STORMWATER MANAGEMENT BASED ON EVAPOTRANSPIRATION AS A TOOL TO MITIGATE URBAN HEAT ISLAND (UHI) EFFECT

by

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(Under the Direction of Ron Sawhill)

ABSTRACT

Many urban dwellers throughout the world are suffering from health problems and thermal discomfort resulting from the Urban Heat Island (UHI) effect. One possible UHI mitigation strategy is Evaporative Cooling Stormwater Management (ECSM), reducing temperature by improved stormwater measures to regulate evapotranspiration. This research studies mechanisms and characters of ECSM to understand how to maximize its cooling effect. The cooling intensity depends on a multitude of factors including environmental conditions and climate. To further understand, we examine the spatial correlation between temperature and ECSM practices in Atlanta, GA. Then simulations by Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) model is conducted in five practice-based scenarios to detect which ECSM practice contributes most in temperature reduction. Application to urban green space design is discussed.

KEYWORDS: Urban Heat Island, stormwater, evapotranspiration, Atlanta, green space

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The Urban Heat Island (UHI) effect has become a global problem, increasingly damaging living environments in urban areas worldwide. The UHI effect is caused by differences between urban and rural landscapes and is mainly a night-time phenomenon (Virk et al. 2015). It has become one of the most prominent climate-change challenges that societies face (Hoeven and Wandl, 2015). As cities are the most distinctly anthropogenic and possibly the most consequential ecosystems on Earth, their form, function, and management directly affect their inhabitants and indirectly effect other ecosystems via consumption, waste, and pollution (Schatz and Kucharik 2014). What is more, as of 2010, city dwellers constituted 50% of the population worldwide and 80% of the population in North America, and, by 2030, these percentages are predicted to reach 70% worldwide and 87% in North America (Cohen 2006; WHO 2010). Given this, the UHI effect has become an issue critical to the future of humankind.

To address the increasingly intense effects of UHI, various measures have been studied, including using high albedo materials, planting more trees, and extending permeable surfaces (e.g. Taha, 1997; Norton et al., 2014; Li, Harvey and Ge, 2014; Tan et al., 2015). Another potential method is modifying evapotranspiration to mitigate the thermal environment, as evapotranspiration is a fundamental controller of urban climates. This method is supported by the urban energy balance, which can be expressed as:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A (Wm^{-2})$$

where $Q^*$ refers to the net all-wave radiation, $Q_F$ is the anthropogenic heat flux, $Q_H$ is the sensible heat flux, $Q_E$ is the latent heat flux, $\Delta Q_S$ is the net change in storage heat flux, and $\Delta Q_A$ is the net change in horizontal advective heat flux (Grimmond et al., 2010). In this equation, net all-wave radiation ($Q^*$) and anthropogenic heat flux, which are determined by the climatic background and human activities, set the energy bounds for the other fluxes (Grimmond and Oke, 2002). In addition, latent heat flux ($Q_E$) is associated with the process of evapotranspiration, and sensible heat flux ($Q_H$) is related to the change in temperature. Hence, when evapotranspiration increases under certain conditions of net all-wave radiation and anthropogenic heat flux, it is possible to reduce the other heat fluxes on the right-hand side of the equation, especially the sensible heat flux, and, subsequently, the temperature. However, if evapotranspiration changes in the wrong direction, it may create discomfort as well.

Based on the above, many cities have increased the amount of their internal area covered in vegetation in order to increase evapotranspiration. Most studies investigating the air temperature within parks broadly support the conclusion that green spaces are generally cooler than non-green and extend this cooling effect beyond the park boundaries (Bowler, 2010; Chen and Wong, 2006; Upmanis et al., 1998; Jauregui, 1991; Shashua-Bar and Hoffman, 2000). However, no studies have considered the water budget needed to ensure that vegetation systems have adequate water to support evapotranspiration's cooling effect. Irrigating parks in hotter regions can cause water shortages (Gober et al., 2009). In addition, Brown et al. (2015) pointed out that because turf areas have higher evapotranspiration rates, there is higher demand for water in landscapes dominated by turf grass than in those consisting of desert-adapted trees and shrubs.

Meanwhile, another potential way to provide water for evapotranspiration is stormwater. According to Mitchell et al. (2008), the urban water balance is expressed by:

$$P + I = E + D + \Delta S (mmh^{-1})$$

where $P$ is the precipitation, $I$ is the piped water supply, $E$ is the evapotranspiration, $D$ is the drainage, and $\Delta S$ is the net change of water storage in the natural (soil and groundwater aquifers) and built environments in the urban system. In this equation, precipitation ($P$) is determined by the climate conditions of a city and cannot be controlled by humans. Thus, the objective of increasing the water available for evapotranspiration ($E$) can be achieved in two ways. One is to increase the piped water supply ($I$) through the process of irrigation. The other is to collect water instead of drainage ($D$) and use that collected water to support evapotranspiration ($E$). Usually, drainage consists of two major factors: stormwater and wastewater (Mitchell et al. 2008), but considering the health of humans, plants, and other life, wastewater is not a desirable source of evapotranspiration. Therefore, collecting stormwater by methods other than draining is an ideal approach to enhance evapotranspiration. However, impervious urban surfaces prevent infiltration, and runoff is rapidly transported from urban environments through the conventional stormwater network, which does not enable retention or harvesting. This produces a deficit of water in urban areas, resulting in drying cities and then in heated thermal environments (Coutts et al., 2012).

Therefore, to manage stormwater in green sites or public urban spaces, it is necessary to consider innovative measures that not only satisfy the usual object of reducing runoff, but also provide water to support evapotranspiration by decreasing drainage.

### 1.2 Research Questions

This study focused on how innovative stormwater management could alleviate the UHI effect through evapotranspiration. Accordingly, the first research question was: in hot weather, how does evapotranspiration influence the urban thermal environment? The answer to this question clarified the detailed mechanism of evapotranspiration's cooling effect, including the cooling process, restrictions, and related factors affecting the magnitude of the cooling effect. Then, the second question was: based on the mechanism illustrated in the first question, how can an innovative stormwater-management system be designed to maximize evapotranspiration's cooling effect? The answer provided valuable suggestions in practice. However, the cooling effect depends on multiple factors. To further examine the effect of innovative stormwater management on the UHI effect in specific practice, we proposed a third question: in a city like Atlanta, GA, how do these types of stormwater-management practices work? A fourth question was: how can the design of innovative stormwater management be optimized in the future in Atlanta to maximize evapotranspiration's cooling effect? By following these questions, we acquired a deep, comprehensive understanding, in both theory and practice, of the relationship between innovative stormwater management and mitigation of the UHI effect.

### 1.3 Research Purpose

Generally, the objective of this research was to investigate, the cooling effect on the urban thermal environment created by innovative stormwater management in public green spaces. The study's specific purpose was to identify the types of innovative stormwater management that most contribute to Atlanta in terms of reducing urban temperatures by evapotranspiration, which could provide data to increase the city's thermal comfort in the future. In addition, the study's ultimate goal was to generate suggestions useful to landscape architects designing optimized, innovative stormwater management that can maximally mitigate the UHI effect in the given circumstances.

## 1.4 Research Strategies

### 1.4.1 Overall Strategies

Figure 1.1 shows the research structure of this thesis. The research began with a review of scholarly literature pertaining to urban climate and evapotranspiration, with an emphasis on stormwater-management practices that have a cooling effect through evapotranspiration in the open, green spaces of urban areas. A significant amount of information was derived from this literature review, including (1) the cooling mechanism of evapotranspiration; (2) the elements that affect the magnitude of the cooling effect; (3) the types and processes of innovative stormwater-management methods used to reduce temperatures via controlled evapotranspiration, along with comparative analysis of their characteristics and potential effects on urban climate. This type of stormwater management is defined as Evaporative Cooling Stormwater Management (ECSM). And then, a comparative analysis among the ECSM practices is conducted, so as to identify their pro and con in improving thermal comfort.

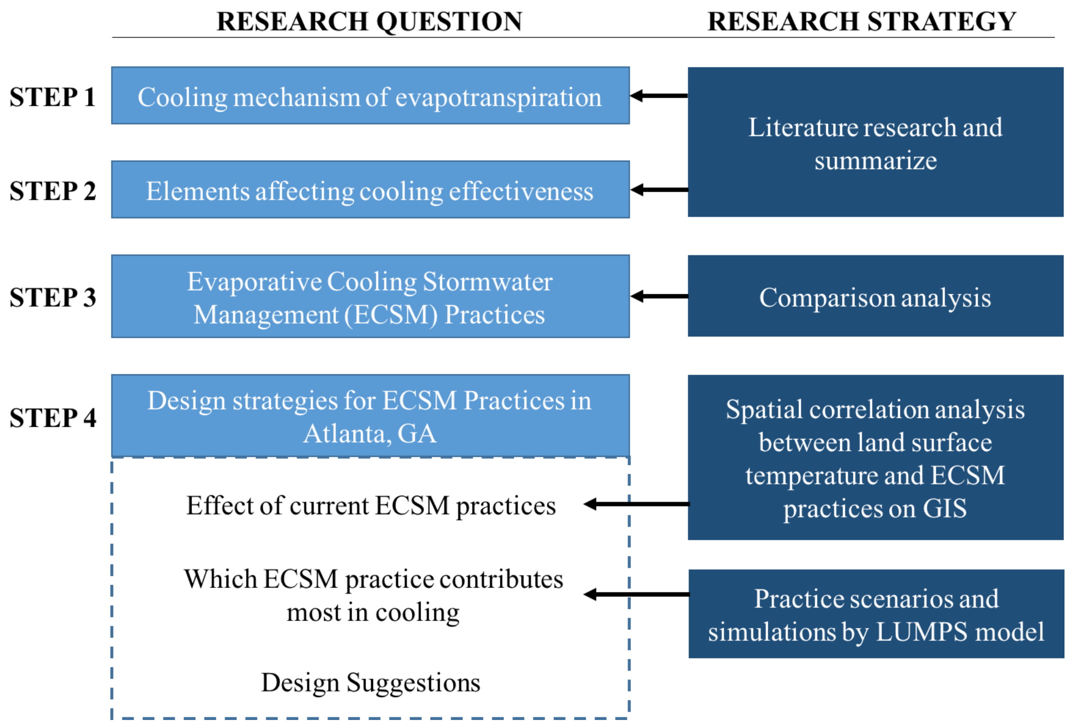



Fig. 1.1. Research Structure.

However, all the analysis above is based on theories. To learn how to apply ECSM practices to maximize the cooling effect produced by evapotranspiration in a specific city, we conducted research in Atlanta, which has both an obvious UHI effect in the metropolitan area during the heat of summer (Stone and Norman, 2006) and data that is accessible to us. Therefore, the second major process was a GIS-based quantitative analysis that aimed to examine the effects of current ECSM practices in Atlanta through a spatial correlation analysis of land surface temperature (LST) and ECSM practices in city-level scale. LST is often used to estimate the intensity of surface UHI (Tomlinson, 2011). Followed the study conducted by Yang et al. (2013), the landsat data is a precious source providing spatial temperature data. According to their research, estimating LST requires data on land use and land cover (LULC) and corresponding infrared data. The LULC data (2011 edition; 30-m resolution) was from the National Land Cover Dataset (NLCD), and infrared data was assessed from high spatial-resolution (60-m) satellite images provided by the Landsat Enhanced Thematic Mapper (ETM+) sensor on Landsat 7 satellite. Satellite images acquired in summer (June, July, and August) were used to calculate the LST because summer is typically the hottest time of year in Atlanta, according to data from the University of Georgia's College of Agricultural and Environmental Sciences. After integrating the LULC and infrared databases, the LST is estimated using the methodology developed by Stathopoulou and Cartalis (2007). A temperature-distribution map of Atlanta was produced by reclassifying the LST in GIS. In addition, the cover area of ECSM practices in public open spaces was derived by GIS, using the LULC data (30-m resolution) from NLCD. Spatial correlation analysis was conducted by GIS using both the temperature-distribution map and those showing each typical, innovative stormwater-management method. If the results showed that the two types of maps were negatively correlated in spatial distribution, it proved the cooling effect on Atlanta's climate of current innovative stormwater-management practices. In addition, the GIS maps, which demonstrated the differing magnitudes of the cooling effect in Atlanta from a spatial perspective, showed differences among areas that were caused by the various types of innovative stormwater management.

The final but most important process was further quantitative analysis that conducted simulations using the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) model (explained further in section 1.4.2), following the research of Grimmond and Oke (2002). The purpose of these simulations was to identify which types of ECSM practices most contributed to mitigating the UHI effect in Atlanta in neighborhood-level scale. The LUMPS model is used to simulate the consequences of hourly temperature and evapotranspiration from input that comprises the proportions of various land surfaces (impervious surface, tree canopies, grassland, open water, and wetland) and local climatic conditions (air temperature, humidity, wind speed, air pressure, and solar radiation) (Grimmond and Oke, 2002). Simulations were conducted for five practice-based scenarios and three watersheds in and near Atlanta's urban core, since the UHI effect is most intense there, according to the study' first round of analysis. The five scenarios addressed five types of innovative stormwater-management practices: ecoroof, non-canopy green park, trees, permeable pavement, and bioretention facility, all of which were derived from the literature review. The three watersheds, defined by HUC-12 (Hydrologic Unit Code), were selected as representing the three types of watersheds in Atlanta's urban area (commercial, low-green residential, and high-green residential). Selection was based on data from the National Hydrography Dataset (NHD) of the U.S. Geological Survey (USGS), building information from the Census of Population and Housing (U.S. Census Bureau), and LULC data (30-m resolution) from the NLCD. The commercial watershed was chosen because of its high-density buildings, many impervious surfaces, and sparse vegetation. The low-green residential watershed was chosen because of its sparse vegetative cover and low-to-medium building density. The high-green residential watershed was chosen because of its high proportion of vegetation cover and low or medium building density. We expected that the results of simulations in these three watersheds would vary, as the surrounding context influences the urban climate (Ramamurthy and Bou-Zeid, 2014; Chang and Li, 2014; Middel et al., 2012; Stone and Norman, 2006), meaning that the best practices for innovative stormwater management in watersheds that have differing characteristics might also differ. However, the results of this process could provide data valuable to improving Atlanta's thermal environment.

