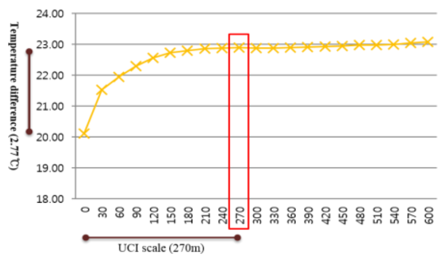
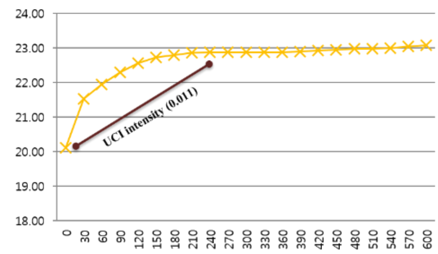
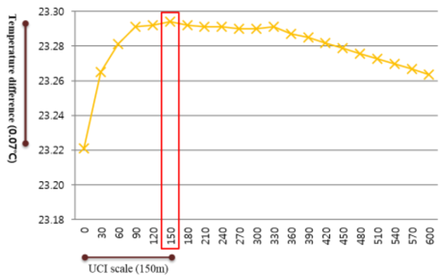
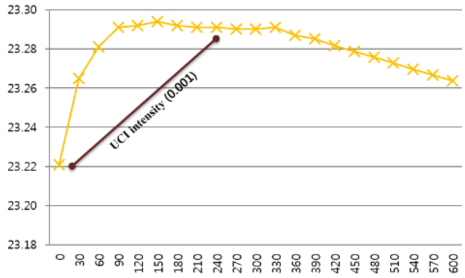
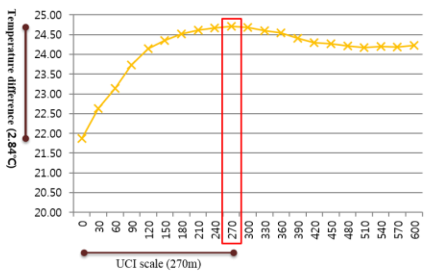
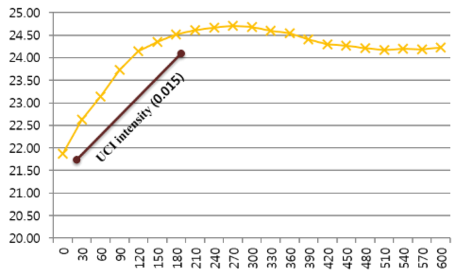
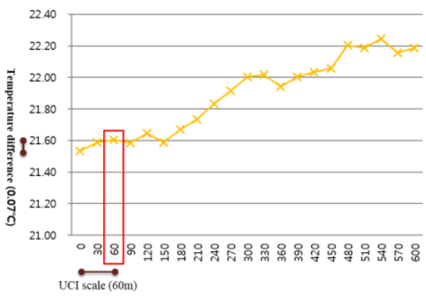
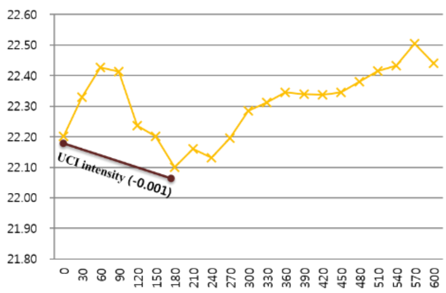
E. Relationship between UCI Indices and Water Spaces Characteristics

1) Streams

Table V shows the regression analysis results regarding the temperature differences and UCI intensity on the streams. Some dependent variables show that low standardized coefficients were excluded due to multicollinearity. The R^2 of the temperature difference model is 0.823 and the F-value is

16.524. The results show that the lower the average temperature, the more shape index and temperature differences increase. Otherwise, for the perimeter, the impervious surface ratio and coverage ratio increased, while the temperature difference also increased. Furthermore, the average temperature had the highest impacts among the dependent variables by standardized coefficients. In addition, perimeter, impervious surface ratio, and shape index also turned out to be major variables that were highly influential.