### 1.4.2 LUMPS Model

As illustrated by Grimmond and Oke (2002) in the study of turbulent heat fluxes in urban areas, the LUMPS model can be used to estimate the surface heat energy. It separates the net all-wave radiation into three parts: sensible heat flux, latent heat flux and the change in storage heat flux, with the inputs of percentages of land covers and climate data. With the estimation of latent heat and sensible heat, the evapotranspiration rate and air temperature heating rate can be calculated. The LUMPS model has been proved mature and accurate enough to predict changes in temperature and evapotranspiration (Grimmond and Oke, 2000). Gober et al. (2010) used this model to simulate the amount of required water in manipulating UHI by watered landscapes. The simulation results of LUMPS model helped them achieve a comprehensive understanding of how to apply watered landscapes to acquire more cooling effect with less water using. The calculation process of LUMPS model mainly includes five steps:

(1) Acquire change in storage heat flux ($\Delta Qs, W * m^{-2}$) with entering observed solar radiation ($Q*$) by the equation as below:

$$\Delta Q_S = \sum_{i=1}^{n} (f_i a_{1i}) Q* + \sum_{i=1}^{n} (f_i a_{2i}) \left( \frac{\partial Q*}{\partial t} \right) + \sum_{i=1}^{n} (f_i a_{3i}).$$

In this equation, f represents the fractions of land covers; a1, a2, a3 are corresponding coefficients based on types of land cover and they can be achieved in the research conducted by Grimmond and Oke (2002).

(2) Calculate sensible heat ($Q_H, W * m^{-2}$) with solar radiation ($Q*$) and changed storage heat flux ($\Delta Qs$) acquired in step (1) by the equation as below:

$$Q_H = \frac{(1 - \alpha) + (\gamma/s)}{1 + (\gamma/s)} (Q* - \Delta Q_S) - \beta$$

where s is the slope of the saturation vapor pressure curve (explained in the section of Definitions) and $\gamma$ is the psychrometric “constant” (explained in the section of Definitions); $\alpha$ and $\beta$ are parameters that can be acquired in the study of Grimmond and Oke (2002).

(3) Calculate latent heat ($Q_E, W * m^{-2}$) with solar radiation ($Q*$) and changed storage heat flux ($\Delta Qs$) acquired in step (1) by the equation as below:

$$Q_E = \frac{\alpha}{1 + (\gamma/s)}(Q* - \Delta Q_S) + \beta,$$

where s, $\gamma$, $\alpha$ and $\beta$ are same with step (2).

(4) Convert the sensible heat ($Q_H, W * m^{-2}$) to temperature heating rate ($\Delta T$, ℃ $* s^{-1} * m^{-2}$) based on the heating process of air by the equation as below:

$$\Delta T = \frac{Q_H}{c_p * \rho * q * \Delta t}$$

where $c_p$ (1.006 kJ/kg*°C) is the specific heat of air; $\rho$ (1.202 kg/m$^3$) is the density of air; q (m$^3$/s) is the air volume flow; $\Delta t$ $(s)$ is the change in time (The Engineering Toolbox).

(5) Convert latent heat ($Q_E, W * m^{-2}$) to evapotranspiration rate (E, mm/h) by the following equation:

$$E = \frac{Q_E}{L_v * \rho_W}$$

where $L_v$ (2260 kJ/kg) is the latent heat of evapotranspiration of water; $\rho_W$ (1000 kg/m$^3$) is the water density (Mitchell et al., 2008).

## 1.5 Limitations and Delimitations

### 1.5.1 Limitations

For this research, Atlanta is an appropriate case through which to examine the effects of innovative stormwater management on the urban thermal environment. However, the cooling effect based on evapotranspiration varies along with the characteristics of cities (Taha et al., 1988; Oke, 1989; Sham, 1990). Hence, the suggestions proposed for Atlanta may not be directly applicable to other cities.

Another limitation of this study is the current limited use of innovative stormwater management compared to traditional stormwater management. Thus, the data provided by existing practice is limited. To partially redress this limitation, simulations were conducted to identify which innovative stormwater-management methods in Atlanta produce the most cooling effect by evapotranspiration.

Moreover, the spatial resolution of data (30-meter NLCD data and 60-meter Landsat data) is a limitation of this research as well. Due to the resolution, the spatial analysis and simulations are limited to city-level and neighborhood-level scales. Data with higher spatial resolution is required in order to conducting further researches in site level.

Lastly, the analysis of spatial correlation between ECSM practices and Land Surface Temperature (LST) in Chapter 4 is only a visual analysis. These results only consider the on-site cooling effect of ECSM practices, but the cooling effect of these practices extended to the surroundings is not able to be taken into consideration in this analysis. Thus a more statistical approach should be applied to further research the spatial relationship between them.

### 1.5.2 Delimitations

The scope of this thesis is limited to those innovative, as opposed to traditional, stormwater-management practices, that provide water to support and control evapotranspiration. This choice was made because traditional methods are designed mainly to rapidly export stormwater to reduce runoff in urban areas (Coutts et al., 2012), which dries cities and increases the UHI effect. Traditional methods are counter to both the need to collect stormwater for evapotranspiration and the purpose of improving uncomfortable thermal environments.

Another delimitation of this research is the choice to focus on public open spaces in urban areas. Although innovative stormwater management is not limited to public spaces and may be spread broadly throughout the entire metropolitan area, only public, open sites offer relatively large, sufficient space for installing new stormwater-management devices. The other spaces in urban areas are mostly streets and high-density buildings with small and relatively few open spaces. According to Bowler et al. (2010), the magnitude of the cooling effect correlates positively with the size of the green space, meaning that public, open spaces, because of their size, have higher potential to produce the cooling effect. Hence, for this research, we chose to use public, open spaces in an urban area.

Finally, the perspective of this paper focuses only on creating an improved thermal environment by means of evapotranspiration facilitated by stormwater-management measures in public, open spaces. However, many other factors could be taken into consideration when developing designs for public sites, including public safety, human activities, and esthetic requirements. It is necessary to discuss further how innovative stormwater-management measures could also satisfy other human requirements regarding public, open spaces.

**1.6 Thesis Structure**

Chapter 2 is a literature review focused on basic knowledge about and the mechanism for evaporative cooling, including the major elements influencing climate and the detailed process of reducing temperatures by evapotranspiration. In addition, the restrictions and related factors influencing the effectiveness of evaporative cooling were explored to increase understanding of how its positive influences can be maximized.

Chapter 3 introduces five typical categories of innovative stormwater management: ecoroof, non-canopy green parks, tree canopy, non-green permeable surfaces, and bioretention basins. It also provides a comprehensive understanding of how these stormwater-management measures interact with the evapotranspiration process, thereby affecting the thermal environment.

Chapter 4 studies the effects of innovative stormwater management in practice, using the case of Atlanta. The study is a GIS-based quantitative analysis that explores the current conditions and distribution of the UHI effect in Atlanta. In addition, a spatial correlation analysis is conducted using GIS to examine the relationship between the distribution of UHI and each type of innovative stormwater-management method currently used.

Chapter 5 attempts to identify which innovative stormwater-management practices most contribute to mitigating the UHI effect in Atlanta. The chapter discusses further quantitative analysis involving simulations that employ the LUMPS model, which simulates temperature and evapotranspiration in three Atlanta watersheds in five practice-based scenarios: ecoroof, non-canopy green park, trees, permeable pavement, and bioretention facility. The results provide data for future improvements to Atlanta's thermal environment.

Chapter 6 concludes the thesis by evaluating the modeled relationships between ECSM practices and urban climate. It also proposes and discusses strategies for applying innovative stormwater-management measures to increase urban thermal comfort. Finally, it proposes directions for future research.

### 1.7 Definitions

Net All-wave Radiation

A component of the surface energy budget; specifically, this is the net energy value after transforming longwave and shortwave radiation fluxes between the Earth's surface and the atmosphere.

Anthropogenic Heat Flux

The heat flux resulting from human activities, including transportation, space heating and cooling inside buildings, industrial activity, and the metabolic heat released by people (Mitchell et al., 2008; Nektarios et al., 2016).

Sensible Heat Flux

The process by which heat energy is emitted by the Earth's surface into the atmosphere through conduction and convection, which is related to changes in the temperatures of the Earth's surface and the atmosphere. This heat energy is moved horizontally by air movement (Goddard Earth Sciences Data and Information Services Center; http://climate.ncsu.edu/).

Latent Heat Flux

The heat flux from the Earth's surface to the atmosphere that is associated with the evaporation and transpiration of water (Mitchell et al., 2008).

Storage Heat Flux

The heat flux that is transferred to the Earth's surface (e.g., into buildings or the ground) from the atmosphere (Offerle et al., 2005; Mitchell et al., 2008).

Horizontal Advective Heat

Heat advection is the process by which the wind transfers heat energy horizontally through the atmosphere. Therefore, horizontal advective heat is the sensible, or latent, heat that is transported horizontally by air.

Slope of the saturation vapor pressure curve

The slope of the relationship between saturation vapour pressure (kPa) and air temperature (T, °C) is given by (CRA. Clima):

$$s = \frac{4098 * 0.6108 * e^{17.27T/(T+237.3)}}{(T + 237.3)^2} \qquad (kPa * °C^{-1})$$

Psychrometric "constant"

The psychrometric "constant" $\gamma$ is expressed as follows:

$$\gamma = \frac{c_p p}{\lambda r_{MW}} \qquad (kPa * °C^{-1})$$

where $c_p$ (0.001013 $MJ * kg^{-1} * °C^{-1}$) is the specific heat of air at constant pressure; P (kPa) is the atmospheric pressure; λ (2.26 $MJ * kg^{-1}$) is the latent heat of water vaporization; $r_{MW}$ (0.622) is the ratio of molecular weight of water to dry air (CRA. Clima; Wikipedia; http://ponce.sdsu.edu/psychrometric_constant.html).

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Elements of Climate Control

When people talk about climate, climate generally refers to temperature. However, in addition to temperature, other climatic aspects, such as solar radiation and wind, affect human thermal comfort as well (Brown & Gillespie, 1995; Fanger, 1970; Mayer & Hoppe, 1987; Parsons, 2003a, 2003b). According to Gary O. Robinette (1972), there are four major elements of climate that affect the heat environment and human comfort. They are: air temperature, solar radiation, air movement or wind, and humidity. Thus, controlling these factors is the key to improving the urban thermal environment. While air temperature and relative humidity can be slightly altered by large areas of green space, wind and radiation can be greatly modified through small-scale design interventions, which can change the experienced temperature and humidity, and eventually make an improvement in thermal comfort (Ahmed, 2003; Brown & Gillespie, 1995; Klemm et al., 2015; Lin, 2009; Shashua-Bar, Pearlmutter, & Erell, 2011).

Research also points out that these elements have various effects on climate control. Robert D. Brown et al. (2015) detected the impact of factors that affect climate using human energy budget simulations. Results in all test cities showed that blocking solar radiation was the most effective way to reduce heat. Reducing air temperature was the second most effective way, and in certain climates was almost as effective as intercepting solar radiation. Humidity involves the key process of evapotranspiration, which means the process by which water is transferred into the atmosphere as vapor. This process consumes energy from solar radiation and the surrounding heat environment, and increases latent rather than sensible heat, cooling the temperature of the air (Taha et al., 1988; Grimmond and Oke, 1991). Thus, a greater amount of moisture in the environment increases the amount of heat needed to raise air temperature significantly (Robinette, 1972). In contrast to the elements above, the cooling effect of increasing wind speed needs further discussion. Some people, including Robert F. White, who was concerned with wind control to provide natural ventilation in warm areas of the world, may associate increased wind speed with greater cooling effect (Robinette, 1972). However, it was found that the cooling effect of increasing wind is minimal among factors that can improve thermal environment. In addition, at very high temperatures, wind can even make people more thermally uncomfortable (Brown et al., 2015). This is because conduction, or the transfer of heat between two materials caused by a temperature difference, is driven by the difference between skin and air temperatures. In a very hot climate, conduction is turned toward the body, and the greater the difference, the more heat is conducted toward a person (Parsons, 2003a, b).

When these elements (air temperature, solar radiation, air movement or wind, and humidity) alter the climate, the effect of each is not independent. They work as mutual variables, which means the changing of any element will lead to an alteration of the others, especially temperature control, which is linked directly to – and is a result of – solar radiation control, wind control, and humidity control (Gary O. Robinette, 1972). Robert D. Brown et al. (2015) also found that it is not realistic to modify vapor pressure without changing temperature. As all elements of climate control are interconnected, it is difficult to separate the effect of one element from another. Therefore, when this thesis discusses mitigating the heat environment from aspects of evapotranspiration, it is crucial to figure out how this factor interacts with the other variables.

## 2.2 The Mechanism of Evaporative Cooling

### 2.2.1 Cooling Mechanism

Water evaporation from moist surfaces such as grasses, asphalt pavements and soils, can potentially reduce the local temperature in urban areas, a process known as evaporative cooling (EC). Many studies have observed this phenomenon. A study conducted by Saneinejad et al. (2012) demonstrated that evaporation from a wall surface not only caused an obvious temperature reduction at the wall surface, but also affected the average air temperature in an entire canyon. Generally, EC reduces air temperature by means of an adiabatic process, in which water plays a role as coolant. During this process, water changes its status from liquid to vapor. The energy needed for this change (vaporization latent heat: 2501 kJ/kg, at 0ºC and 610 Pa) is taken from the air, reducing air temperature and raising air humidity (Morgado Baca I. et al., 2011).

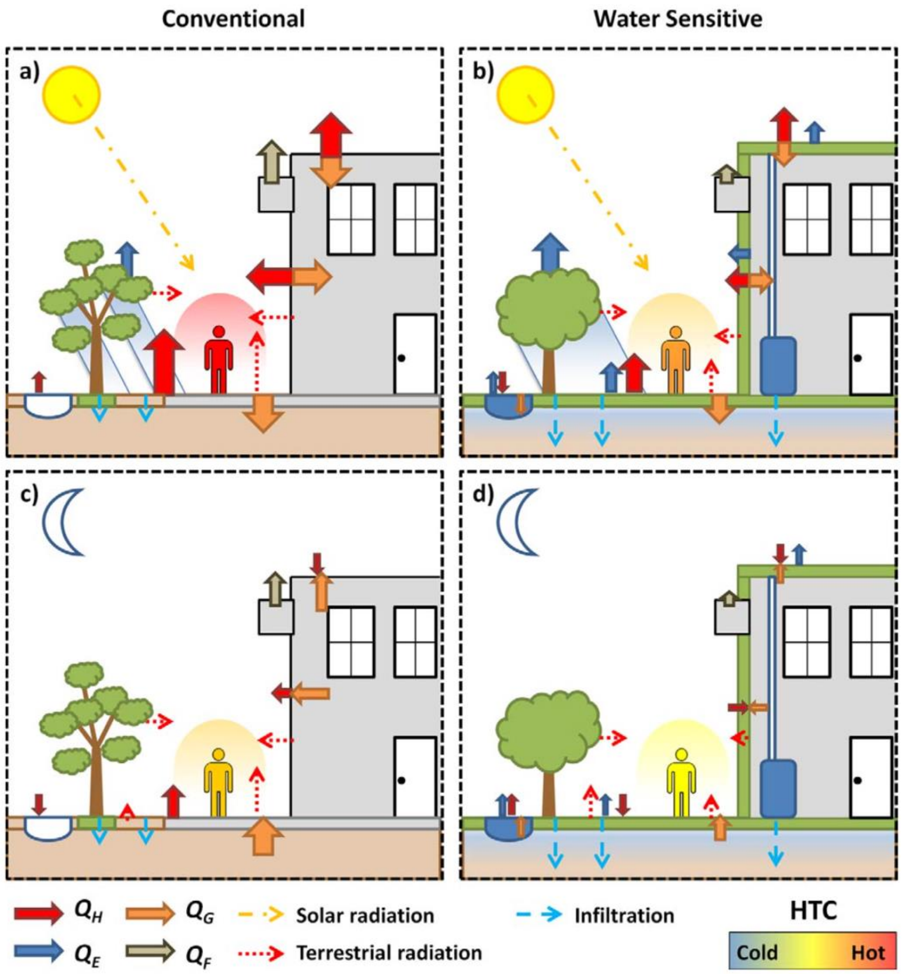



Fig. 2.1 General Illustration of Key Processes in Mitigating UHI Through EC (under warm summertime conditions). We compare a water-limited (low evapotranspiration) urban landscape (a and c) with a water-sufficient (high evapotranspiration) urban landscape (b and d). Surface radiative and heat balance are presented with arrows, indicating direction and relative strength of fluxes. The relative level of human thermal comfort experienced in each case is presented by the human figure and the human thermal comfort scale.

(Source: adapted from Coutts et al., 2012)

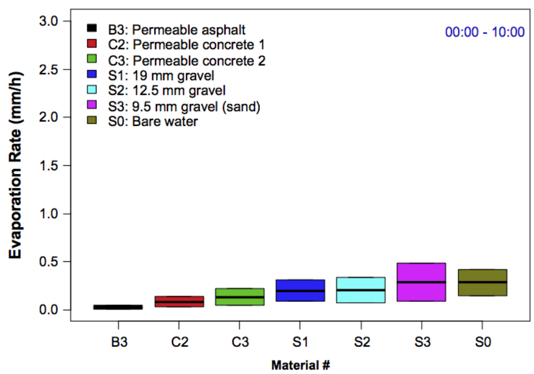
Based on energy exchange, the EC mitigates the effects of UHI in two aspects, directly reducing temperature during daytime and indirectly cooling the nocturnal temperature. Figure 2.1 presents the key processes involved in improving the heat environment through EC (adapted from Coutts et al., 2012) under warm summertime conditions, comparing a water-limited (low evapotranspiration) urban landscape (Figure 2.1, a and c) with a water-sufficient (high evapotranspiration) urban landscape (Figure 2.1, b and d). In the water-limited urban landscape, during the day high sensible heat fluxes combined with strong radiative heat create an extremely hot environment for inhabitants. In contrast, a landscape with adequate water highly increases evapotranspiration, which provides an environment of thermal comfort by directly transforming sensible heat into latent heat.

The effect of EC on an urban climate at night is more complex. Usually, the UHI is more severe at night because of high humidity. In general, an urban climate will experience moisture deficit during the daytime and moisture excess at night, compared with the humidity of adjacent rural areas (Holmer & Eliasson, 1999). In addition, multiple regression analyses have indicated a positive correlation between nocturnal heat island intensity and vapor pressure (Sundborg, 1951; Emonds, 1954; Lindqvist 1970). Based on these theories, the nocturnal thermal environment should be more uncomfortable when there is higher humidity at night. However, increased moisture in the atmosphere during the day is not the cause of increased humidity at night. Higher nocturnal humidity results from the urban-rural moisture difference, which produces UHI circulation, directing humid rural air into the urban area and resulting in increased urban air humidity at night (Okita, 1965; Goldreich and Surridge, 1988; Barlag and Kuttler, 1990, 1991; Hage, 1975; Ackerman 1971, 1987). Therefore, there is no need to worry that the higher humidity at daytime would result in increased moisture and consequent thermal discomfort at night. Furthermore, Coutts et al. (2012) demonstrated that when natural, vegetated landscapes (high evapotranspiration) are replaced with impervious infrastructures (low evapotranspiration), excess heat storage will be slowly released at night. This found indicates that landscapes with high evapotranspiration have potential in reducing heat storage. During daytime, the more evapotranspiration, the more heat energy transferred into latent heat. Thus, the available amount of heat can be absorbed by Earth's surface (e.g. buildings, pavements) and then transferred into heat storage is decreased. During night, the heat storage will be released into atmosphere when air temperature is lower than the temperature of Earth's. However, benefited from high evapotranspiration at daytime, heat storage is reduced and the released heat for air warming is consequently decreased at night.

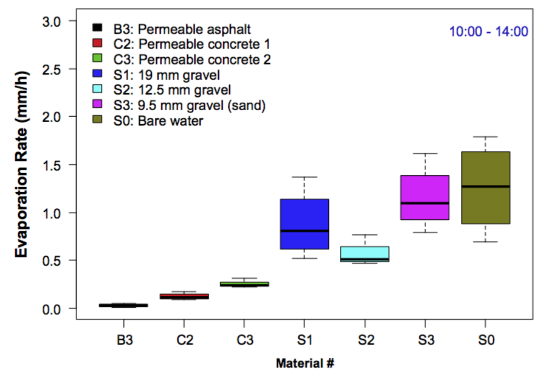
### 2.2.2 Restrictions of Evaporative Cooling

Generally, in certain temperature environments, as vegetation cover increases, the evapotranspiration rate will increase (Christen and Vogt, 2004; Offerle et al., 2006). In addition, the increasing evapotranspiration prevents energy from taking part in urban heat storage, as well as sensible heating of the atmosphere. However, there are exceptions to this common phenomenon. Thermal conditions and relative humidity were found to be significantly different among locations with varied tree canopies and neighborhood characteristics. Research suggests that trees may eliminate a portion of urban heat but also produce greater humidity. As a result, the temperatures of locations with more trees are significantly higher than those of downtown and areas with fewer trees (Hass et al., 2016). In addition, a considerable variation in heat island intensity has been observed, even on apparently clear and calm nights, which are the typical UHI weather conditions (Holmer & Eliasson, 1999). On these special occasions, Oke (1988b) suggested that there are spatial and temporal complexities in the process of EC. Usually, evapotranspiration changes air temperature and humidity, and in return, these two conditions also influence the ability of water to evaporate. Air temperature and air humidity as well play a vital role in the evaporation rate of materials in urban spaces (Li, Harvey and Ge, 2014). These two conditions have become major restrictions on EC. In general, high air temperature and low humidity will help enhance the evaporation rate, which is just what is expected during hot periods (Li, Harvey & Ge, 2014).

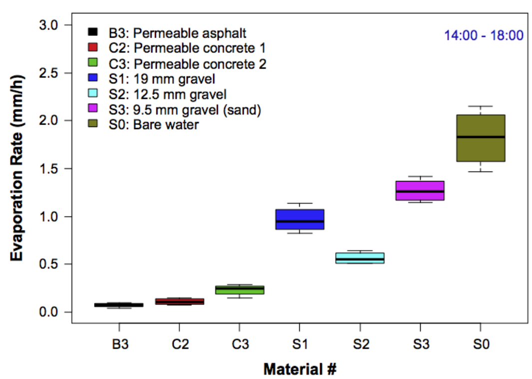
Air temperature and humidity limit Potential Evapotranspiration (PET), which is defined as the amount of evaporation that would occur if a sufficient water source were available and is a measure of the ability of the atmosphere to remove water from surfaces of various objects through the processes of evaporation and transpiration, assuming no control on water supply (Beyerlein, 2012). Higher temperatures mean more heat can be provided for the energy transforming process of evapotranspiration. The evaporation rates in all studies show a pattern that is similar to the pattern of air temperature, which is high in the daytime and low in the nighttime. Li, Harvey and Ge (2014) also noted in their study that the evaporation rate is high during the day, especially on hot afternoons in summer (Figure 2.2, d and e), and low during the nighttime, with an especially low rate in the cold early morning (Figure 2.2, c and f).



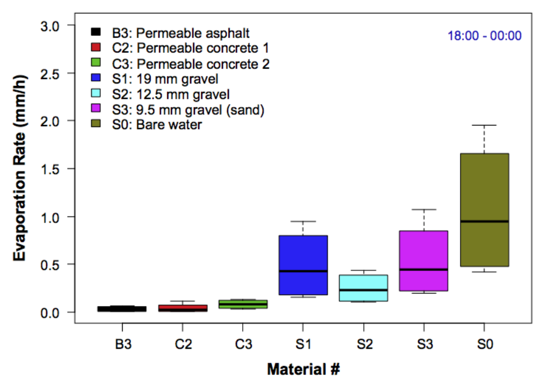

(c) Morning (00:00 – 10:00, July 10)




(d) Noon (10:00 – 14:00, July 10)




(e) Afternoon (14:00 – 18:00, July 10)




(f) Night (18:00 – 00:00, July 10)

Fig. 2.2 Average Evaporation Rates of Different Pavement Materials

(Source: Li et al., 2014)

Meanwhile, in climates with high Relative Humidity (RH%), or more than 50-60%, cooling capacity goes down significantly (Morgado Baca I. et al., 2011). Holmer and Eliasson (1999) also demonstrated that evapotranspiration, to a considerable extent, depends on processes related to air humidity. As evapotranspiration rate reduces in high-moisture weather conditions, the evaporation rate of sweat decreases, reducing the heat that can be carried off from human skin and leading to a weak EC effect. This effect is calculated in a heat index table (Figure 2.3) from U.S. National Oceanic and Atmospheric Administration, which shows that when Relative Humidity (RH) is more than 40%, the effects of environmental heat suffered by humans will increase as the RH% increases. However, while EC may not be significantly strong under humid conditions, providing water for vegetation to promote shading and reduce surface radiative temperatures is still beneficial. Even small temperature reductions of 1-2°C can make a difference in mortality rates of humans (Nicholls et al., 2008).