TABLE II: ANALYSIS RESULTS OF UCI INDICES

-		Temperature difference	UCI intensity
(a) Stream	MAX	22.89℃ - 20.12℃ = 2.77℃ 	(22.88℃ – 20.12℃) / 240m = 0.011℃/m 
	MIN	23.29℃ - 23.22℃ = 0.07℃ 	(23.29℃ - 23.22℃) / 240m = 0.001℃/m 
(b) Lake	MAX	24.34℃ - 21.58℃ = 2.76℃ 	(24.18℃ – 21.58℃) / 180m = 0.014℃/m 
	MIN	21.60℃ - 21.53℃ = 0.07℃ 	(22.10℃ – 22.20℃) / 180m = -0.001℃/m 

Meanwhile, the R^2 of the UCI intensity model was 0.861 and the *F*-value was 21.576. The analysis results obtained a similarity with the temperature difference model. However, the influence of the average temperature and impervious surface ratio increased 1.5 times. This means that the UHI efficiency increased in the impervious surface area.

2) Lakes

Table 6 shows the regression analysis results regarding the temperature difference and UCI intensity on the streams. Some dependent variables that had low standardized coefficients were excluded due to multicollinearity. The R^2 of the temperature difference model was 0.6 and the F-value was 21.108. The results show that the lower the average temperature of water space, the more the temperature difference increases. Otherwise, for the shape index, the more impervious surface ratio increased, the more temperature difference increased. Furthermore, the average temperature had the highest impacts among the dependent variables by standardized coefficients. Also, the impervious surface ratio turned out to be a major variable that was highly influential.

TABLE III: CHARACTERISTICS OF THE STREAMS

-	Streams characteristics indices					Surrounding area characteristics indices			
	Average temperature (°C)	Area (km^2)	Shape index	Perimeter (km)	Width (km)	Impervious area ratio (%)	Building stories (Stories)	Coverage ratio (%)	Floor area ratio (%)
Max.	24.35	53.45	16.09	163.46	0.65	89.70	4.98	40.00	82.92
Min.	19.65	0.09	3.04	4.23	0.06	26.87	1.31	1.40	1.83
Avg.	22.43	3.60	8.15	32.43	0.11	55.99	2.96	11.04	30.38
SD	1.13	11.53	3.56	33.93	0.14	17.58	1.10	10.63	22.55

TABLE IV: CHARACTERISTICS OF THE LAKES

-	Streams characteristics indices					Surrounding area characteristics indices			
	Average temperature (°C)	Area (km^2)	Shape index	Perimeter (km)	Width (km)	Impervious area ratio (%)	Building stories (Stories)	Coverage ratio (%)	Floor area ratio (%)
Max.	24.32	2.010	2.67	8.76	92.53	26.40	21.46	78.99	82.92
Min.	20.45	0.005	1.05	0.27	0.00	0.00	0.00	0.00	1.83
Avg.	21.57	0.121	1.32	1.30	23.32	1.46	2.47	3.34	30.38
SD	0.77	0.299	0.26	1.48	20.50	2.73	3.49	10.45	22.55

TABLE V: REGRESSION ANALYSIS RESULTS OF TEMPERATURE DIFFERENCE AND UCI INTENSITY (STREAMS)