| Relative humidity (%) | Temperature | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 80 ° F (27 ° C) | 82 ° F (28 ° C) | 84 ° F (29 ° C) | 86 ° F (30 ° C) | 88 ° F (31 ° C) | 90 ° F (32 ° C) | 92 ° F (33 ° C) | 94 ° F (34 ° C) | 96 ° F (36 ° C) | 98 ° F (37 ° C) | 100 ° F (38 ° C) | 102 ° F (39 ° C) | 104 ° F (40 ° C) | 106 ° F (41 ° C) | 108 ° F (42 ° C) | 110 ° F (43 ° C) |
| 40 | 80 ° F (27 ° C) | 81 ° F (27 ° C) | 83 ° F (28 ° C) | 85 ° F (29 ° C) | 88 ° F (31 ° C) | 91 ° F (33 ° C) | 94 ° F (34 ° C) | 97 ° F (36 ° C) | 101 ° F (38 ° C) | 105 ° F (41 ° C) | 109 ° F (43 ° C) | 114 ° F (46 ° C) | 119 ° F (48 ° C) | 124 ° F (51 ° C) | 130 ° F (54 ° C) | 136 ° F (58 ° C) |
| 45 | 80 ° F (27 ° C) | 82 ° F (28 ° C) | 84 ° F (29 ° C) | 87 ° F (31 ° C) | 89 ° F (32 ° C) | 93 ° F (34 ° C) | 96 ° F (36 ° C) | 100 ° F (38 ° C) | 104 ° F (40 ° C) | 109 ° F (43 ° C) | 114 ° F (46 ° C) | 119 ° F (48 ° C) | 124 ° F (51 ° C) | 130 ° F (54 ° C) | 137 ° F (58 ° C) | |
| 50 | 81 ° F (27 ° C) | 83 ° F (28 ° C) | 85 ° F (29 ° C) | 88 ° F (31 ° C) | 91 ° F (33 ° C) | 95 ° F (35 ° C) | 99 ° F (37 ° C) | 103 ° F (39 ° C) | 108 ° F (42 ° C) | 113 ° F (45 ° C) | 118 ° F (48 ° C) | 124 ° F (51 ° C) | 131 ° F (55 ° C) | 137 ° F (58 ° C) | | |
| 55 | 81 ° F (27 ° C) | 84 ° F (29 ° C) | 86 ° F (30 ° C) | 89 ° F (32 ° C) | 93 ° F (34 ° C) | 97 ° F (36 ° C) | 101 ° F (38 ° C) | 106 ° F (41 ° C) | 112 ° F (44 ° C) | 117 ° F (47 ° C) | 124 ° F (51 ° C) | 130 ° F (54 ° C) | 137 ° F (58 ° C) | | | |
| 60 | 82 ° F (28 ° C) | 84 ° F (29 ° C) | 88 ° F (31 ° C) | 91 ° F (33 ° C) | 95 ° F (35 ° C) | 100 ° F (38 ° C) | 105 ° F (41 ° C) | 110 ° F (43 ° C) | 116 ° F (47 ° C) | 123 ° F (51 ° C) | 129 ° F (54 ° C) | 137 ° F (58 ° C) | | | | |
| 65 | 82 ° F (28 ° C) | 85 ° F (29 ° C) | 89 ° F (32 ° C) | 93 ° F (34 ° C) | 98 ° F (37 ° C) | 103 ° F (39 ° C) | 108 ° F (42 ° C) | 114 ° F (46 ° C) | 121 ° F (49 ° C) | 128 ° F (53 ° C) | 136 ° F (58 ° C) | | | | | |
| 70 | 83 ° F (28 ° C) | 86 ° F (30 ° C) | 90 ° F (32 ° C) | 95 ° F (35 ° C) | 100 ° F (38 ° C) | 105 ° F (41 ° C) | 112 ° F (44 ° C) | 119 ° F (48 ° C) | 126 ° F (52 ° C) | 134 ° F (57 ° C) | | | | | | |
| 75 | 84 ° F (29 ° C) | 88 ° F (31 ° C) | 92 ° F (33 ° C) | 97 ° F (36 ° C) | 103 ° F (39 ° C) | 109 ° F (43 ° C) | 116 ° F (47 ° C) | 124 ° F (51 ° C) | 132 ° F (56 ° C) | | | | | | | |
| 80 | 84 ° F (29 ° C) | 89 ° F (32 ° C) | 94 ° F (34 ° C) | 100 ° F (38 ° C) | 106 ° F (41 ° C) | 113 ° F (45 ° C) | 121 ° F (49 ° C) | 129 ° F (54 ° C) | | | | | | | | |
| 85 | 85 ° F (29 ° C) | 90 ° F (32 ° C) | 96 ° F (36 ° C) | 102 ° F (39 ° C) | 110 ° F (43 ° C) | 117 ° F (47 ° C) | 126 ° F (52 ° C) | 135 ° F (57 ° C) | | | | | | | | |
| 90 | 86 ° F (30 ° C) | 91 ° F (33 ° C) | 98 ° F (37 ° C) | 105 ° F (41 ° C) | 113 ° F (45 ° C) | 122 ° F (50 ° C) | 131 ° F (55 ° C) | | | | | | | | | |
| 95 | 86 ° F (30 ° C) | 93 ° F (34 ° C) | 100 ° F (38 ° C) | 108 ° F (42 ° C) | 117 ° F (47 ° C) | 127 ° F (53 ° C) | | | | | | | | | | |
| 100 | 87 ° F (31 ° C) | 95 ° F (35 ° C) | 103 ° F (39 ° C) | 112 ° F (44 ° C) | 121 ° F (49 ° C) | 132 ° F (56 ° C) | | | | | | | | | | |

Fig. 2.3 Heat Index Chart

(Source: U.S. National Oceanic and Atmospheric Administration)

## 2.3 Maximizing Cooling Effectiveness

The degree of the intensity of EC and improvements in human thermal comfort depend on a multitude of factors, including local environmental conditions, the design and the placement of stormwater management systems, and the nature of the surrounding urban landscape (Coutts et al., 2012). Hence, before implementation of designs, it is essential to figure out under which conditions the potential evaporative cooling can be maximized.

### 2.3.1 Effect Based on Regional Climates

In the United States, there is a great range of regional climates and climatic conditions that affect EC. Thus, the magnitude of the cooling effect through evapotranspiration varies by location. Bowler et al. (2010) point out that local climate, specifically temperature and precipitation, may also affect the thermal environment of green spaces. But the kind of EC landscape that is highly effective in improving thermal comfort in one climate region might not be effective in another (Brown et al., 2015). For instance, Georgescu et al. (2014) examined the effect of using white roofs in different urban regions by climate modeling to predict temperatures in the year 2100. Overall, white roofs were effective in reducing urban temperatures in all of the regions modeled (California, Arizona, Texas, Florida, Mid-Atlantic, and Chicago/Detroit). However, the magnitude of the impact depended on the background climatic conditions. This means that if all the roofs in urban areas were white, the urban-induced warming rate would be decreased by 1.2°C by 2100 in California, while this difference would be less in more humid areas such as Florida, whose urban-induced warming rate would be reduced by only 0.2°C. Another study investigating the effect of background temperature also found that the cooling effect of evapotranspiration is greater in urban areas with warmer temperatures (Shashua-Bar and Hoffman, 2000).

As mentioned before, the EC effect is mainly controlled by air temperature and humidity. The high temperature background is pre-determined as this is the typical climate characteristic of the UHI. Therefore, the only variable factor of climate that needs to be discussed in this thesis is humidity. Climate zones with sunny summer skies and low moisture in the air are the most suitable climate conditions for the ideal effectiveness of EC, as the evapotranspiration rate may be high, provided there is an adequate water supply, under warm and dry climate condition. In addition, adding shading facilities or tree canopies can enhance the cooling effect by blocking solar radiation on sunny days. In contrast, in climates where there are fewer hours of full sun and more cloud conditions, the effect of EC and shading have been somewhat less effective. In these regions, the effect of a strong wind is usually larger than the effect of evapotranspiration, with evaporative heat loss not found to be greater unless with there was a much higher wind speed (Brown et al., 2015).

In general, regional climate differences cannot be ignored when seeking to maximizing the effectiveness of EC. A mixed usage of EC, shading and wind is also encouraged in order to reach the largest cooling effect under varied and complex climate conditions.

### 2.3.2 Effect Based on Water Supply

The major strategy for enhancing EC is to plant more trees and other irrigated vegetation, so as to limit heat storage during the day and assist in nighttime cooling, but this requires sufficient water resources (Gober et al., 2010). Not surprisingly, surfaces that have large amounts of water evaporation during the day will have the greatest nighttime cooling. More irrigated vegetation produces more evaporation and less stored heat to be released during night. Spronken-Smith and Oke (1998) studied the temperature differences between 10 parks and their surrounding areas in both Sacramento (dry-summer subtropical climate) and Vancouver (maritime climate). Similar temperature reductions were detected in the parks of both cities, but lower air temperatures were found within the irrigated parks in Sacramento.

However, the relationship between evapotranspiration rate and the magnitude of cooling effect is not linear. Gober et al. (2010) suggested that cooling levels decreased when evaporation rates were high. As the area of wet surface increases, the efficiency of cooling declines. According to Gober et al. (2010), adding water is not an efficient strategy for evaporative cooling in densely vegetated neighborhoods, while the greatest temperature reductions occur in the least vegetated neighborhoods. Another important finding put forward by Gober et al. (2010) is related to the impact of the change in the ratio of used water to reduced temperature . This ratio reaches a threshold, beyond which increased outdoor water use produces little additional cooling to ameliorate UHI, although using a lot of water. In cities with abundant water supply, this will be of less importance, but in areas where the water source is inadequate, this will be an essential consideration. In this situation, a uniform strategy for UHI mitigation by EC may not be reasonable. To be more specific, increasing irrigated vegetation should focus mainly on neighborhoods with the least vegetation, where the maximum magnitude of the cooling effect can be achieved with minimal use of additional water.

## 2.4 GIS Methodology

### 2.4.1 LST Retrieval from Remote Sensing Data

Land Surface Temperature (LST) is often used to estimate the intensity of surface UHI (Tomlinson, 2011). To acquire LST from satellite data has been widely adopted by researchers specializing in climatology since remotely-sensed data became available for the public (Yang et al., 2013). Followed the study conducted by Yang et al. (2013), the landsat data is a precious source providing spatial temperature data. Yang et al. (2013) acquired remote sensing data from the Landsat Enhanced Thematic Mapper (ETM+) sensor with Landsat 7 satellite, and combined this data with LULC data to develop the distribution map of surface temperature based on the methodology developed by Stathopoulou and Cartalis (2007). Besides Yang et al. (2013), Landsat 7 Science Data Users Handbook is also referenced in this thesis to estimate LST by the satellite data from Landsat 7. The estimation process of LST includes three major steps, which is further illustrated in section of 4.3.1.

### 2.4.2 Spatial Correlation Analysis in GIS

In order to figure out weather current ECSM practices have cooling effect in temperatures of Atlanta, this study examine the spatial correlation between ECSM practices and LST. Although we have not found researches that studied spatial correlation between ECSM practices and LST by GIS so far, we are able to analyze distribution patterns of ECSM practices and LST in GIS. If spaces with more ECSM practices have lower temperatures, then it can be concluded that ECSM practices are effective in reducing temperature. Distribution maps of ECSM practices and LST are normalized on a scale ranging from 0 to 1 as raster maps (the normalization process is further introduced in the section of 4.3.2). In raster maps of ECSM practices, spaces with more ECSM practices have values closer to 1; and in raster map of LST, spaces with lower temperatures have values closer to 1. Then each normalized raster map of ECSM practices is multiplied with normalized LST map in GIS by the raster math tool of multiply. The areas in the output map with values closer to 1 means that these spaces have both more ECSM practices and lower temperatures at the same time. The more areas with values closer to 1 in the output map, the more effective of the ECSM practices in reducing temperatures.

### 2.4.3 Analysis Unit for Simulation

Watershed is used as analysis unit in simulation. The boundaries of watersheds are defined by the Hydrologic Unit Code (HUC), with the data of HUC-12 in the National Hydrography Dataset (NHD) from U.S. Geological Survey (USGS). To use watershed as analysis unit is based on the research conducted by Yang et al. (2013). They studied three watersheds with different environmental characters to discuss how to design with nature for multifunctional landscapes. As for ECSM practices, the environmental characters also play an important role in their cooling effectiveness. Therefore, it is necessary to discuss the design of ECSM practices based on watersheds with different environmental characters as well. What is more, to use watershed other than community or census tract as analysis unit is helpful for further research in the future to take hydrographic conditions and water supplies into consideration when design ECSM practices. From this perspective, it is reasonable to choose watershed as analysis unit.

# CHAPTER 3

# EVAPORATIVE COOLING STORMWATER MANAGEMENT (ECSM)

## 3.1 ECSM

To relieve the UHI based on evaporative cooling (EC), an innovative, improved stormwater management approach should take advantage of the technologies and strategies used to retain water in an urban landscape by harvesting and reusing stormwater, and infiltrating it into soil. Generally, stormwater management practices are designed to address urban stormwater concerns, but with improved designs, they could address UHI problems as well and better serve society and the environment. Moreover, in EC it is critical to ensure sufficient water availability for evapotranspiration (Allen et al., 2010), and stormwater is an available source of water in urban areas. Traditionally, an urban drainage infrastructure is designed to export stormwater away from the urban environment as quickly as possible to minimize the runoff and flood risk created by extensive impervious surfaces (e.g. concrete), which contribute to heating and drying, making the thermal environment more uncomfortable (Coutts et al., 2012). Unlike traditional stormwater management practices, improved stormwater management approaches can meet the requirement of runoff control and incorporate EC to ease the UHI effect.

Many studies have mentioned the application of various stormwater management practices that could mitigate the UHI (e.g., Coutts et al., 2012; Grimmond & Oke, 1991; Gober et al., 2010; Li et al., 2014; Mitchell VG et al., 2008; USEPA, 1999). Furthermore, a stormwater management infrastructure could be incorporated in a variety of ways, including vegetated parks, planting trees along urban streets, and constructing vegetated roofs (Givoni, 1991). This present research study aims to examine the effects of stormwater management practices on evapotranspiration; thus, it focuses on specific and relevant stormwater measurements that are suitable for public open spaces. We define this type of stormwater infrastructure as Evaporative Cooling Stormwater Management (ECSM). A summary of previous research indicates that ECSM mainly uses three approaches to ensure that stormwater management contributes to evapotranspiration and provides a better thermal environment: (1) promoting the proportion of land surfaces that support evapotranspiration, including vegetated land, permeable pavement, and open bodies of water; (2) increasing the water availability near the land surface and the amount of moisture exposed to the atmosphere; and (3) reducing runoff and increasing stormwater storage to ensure a sufficient source of water for future evapotranspiration. Some ECSM practices merely address evapotranspiration while others play a wider role by integrating mixed approaches that impact the climate as well as evapotranspiration (e.g., shading to block solar radiation, high albedo to reflect radiation). Based on the ECSM approaches involving evapotranspiration and climate, we summarized five types of practices that have high potential in UHI mitigation: ecoroofs, non-canopy green parks, tree canopies, permeable pavements, and bioretention facility. In order to design an ECSM that will have an optimal cooling effect on a thermal environment during the heat of summertime, a landscape architect must comprehensively understand the effect of various ECSM practices.

### 3.2 Ecoroofs

Ecoroofs, also known as living roofs or green roofs, turn the tops of commercial buildings into gardens where plants are cultivated (Copeland, 2002). Rooftop greenery is broadly encouraged because it provides multiple benefits to the environment, society, and the economy, such as air quality improvement, better thermal performance in a building, esthetic advancement, and community construction (Liu & Baskaran, 2003; Peck, Callaghan, and Kuhn, 1999; Tan and Sia, 2005). From the perspective of stormwater management, roofs are natural sponges in heavy rainstorms and they are able to reduce water runoff by up to 90% (Copeland, 2002). According to Beyerlein (2012), evapotranspiration is the mechanism for reducing stormwater runoff via an ecoroof. Unlike other stormwater management practices, ecoroofs cannot infiltrate water into the native soil, since the infiltration is limited to the depth of the growing media used on the roof. With limited available moisture storage in soil, the majority of the stormwater reduction results from evapotranspiration. At the same time, evapotranspiration is also the major approach used to ensure that the area surrounding the ecoroof is cooler.

Many studies have compared temperatures on or above a vegetated roof with those on a regular roof (usually the same roof) without vegetation; therefore, they have examined the cooling effects of ecoroofs. These studies reported mixed results. The majority of the findings have proven that ecoroofs have a positive effect on mitigating intensely high temperatures; they have shown that the surface temperature of ecoroofs is cooler than non-green roofs (Alexandri & Jones, 2007; Harazono et al., 1991; Wong et al., 2003 and 2007). Gober et al. (2010) also noted that adding vegetated roofs without decreasing irrigation on the roof reduces the maximum temperatures by 0.5°C in comparison to a typical urban design. However, some studies have indicated that the temperatures on ecoroofs can be higher under some conditions, such as water shortage for plants and using the wrong species of vegetation (Alexandri & Jones, 2007; Wong et al., 2007). Actually, the temperature difference can depend on the month or the time of day (Harazono et al., 1991; Takebayashi & Moriyama, 2007). Despite the common factors that influence evapotranspiration, the primary restriction on an ecoroof is the soil's inability to retain sufficient stormwater. Due to a roof's capacity to handle the added weight of liners, dirt, and plant cover, the depth of the soil is limited (Copeland, 2002); this impacts the amount of stormwater that can be retained and used for evapotranspiration (Beyerlein, 2012). If an ecoroof is designed to maximize the potential of the cooling effect, plant species that actively transpire during the day to support EC should be utilized. Transpiration aids in cooling the roof surface while removing water from the soil (Lundholm et al., 2010). However, high water use vegetation will make the soil on the roof dry out more quickly. This threatens the health of the vegetation, and makes it difficult to benefit from the cooling effect of evapotranspiration. Lazzarin et al. (2005) investigated the EC effects of an ecoroof in Vicenza, Italy; they found that evapotranspiration was very limited for dry soil during the summer. Sfakianaki et al. (2009) found an average 1.4°C surface temperature reduction when ecoroof soil was watered on a sunny day in comparison to dry soil. Therefore, a supporting irrigation system is necessary to ensure that the soil and plants benefit from a balance between plant survival and high evapotranspiration rate (Wolf & Lundholm, 2008). In addition, when an irrigation system is introduced, the soil's capacity to retain stormwater decreases, while the retention of stormwater is the primary purpose of an ecoroof (Coutts et al., 2012). Consequently, irrigation systems need to be carefully designed to guarantee that the soil has sufficient capacity to retain water from rainfall to support the intention of stormwater runoff reduction. Combining harvested stormwater with an irrigation system on an ecoroof is a possible complementary solution.

### 3.3 Non-canopy Green Parks

As a stormwater management practice, green parks use infiltration and evapotranspiration to reduce stormwater runoff (Beyerlein, 2012). From the perspective of EC, among the various options for practicing ECSM in urban areas, green parks are the best documented approach, as they have the potential to provide more comfortable thermal environments and help alleviate the UHI effect. In the literature, these cooler areas are known as Park Cool Islands (PCIs), the intensity of which is often greatest at night (e.g., Chow, Pope, Martin, & Brazel, 2011; Oke, 1987; Upmania, Eliasson, & Lindqvist, 1998; Upmanis & Chen, 1999). In comparison to ecoroofs, one advantage of green parks is the infiltration of stormwater into native soil, and this is the only significant functional difference between these two ECSM practices (Beyerlein, 2012). While this provides one more approach (in addition to evapotranspiration) to reduce runoff, infiltration into the soil, or even into deeper ground levels, means more retained stormwater and increased groundwater, which provides more sufficient water for evapotranspiration and more available water near the land surface to keep the soil wet for a longer period of time than is possible on ecoroofs.

In this present research study, we examine non-canopy green parks and tree canopies separately because the mechanisms for short vegetation and trees in UHI mitigation are different. Without any canopy intervention, the ability of shading to block solar radiation is not considered in a study of a non-canopy green park that only has short vegetation. In this situation, the EC effect of non-canopy green parks is supposed to primarily benefit from the presence of grasses and shrubs. Studies have demonstrated that air temperatures are usually cooler above grass than above concrete (Huang et al., 2008; Mueller & Day, 2005; Yilmaz et al., 2008). However, other studies have consistently reported lower surface temperatures on grass than on concrete or asphalt (Gill, 2006; Kjelgren & Montague, 1998; Mueller & Day, 2005; Yilmaz et al., 2008). This is due to the differences between vegetation and urban materials in albedo, moisture, aerodynamics, and thermal properties; thus, the type of green vegetation could affect temperatures through different processes (Givoni, 1991; Oke, 1989). Evapotranspiration is one of these important processes; it usually takes place on grasses more than on concrete or asphalt surfaces, and it guarantees higher air moisture above grasses. It was also found that vegetation may affect air movement and heat exchange (Bonan, 1997), and the cool air from parks can extend some distance into downwind neighborhoods (e.g., Slater, 2010; Yokohari et al., 2001).

Many factors affect the magnitude of the cooling effect produced by green parks, despite of the influence of shading canopies above vegetation. Variation in the combinations of plants in a park, such as the amount of shrubs and grass cover, is one factor that affects the temperature (Bowler et al., 2010). Chang et al. (2007) also demonstrated that the percentage of vegetation cover within a park explains the temperature variations between parks. Another factor that impacts temperature is that parks can also vary in the percentage of area without vegetation, especially multi-use parks. Increased paved areas within a park have also been found to positively correlate to higher air temperature in studies in Mexico City and Taipei (Barradas, 1991; Chang et al., 2007).

Other studies have demonstrated that the size of a park is related to its cooling effect. Larger parks are not only more likely to be cooler; they also have a greater cooling effect on surrounding areas than smaller parks (Bacci et al., 2003; Barradas, 1991; Chang et al., 2007; Upmanis et al., 1998). Chang et al. (2007) compared the temperatures of 61 parks at noon during the summer in Taipei City; they found that parks over 3 hectares were commonly much cooler than the surrounding areas. In another study conducted by Barradas (1991), the temperatures of 5 parks (ranging in size from 1.9 ha to 9.9 ha) in Mexico City were evaluated every week during the rainy season. The results indicated that the temperature difference between larger parks and their surroundings tended to be greater than that between smaller parks and their surroundings.

However, the temperature difference between non-canopy green parks and their surroundings is determined not only by the characteristics of the parks, but also by the characteristics of the surrounding environment. The extended distance of the cooling effect from parks is affected by wind speed, wind direction, and the layout and height of the nearby buildings (Chen & Wong, 2006). Moreover, Jauregui (1990) noticed that, although Chapultepec Park in Mexico City was cooler than its surroundings, in general, the temperature was about the same or even somewhat (0.5 °C) warmer than the surrounding urban space; this could be due to the fact that vegetation has a lower albedo than urban materials. A lower albedo means that the plants receive more heat energy. When the sun is high at noon, the temperature can increase in a park area due to the received heat energy; this is more likely to occur than the decrease in temperature due to evapotranspiration. This produces a warmer environment in the park than in the surrounding area. The cooling effect also extends into downwind neighborhoods located about one park-width from the green park (Spronken, Smith, & Oke, 1998). Therefore, to maximize the cooling effect the fit-for-place approach should be used for non-canopy green parks.

### 3.4 Trees

In this study, the ECSM practice of trees refers to both tree canopies and the space under trees. The ability of trees to intercept precipitation and slow it down helps control surface water runoff (Robinette, 1972). Moreover, the addition of organic material loosens soil and maintains the porosity of the soil, which helps the soil retain more water (Robinette, 1972). In terms of stormwater management approaches, non-canopy green parks and trees are similar; both use infiltration and evapotranspiration. But from the perspective of the effect that cooling has on urban climate and thermal comfort, trees have been demonstrated to be significantly more effective because they cool the environment by evapotranspiration and by blocking solar radiation (Georgi & Dimitriou, 2010; Tsiros, 2010).

In comparison to short vegetation, the influence of evapotranspiration by trees is a bit different. Similar to other vegetation, the leaf surfaces of trees cause transpiration of water from soil into the atmosphere to cool the air. However, a microclimate of controlled humidity and temperature exists under trees, especially in “forest parks”; and this is a unique characteristic among the ECSM practices. Tree canopies block and filter solar radiation, obstruct wind, transpire water into the atmosphere, and prevent evaporation of moisture from the soil into the atmosphere, thereby preserving and retaining moisture in the soil (Robinette, 1972). Thus, the relatively high humidity and low evaporation rate under trees stabilize the temperature, keeping it lower than the surrounding area during the day and preventing it from significantly decreasing at night.

In addition to EC, shading from trees is also effective in cooling the atmosphere by blocking solar radiation and preventing the warming of the land surface and air (Oke, 1989). A tree canopy not only reduces the amount of incoming solar radiation that directly reaches a person, it also decreases the amount of solar radiation that is received by the land surface that is reflected from the land to humans. Vanos et al. (2012a) demonstrated that, in parks in Toronto, Canada, open areas without tree cover lead to a significant increase in absorbed radiation by a human in comparison to the areas that are shaded by trees within the park. Thus, a tree canopy is an essential measure for improving thermal comfort and reducing the vulnerability of humans to heat stress during the hot summer months. In fact, as much as 80% of the cooling effect of trees comes from shading (Shashua-Bar & Hoffman, 2000). The greatest cooling effect produced by parks results from the reduction of solar radiation through shading (Brown et al., 2015). This findings is supported by many studies (e.g., Ahmed, 2003; Cheng et al., 2012; Lin, 2009; Lin, Matzarakis, & Hwang, 2010; Shahidan et al., 2010; Shashua-Bar et al., 2011).

Due to the shading effect, spaces with tree canopies tend to be cooler during the afternoon while open green spaces with short vegetation are cooler at night (Chang et al., 2007; Spronken-Smith & Oke, 1998). Spronken-Smith and Oke (1998) examined a variety of parks, such as grass parks, savannahs, and multi-use parks; their results support the positive cooling effect of trees during the day. Other evidence also indicates that the air temperatures under both single trees and groups of trees are lower than temperatures in an non-canopy green park during the day (de Kauffman et al., 2002; Georgi & Zafiriadis, 2006; Golden et al., 2007; Streiling & Matzarakis, 2003; Taha et al., 1991). However, research also demonstrates that a tree canopy can retain heat at night due to the controlled microclimate of high humidity and the low evapotranspiration rate beneath the canopy (Huang et al., 2008; Souch & Souch, 1993; Taha et al., 1991). Thus, the cooling effect of tree varies during the day.

Many factors impact the cooling intensity from tree canopies, including the location of the trees, the canopy coverage, the planting density, the irrigation management, and so on (Pataki et al., 2011a; Shashua-Bar et al., 2010a). Shashua-Bar and Hoffman (2000) proposed that the amount of shading area affects the temperature. In comparison to areas of low-density trees, temperatures are higher in "forest parks" where a greater density of trees are planted (Padmanabhamurty, 1991; Yilmaz et al., 2007). Streiling and Matzarakis (2003) compared the cooling effect of a single tree with a cluster of trees; they found slightly higher temperatures under the single tree. Since the cooling effect of small groups of trees has been found to be less strong than the cooling effect of large groups of trees, parks tend to contain many trees (Klemm et al., 2013, 2015; Streiling & Matzarakis, 2003). Moreover, important cooperative relations exist between different greening infrastructures. Studies have compared air temperatures beneath the trees growing near concrete surfaces and those growing on grass surfaces, and warmer temperatures were found under the trees growing near the concrete (Kjelgren & Montague, 1998; Souch & Souch, 1993). Therefore, to maximize the cooling effect, it may be important to combine different green interventions.

### 3.5 Permeable Pavement

In urban areas, the increase in the number of impermeable surfaces, such as asphalt and concrete, have generated extreme modifications in the natural hydrological cycle, which do not reserve water for evaporation and quickly absorb and retain heat when exposed to solar radiation (Beach, 2002; Bowler et al., 2010; Carbone et al., 2016). Gober et al. (2009) examined the effects on urban climate across a range of land cover characteristics, including impervious pavement, irrigated landscapes, lot size, the presence of pools, and residential water use. Their result indicated that impervious surfaces can increase UHI intensity and influence the distribution of high temperatures. Many studies have introduced the negative effects of impervious surfaces on urban climate and stormwater management (Guhathakurta & Gober, 2009; Sailor, 2006; Stone & Norman, 2006). In contrast, permeable pavement not only reduces runoff on heavily rainy days by infiltration (Beyerlein, 2012), it also helps mitigate the human and ecological stress from the UHI effect by resetting the fundamental hydrological processes of infiltration and evapotranspiration (Oke, 1973). The ability of permeable pavement to infiltrate and retain stormwater has the potential to increase the water availability near the surface as well as the moisture exposed to the atmosphere, which are critical for the evaporation rate and the subsequent EC effect of pavement materials (Li, Harvey, & Ge, 2014).