Model		Unstandardized coefficients	Standardized coefficients	*p*-Value	VIF
Temperature difference	Constant value	7.337		0.001	
	Average temperature (℃)	-0.293	-0.511**	0.003	2.233
	Shape index	-0.061	-0.337**	0.014	1.638
	Perimeter (km)	0.009	0.449**	0.008	2.359
	Impervious surface ratio (%)	0.013	0.355*	0.091	4.320
	Building stories	-0.072	-0.122	0.325	1.625
	Coverage ratio (%)	0.006	0.100	0.595	3.834
UCI Intensity	Constant value	0.044		0.000	
	Average temperature (℃)	-0.002	-0.820**	0.000	4.359
	Shape index	-0.001	-0.152*	0.099	1.827
	Perimeter (km)	2.193E-005	0.284*	0.053	2.587
	Impervious surface ratio (%)	6.621E-005	0.598*	0.031	8.874
	Building stories	-1.286E-005	-0.001	0.995	1.104
	Coverage ratio (%)	1.614E-005	0.137	0.590	8.872

** p<0.05, * p<0.1

TABLE VI: REGRESSION ANALYSIS RESULTS OF TEMPERATURE DIFFERENCE AND UCI INTENSITY (LAKES)

Model		Unstandardized coefficients	Standardized coefficients	*p*-Value	VIF
Temperature difference	Constant value	7.831		0.000	
	Average temperature (℃)	-0.361	-0.387**	0.000	1.407
	Area (km^2)	0.244	0.101*	0.100	1.477
	Shape index	0.391	0.141*	0.050	1.276
	Impervious surface ratio (%)	0.019	0.539**	0.000	1.836
	Building stories	0.025	0.095	0.185	1.189
	Coverage ratio	0.011	0.053	0.656	3.308
	Floor area ratio	0.002	0.029	0.790	2.731
UCI Intensity	Constant value	0.053		0.000	
	Average temperature (℃)	-0.002	-0.497**	0.000	1.600
	Area (km^2)	0.002	0.136*	0.092	1.400
	Shape index	0.002	0.129*	0.059	1.361
	Impervious surface ratio (%)	6.218E-005	0.366**	0.002	2.115
	Building stories	0.001	0.164*	0.063	1.247
	Coverage ratio (%)	7.351E-005	0.110	0.492	4.226
	Floor area ratio (%)	6.698E-005	0.040	0.789	3.617

** p<0.05, * p<0.1

Meanwhile, the R^2 of the UCI intensity model was 0.558 and the *F*-value was 11.196. The analysis results obtained were similar with the temperature difference model. However the influence of the average temperature and impervious surface ratio decreased about 1.5 times. This means that the UHI efficiency could be increased in the impervious surface area.

IV. Conclusions

This study analyzed the relationship between spatial characteristics of water spaces and UCI indices.

In the case of streams, increasing stream length with a simplified shape is more preferable for more temperature difference and UCI intensity. As presented equation 1, in order to secure length with a simplified shape, more area is required. Therefore, if stream area is increased by the presence of water space or green space, the effect of UCI could increase more. If securing areas is impossible, length should be secured preferentially because length is a more influential element for UCI rather than shape.

Meanwhile, the size of area is an important element in lakes for explaining reducing air temperature. In addition, in contrast to streams, a more complex shape is preferable for UCI. Therefore, lakes should be designed or managed more natural-friendly than by artificial methods.

In addition, the urban heat island mitigation effect in particular was found to increase in impervious areas in streams as well as in lakes. This means that streams and lakes near high impervious areas should be managed in advance. The analysis on urban heat island mitigation effects using UHI indices affords useful information as follows: Because temperature difference and UCI scale could be analyzed at the same time using UCI indices, more concrete understanding about the performance of urban heat island mitigation effects is possibly made easier. For example, the results by UCI indices can present priority areas for water spaces creation or restoration. If the water space constructed in the areas exclude UCI scale or has low UCI intensity, the UCI could increase more. Also, the results regarding the relationship of the spatial characteristics of water spaces and UCI indices can be applied as a design guide to determine water space forms.

If more air temperature information can be prepared in time series for entire urban areas, more concrete understanding about UCI indices is possible. Lastly, once water space is classified more systematically through more sample acquisition, the relationship between UCI effects and spatial characteristics can be analyzed more concretely.

Acknowledgment

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