However, not all of types of permeable pavements have a cooling effect on urban climate. Asaeda and Ca (2000) found that the surface temperatures of ceramic permeable pavement at noon were similar to those of turf, while the surface temperature of porous block pavement was similar to asphalt, which is 10°C higher than the surroundings. This is because porous block is made from coarse grains that are unable to retain water for a long time; thus, it absorbs a lot of solar radiation like asphalt. This indicates that other characteristics of permeable pavement should be taken into consideration to ensure an efficient cooling effect. In order to maximize the EC effect of permeable pavement, Li et al. (2014) suggested increasing air voids and permeability to improve moisture exposure to the atmosphere and enhance evaporation. Taking advantage of the capillary effect of the permeable materials is another way to keep the surface wet. To enhance the EC effect of permeable pavement, it should be designed using surface materials with appropriately balanced pore size, capillary effect, and adequate permeability, such as turf blocks, gravel, and sands. Another option to help ensure a better EC effect for permeable pavement is to directly sprinkle water (use harvested stormwater) on the surface.

### 3.6 Bioretention Facilities

Bioretention facilities combine the biological systems of living plants and soils with shallow ponding, including short-term detention and permanent retention (USEPA, 1999). Bioretention facilities are primarily designed to receive stormwater runoff from nearby connected impervious areas as well as water from direct rainfall (Winogradoff & Coffman, 2001). Without bioretention facilities, urban areas conventionally have drainage inlets along their streets to capture stormwater runoff, and these transport the water into sub-surface sewer networks (Urbonas & Roesner, 1993). While sewer networks rapidly drain water away, they not able to recharge soil water stores, thus resulting in a low evapotranspiration rate. However, with a bioretention facility, water will accumulate and take a long time to infiltrate into soil due to the dense vegetation at the bottom. In this situation, bioretention facilities work as open bodies of water to enhance the EC effect. Gradually, the water that has not been evaporated slowly seeps into the underlying and surrounding soil, delivering moisture to the soil to support evapotranspiration (Mitchell et al., 2008). Excess water is either captured by an underdrain and conveyed to the storm sewer or it is captured by a groundwater recharge well for reuse in the future (FAWB, 2009). After all the water is infiltrated into the soil, the vegetated surface is exposed; thus, the EC effect of bioretention basins mainly arises from plants (Mitchell et al., 2008). In this thesis, wetlands are placed in the same category as bioretention facilities because their land surfaces consist of the same substances: living plants, soil, and water. Thus, they have similar stormwater management and EC mechanisms.

In contrast to non-canopy green parks where the cooling effect is most significant at night, studies suggest that the EC effect of bioretention facilities is more obvious during the day. This is because bioretention facilities contain water at the land surface. The surface of water can absorb a large amount of heat energy during the day due to the high Specific

Heat Capacity (SHC) of water (4.184 J/g/°C). SHC refers the heat required to increase the temperature of the unit mass of a given substance by one degree. The SHC of water is 4.184 J/g/°C, which means that 4.184 Joules of heat is needed for the temperature of one gram of water to increase 1°C. For comparison sake, the SHC of copper is only 0.385 J/g/°C and the SHC of concrete and marble is 0.880 J/g/°C. Therefore, when the temperature of the water surface decreases at night, the large amount of heat energy received in the day is released. Although bioretention facilities may still provide a cooler environment in comparison to the surrounding urban areas, because EC counteracts with the heat released from the water, the magnitude of the cooling effect at night is not as obvious as it is in the day (Coutts et al., 2012).

The key challenge of designing bioretention facilities is to balance the conflict between enhancing the EC effect and reducing stormwater runoff (Becciu et al., 2015). To increase evapotranspiration, it is better to keep the harvested water stored on the surface of bioretention facility for a longer time. However, to meet the stormwater management objective of catching runoff, a sufficient amount of space must be available in bioretention facilities. Thus, the volume for the next storm event needs to be ensured. Another challenge is to make the bioretention facilities resilient to a range of water availabilities, as they may experience both extremely dry periods and severe flooding events (Coutts et al., 2012). Irrigation systems could help keep vegetation healthy over drought periods and ensure that the bioretention facilities provide a cooling effect over an extended period of time.

### 3.7 Comparison of ECSM Practices

Based on the information presented above, ECSM practices are very effective ways to achieve a thermal comfort space in an urban area and multifunctional landscapes. These practices not only generate the EC effect, they also intercept solar radiation, improve air and water quality, improve the aesthetic experience, provide opportunities for social and cultural activities, and benefit the natural environment (Boone-Heinonen et al., 2010; Lenzholzer & van der Wulp, 2010; Van Den Berg et al., 2010). However, not all ECSM practices are beneficial in every aspect, so a deep understanding of their strengths and weaknesses is necessary in order for planners and architects to design an optimal ECSM system. This section compares the five ECSM practices from five perspectives:

(1) When considering the most efficient cooling effect, trees are the best choice, as they can block solar radiation in addition to enhancing the EC effect by evapotranspiration. Studies indicated that shading is, by far, the most effective cooling strategy in parks, and preference should be given to tree canopies to block out penetrating solar radiation and provide EC (Brown et al., 2015; Vanos et al., 2012a). Thus, urban planners and designers should focus on developing shaded green space with trees in cities, not just non-canopy green space.

(2) For ECSM development in a city with highly dense buildings, ecoroofs have the most potential. The open space among buildings for greening is quite limited in urban areas; but, the tops of commercial buildings offer a significant amount of space for ecoroofs (Copeland, 2002). In this situation, ecoroofs may be a major ECSM practice option in

the central area of cities.

(3) To meet the objective of satisfying social and cultural activities, which is a primary function of public urban space, relatively more open green spaces with less trees and permeable pavement may be more suitable than a forest-like park or densely vegetated surface, as they can offer more open spaces and safe land cover for human activities.

(4) To provide a comfortable thermal environment during the day and at night, both non-canopy green parks and trees are necessary in a city. During the day, the cooling effect mainly results from "forest parks" because their ability to reduce the temperature is much more effective than grass in non-canopy green parks when the sun is high in the sky. However, at night, "forest parks" produce a forest microclimate where moisture is easily maintained on the ground and warm air is maintained beneath the canopy (Pasternak & Schlissel, 2001). In contrast, an open short vegetation field that provides low resistance to air flow can promote cooling by convection and provide a greater cooling effect during the night (Bowler et al., 2010).

(5) Important synergies exist among different green infrastructures. Thus, a combination of different ECSM practices may enhance the EC effect. For example, if trees were integrated into bioretention facilities, then trees can receive sufficient water for evapotranspiration from the basins to lower temperatures by EC; they can also directly reduce the amount of solar radiation that strikes the surrounding land surfaces to reduce the amount of heat that must be absorbed (Akbari & Taha, 1992; Heisler and Wang, 1998).

Above all, an optimal ECSM design consists of a fit-for-space system with proper proportions of different types of ECSM practices, balancing their strengths and weaknesses to maximize the cooling effect, mitigate the UHI effect, and meet the objectives of stormwater management and the social requirements of public urban spaces.

# CHAPTER 4

# ECSM PRACTICES IN ATLANTA, GA

The objective of this chapter is to detect the spatial correlation between land surface temperature (LST) and the evaporative cooling stormwater management (ECSM) practices in Atlanta, GA, through GIS in the city-level scale. If the distribution of low temperatures is highly correlated with the location of current ECSM practices, then we can conclude that current ECSM practices are effective in reducing temperatures in Atlanta, GA.

## 4.1 Overview of Atlanta

In this chapter, the research is conducted on a city scale and focused on the City of Atlanta, which is approximately 85717.76 acres and contains a population of 463,878 by 2015 (U.S. Census Bureau, 2015). Figure 4.1 illustrates the boundary of the study area. Typical of the southeastern U.S., Atlanta has a humid subtropical climate with four distinct seasons and abundant rainfall year-round, though spring and early fall are drier (Weatherbase). Summers are hot and humid, with high temperatures reaching 90 °F (32 °C) or greater on an average 44 days per year (Weatherbase).

The city of Atlanta experienced a major growth in pavement for a population that has more than doubled since 1980 (Copeland, 2002). In this situation, stormwater cannot be absorbed by the earth in a heavily-raining city like Atlanta, and pollutants from stormwater runoff cause more than 80% of water quality damages over the past decade, which violates the Clean Water Act (Copeland, 2002). Moreover, the growing use of pavement is found to have significant warming effect in the urban core of Atlanta regardless of season (Stone et al., 2013). The intensifying UHI effect has become a common phenomenon in the Atlanta City, where temperatures do not fall below 90°F on a typical summer evening until 7:00 or 8:00 p.m., according to meteorological data from the weather station of Atlanta.

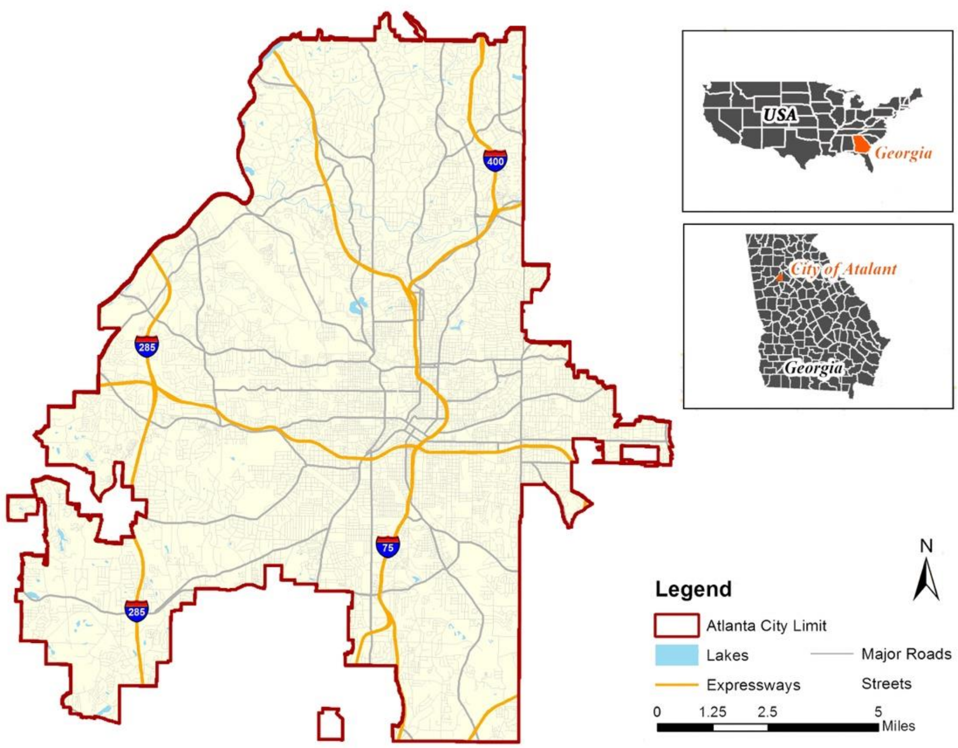



Fig. 4.1 Study Area – The City of Atlanta

(Data Source: U.S. Census Bureau)

### 4.2 Current ECSM Practices

In order to deal with the stormwater runoff and increasing UHI effect, ECSM practices have become the first-rank option in Atlanta due to their multiple functions and effectiveness. At present, the most broadly implemented practice is planting trees. Atlanta has a reputation as a "city in a forest" due to an abundance of trees that is rare among major cities around America (Brown, 2011; Bonner, 2010; Warhop, 2006), with a tree coverage percentage of 36%, the highest among all major American cities, and highly above the national average of 27% (Deep Root Blog, 2010). Stone and Norman (2006) examined the influence of trees on the temperatures of central Atlanta, and found that planting trees is a critical strategy to improve thermal environment under existing development. As indicated in their study, an increase in tree canopy cover from 45% to 60% could reduce the heat flux received into human body by 14%. However, the tree cover in Atlanta once declined from 48% to 38% during the period of 1974 to 1996 (The Tree Next Door, 2009). To prevent further declining of tree canopies, community organizations and the city government have taken multiple actions. A non-profit organization named Trees Atlanta was founded in 1985, and has planted and distributed more than 113,000 trees in the city over 30 years (Trees Atlanta, 2017). The government of Atlanta once awarded $130,000 in grants to neighborhoods to plant trees (Bonner, 2010). Atlanta also set a goal of planting 250,000 trees by 2018 in accordance with the Power to Change plan. The Power to Change plan aims to achieve sustainability of environment and culture in Atlanta, citywide. The Atlanta Tree Protection Ordinance was submitted to the Atlanta City Council on September 23,

2014. This ordinance sets rules regarding the removal of trees, the protection of healthy trees during construction, and provides guidelines about planting new trees (Aceee, 2017). The objective is to prevent a net loss of trees on both public and private property, and to ensure that Atlanta continually enjoys the benefits provided by the urban forest and the reduction of urban heat island effect.

In addition to trees, parks are the second infrastructure type to widely practice ECSM in Atlanta. Currently, there are 343 parks, nature preserves and gardens (City of Atlanta, n.d.) covering 4,990 acres in Atlanta, which is 5.9% of the total acreage (Park Score, 2016) and much lower than the national average of 10% (McWilliams, 2012; Whitney, 2012). The most iconic green space in Atlanta is Piedmont Park in Midtown, attracting visitors from around the city and hosting social and cultural events throughout the year. According to the list of parks of Atlanta, there are other well-known city parks, including Centennial Olympic Park, Woodruff Park, Grant Park, Chastain Park, and the Chattahoochee River National Recreation Area (City of Atlanta. n.d.). The latest project is the BeltLine, which increases the park space in Atlanta by 40%. The BeltLine was once a rail corridor, creating a 22-mile loop around the central area of Atlanta, and is being transformed into a series of parks connected by a multi-use trail (Benfield, 2011). So far, “six spectacular new or renovated parks” on the BeltLine are open for the public (Atlanta Beltline, 2017). One of them is Historic Fourth Ward Park, with an innovative storm water retention lake that provides pleasant scenery and outdoor entertainment space for people.

Also, in recent years, Atlanta has joined the green roof movement. Green roofs are proposed as a good measurement in stormwater management and UHI effect mitigation. Benjamin Taube, the Atlanta Environmental Manager, supports ecoroof in saying, “It could help substantially because commercial roofs are huge spaces.” (Copeland, 2002). The Atlanta City Council is making effort to promote green roofs as one of the many measures for sustainable design and urban heat island mitigation that can be implemented in the City of Atlanta. The first practice was the Atlanta City Hall Pilot Green Roof, which was constructed with the goal of setting an example of sustainable and ecological design, and to “generate reliable technical data on green roof performance in areas such as energy efficiency, stormwater retention, temperature cooling, and plant survival” (Greenroofs, n.d.). However, compared to trees and parks, the number of green roofs in Atlanta is still small and growing.

Besides the remarkable movements illustrated above, a number of unimpressive but important efforts have been made in Atlanta, especially in the southeast (City of Atlanta, 2017):

(1) After a storm event in July 2012, eight short-term projects were developed by the Department of Watershed Management (DWM) to reduce runoff as soon as possible, including bio-swales installed along Crumley Street and Rosa Burney Park, and rain gardens constructed close to Dunbar Elementary School and on Ira and Sydney streets.

(2) In February 2014, a vault for five-million-gallons of water was constructed under the

parking lot at Turner Field, in assistance to the goal of alleviating flooding in the long run.

(3) Six miles of permeable pavement is under construction by the government in the watersheds of Peoplestown, Mechanicsville and Summerhill. The permeable pavement is designed to reduce runoff caused by storm events on roads and adjacent sidewalks.

(4) The number of cleaned catch basins has been doubled by the Atlanta's water/sewer infrastructure improvement program.

(5) Rainwater harvesting infrastructure is planned to be constructed in all of the city's recreation centers and maintenance facilities by the DWM.

Although these measures are not primarily designed for mitigating the UHI effect, they have the potential to function as ECSM practices in the future with a bit of improvement.

## 4.3 Spatial Correlation Analysis

### 4.3.1 LST Retrieval from Remote Sensing Data

Land Surface Temperature (LST) retrieval from satellite data has been widely adopted by researchers specializing in climatology since remotely-sensed data became available for the public (Yang et al., 2013). The remote sensing data for this research is provided by the Landsat Enhanced Thematic Mapper (ETM+) sensor with Landsat 7 satellite. The satellite sensors measure the top layer of the atmosphere and re-scan a location every 16 days (Voogt et al., 2003). To evaluate the maximum intensity of UHI effect, summer days with clear atmospheric conditions are preferred over cloudy or rainy days. As showed in Figure 4.2, the best quality data for this study was available on June 20th, 2016.

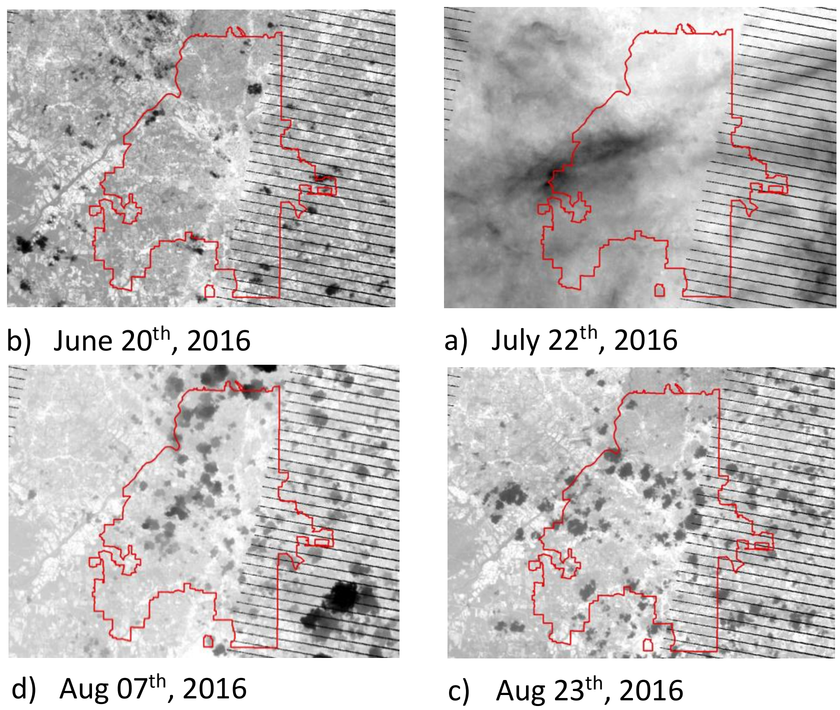



Fig. 4.2 High Spatial Resolution (60-m) Satellite Images Provided by ETM+ Sensor with Landsat 7 Satellite

(Data Source: United States Geological Survey (USGS))

The temperature data recorded by satellite is stored as digital number (DN). To convert DN to the actual temperature values, a third-step process needs to be completed according to the Landsat 7 Handbook. At first, DNs are converted to spectral radiance L ($Wm^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$, the radiance of a surface per unit wavelength) by the following equation (Landsat Science, 2016):

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{QCALMAX - QCALMIN}\right) * (QCAL - QCALMIN) + LMIN_\lambda$$

where:

$L_\lambda$ = Spectral Radiance at the sensor's aperture in watts / (meter squared * ster * µm)

$QCAL$ = the quantized calibrated pixel value in DN

$QCALMIN$ = the minimum quantized calibrated pixel value (corresponding to $LMIN_\lambda$) in DN

= 1 for LPGS products

= 1 for NLAPS products processed after 4/4/2004

= 0 for NLAPS products processed before 4/5/2004

$QCALMAX$ = the maximum quantized calibrated pixel value (corresponding to $LMAX_\lambda$) in DN

= 255

$LMIN_\lambda$ = the spectral radiance that is scaled to QCALMIN in watts / (meter squared * ster * µm), provided by the illustration document of satellite data

$LMAX_\lambda$ = the spectral radiance that is scaled to QCALMAX in watts / (meter squared * ster * µm), provided by the illustration document of satellite data

Second, the spectral radiance values can be converted to surface temperatures, which is also called “effective at-satellite temperatures” (Landsat Science, 2016). In addition, two pre-launch calibration constants K1 and K2 are used in this calculation (Table 4.1). The conversion equation (Landsat Science, 2016) is:

$$T = K2/\ln(\frac{K1}{L_\lambda} + 1)$$

where:

T = Effective at-satellite temperature in Kelvin

K2 = Calibration constant 2 from Table 4.1

K1 = Calibration constant 1 from Table 4.1

$L_\lambda$ = Spectral radiance in watts / (meter squared * ster * μm)

Table 4.1 ETM+ and TM Thermal Band Calibration Constants

| | **Constant 1 – K1** watts / (meter squared * ster * μm) | **Constant 2 – K2** Kelvin |
|---|---|---|
| Landsat 7 | 666.09 | 1282.71 |
| Landsat 5 | 607.76 | 1260.56 |

Data Source: Landsat Science, 2016

The final step is to correct the temperatures acquired above by surface emissivity of different land covers, so as to retrieve the actual Land Surface Temperature (LST). Thermal data recorded by satellite sensors is captured on top of the atmosphere (Weng, 2009). However, the thermal data acquired by sensors is affected by the emissivity of constituents in the atmosphere, such as constructions, soils and water. Thus the original data should be corrected for emissivity to calculate the actual LST (Stathopoulou, et al. 2007; Weng, 2009). Stathopoulou and Cartalis (2006) suggested applying surface emissivity for each specific LULC type with the following values (Table 4.2):

Table 4.2 Emissivity Values by LULC Class

| LULC class | Emissivity values |
|---|---|
| Urban high density built | 0.946 |
| Urban medium density built | 0.950 |
| Urban low density built | 0.964 |
| Agriculture (crops) | 0.980 |
| Agriculture (bare) | 0.946 |
| Vegetation | 0.980 |
| Water | 0.990 |

Source: Stathopoulou and Cartalis, 2006

The corrected LST is computed as follows (Yang et al., 2013):

$$T_s = \frac{BT}{\left\{1 + \left[\frac{\lambda BT}{\rho} \cdot ln\mathcal{E}\right]\right\}}$$

where:

$T_s$ = corrected LST in Kelvin

BT = effective at-satellite temperature in Kelvin acquired in the second step

$\lambda$ = the wavelength of emitted radiance (11.5 µm)

$\rho$ = 1.438 * $10^4$ µm K

$\varepsilon$ = the spectral surface emissivity from Table 4.2

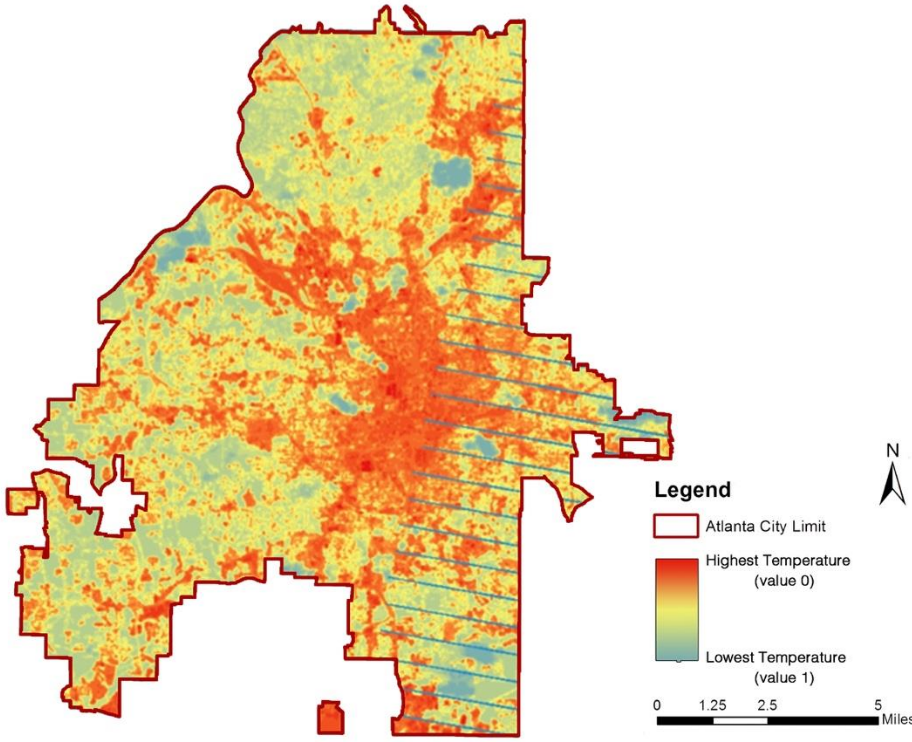



Fig 4.3 LST Distribution in The City of Atlanta
(Data Source: United States Geological Survey (USGS))

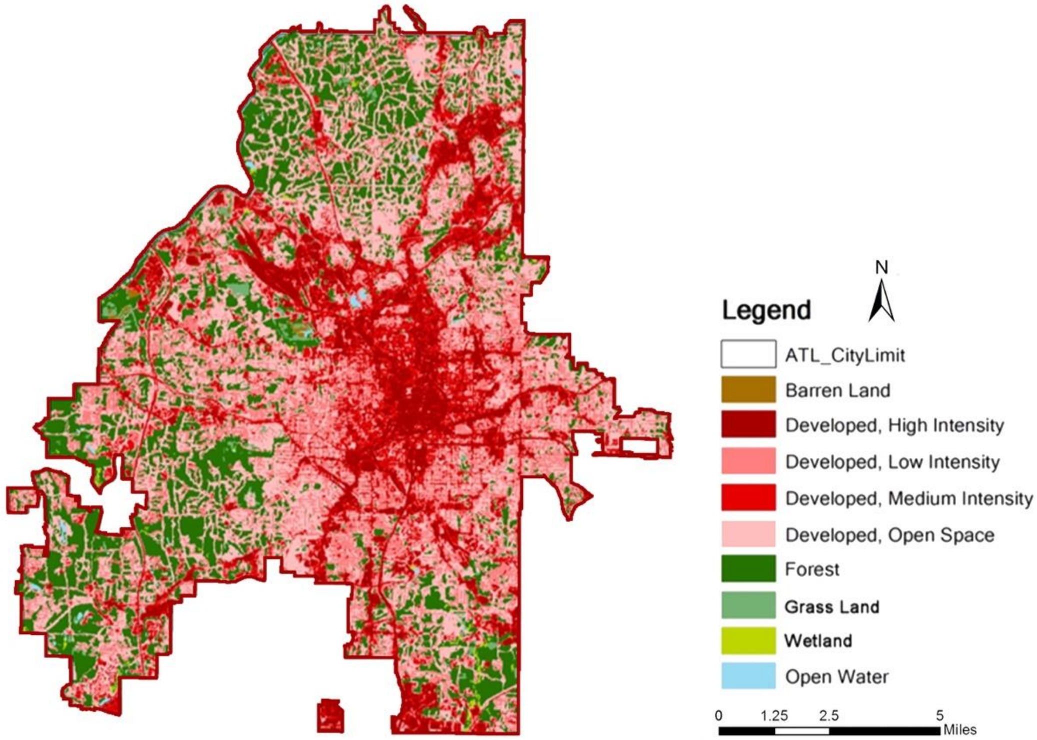



Fig 4.4 LULC in The City of Atlanta
(Data Source: LULC data (2011 edition; 30-m resolution) from NLCD)

Note: the classification of land cover in this map is a result of reclassification. The original classification of land cover is illustrated in Table 5.2 in Chapter 5. Forest includes "Deciduous Forest", "Evergreen Forest" and "Mixed Forest". Grassland consists of "Shrubland", "Herbaceous" and "Planted/Cultivated". Open water, barren land, wetland and the four kinds of developed lands are same with the original classification and description.

After conducting the three steps above, the LST distribution map in the City of Atlanta (Figure 4.3) is produced. Compared with the LULC map of Atlanta (Figure 4.4), it is evident that the areas with high density buildings have higher temperatures, especially around city center, while the areas covered by greens are much cooler. As the distance from the central part of Atlanta increases, so does the green space, and the temperature decreases. This result is consistent with the demonstrations in the literatures reviewed in the chapters above. In the next chapter, further examination is conducted to check the spatial relationship between Atlanta's ECSM and LST.

### 4.3.2 Spatial Relationship Between ECSM and LST

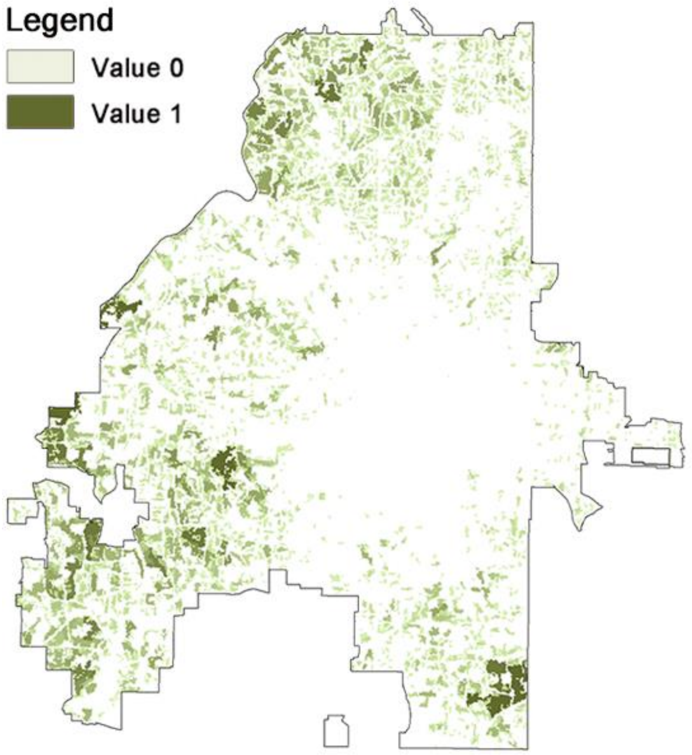
In order to relate ECSM and LST, the cover area of each major ECSM practice in Atlanta is required. The distribution of forest, grassland and wetland are separated from the LULC map as raster maps; the raster map of permeable surface is developed based on Imperviousness data (the 4 "Developed" categories on the Land Cover map on the previous page) from NLCD. Forests represent the ECSM practice of trees; grassland includes the areas with short vegetation, meaning non-canopy green space; wetlands are serving as bioretention facility in this section because of their similar land surface and evaporative cooling mechanism; permeable pavement is illustrated by the percentage of pervious land surface in a unit (30 m by 30 m) determined by the data resolution, other than the exact land cover of permeable pavement. Ecoroofs are not included in this analysis since the number of ecoroofs in Atlanta, so far, is too small to support the calculation in this section. An efficient way to visualize the spatial relationship between ECSM and LST is to normalize the values of raster maps on a 0 – 1 scale by raster calculator, and then multiply each normalized ECSM practice raster map with the normalized LST raster map separately in GIS. This analysis is focused on the cooling effectiveness of ECSM practices in space, or in other words, the relationship between the distribution of low temperature and the ECSM practices. For this purpose, the areas with the lowest temperature are normalized as 1 while the areas with the highest temperature as 0, and the medium thermal areas between 0 to 1. Meanwhile, the areas covered by most forests, grass lands, wetlands or permeable pavement are quantified as 1 while the areas without these kinds of land surfaces as 0. The areas covered with a medium amount of these kinds of land surfaces are quantified as values ranging from 0 to 1. The detailed normalization processes for raster maps of ECSM practices and LST are illustrated in Table 4.3. Multiplying the normalized maps of ECSM practices (Figure 4.5 (a1, b1, c1, d1) ) and LST, we acquire the spatial correlation maps (Figure 4.5 (a2, b2, c2, d2)). In these maps, the spaces with values closer to 1 (darker color) demonstrate higher spatial correlation between ECSM practices and LST in these areas.

Table 4.3 Normalization Process

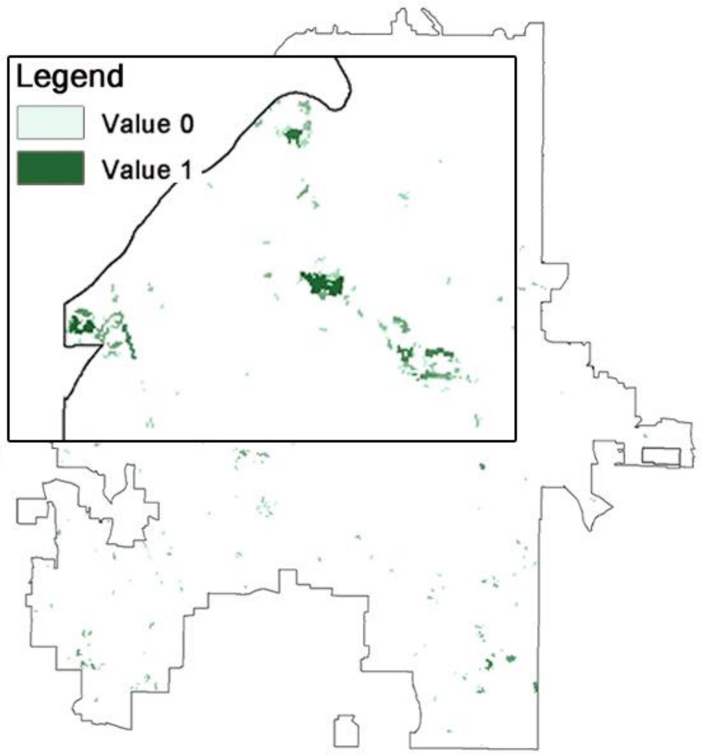
| Maps | Normalization Process |
|---|---|
| Normalized LST Map (Fig. 4.3) | a. identify maximum and minimum value of LST raster map<br>b. normalize its values by raster calculator as below:<br>$1 - \frac{values\ \ of\ \ LST\ \ raster\ \ map - minimum\ \ value}{maximum\ \ value - minimum\ \ value}$<br>c. in the normalized LST map, 1 means the lowest temperature, 0 means the highest temperature |
| Normalized Forest Map (Fig. 4.5 (a1)) | a. export data of forest from LULC map into a new layer<br>b. create density map of forest based on the new layer by the tool of Kernel Density, the density map is a raster map<br>c. identify maximum and minimum values of density map<br>d. normalize density values by raster calculator as below:<br>$\frac{values\ \ of\ \ density\ \ map - minimum\ \ value}{maximum\ \ value - minimum\ \ value}$<br>e. in the normalized forest map, 1 means the highest density of forests, 0 means the lowest |
| Normalized Grassland Map (Fig. 4.5 (b1)) | Same as the normalization process of forest map |
| Normalized Wetland Map (Fig. 4.5 (c1)) | Same as the normalization process of forest map |
| Normalized Permeable Surface Map (Fig. 4.5 (d1)) | a. create raster map of imperviousness based on Imperviousness data (2011 edition) from NLCD<br>b. identify maximum and minimum value of imperviousness<br>c. normalize values by raster calculator as below:<br>$1 - \frac{values\ \ of\ \ imperviousness - minimum\ \ value}{maximum\ \ value - minimum\ \ value}$<br>d. in the normalized permeable surface map, 1 means the most percentage of permeable surface, 0 means the least |

Overall, these four ECSM practices have high spatial correlations with the low temperature environments as the results demonstrated in Figure 4.5 (a2, b2, c2 and d2). This indicates that these types of ECSM practices are greatly effective in lowering temperatures within the city of Atlanta. Also, the distribution maps of ECSM practices (Figure 4.5, a1, b1, c1 and d1) are highly overlaid with the spatial correlation maps (Figure 4.5, a2, b2, c2 and d2). The spaces covered with more ECSM practices have higher spatial correlation with cooler areas, which reveals a negative correlation between ECSM and LST, at least in Atlanta. The more spaces of ECSM practice, the lower surface temperature within these areas. This result supports the illustrations in previous studies. Therefore, applying more of these four ECSM practices can be an efficient way to mitigate UHI within Atlanta in future.

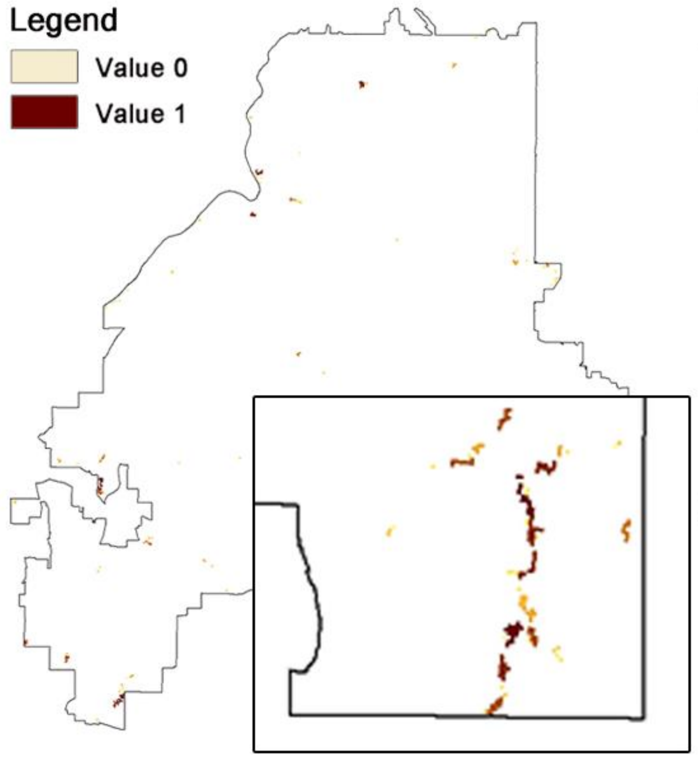
The results of this section only provide a visual analysis of the ECSM-LST relationship in the field of spatial correlation, and a more statistical approach should be applied to further research the relationship between them. These results only consider the on-site cooling effect of ECSM practices, but the cooling effect of these practices extended to the surroundings is not able to be taken into consideration in this analysis. More statistical and convincing research is carried in the next chapter.



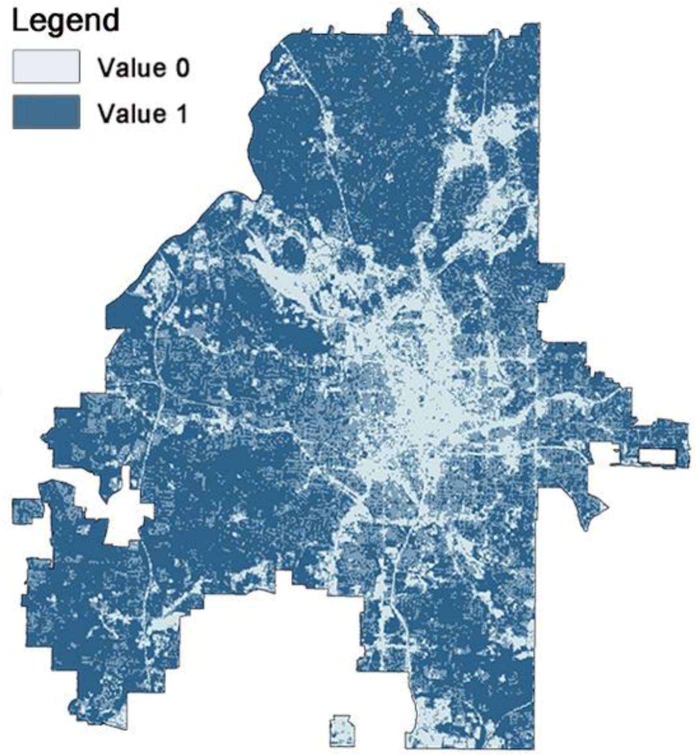

(a1) Distribution of Forests



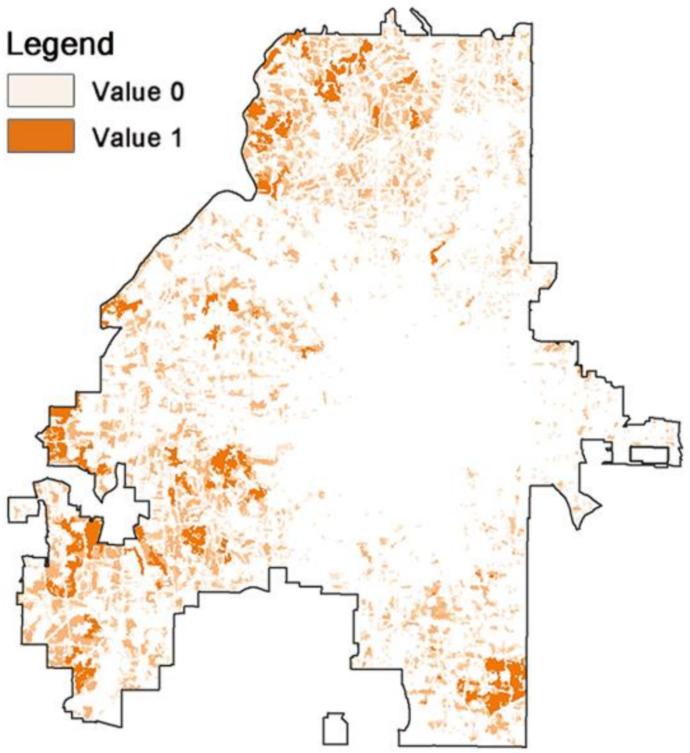

(b1) Distribution of Grass Land



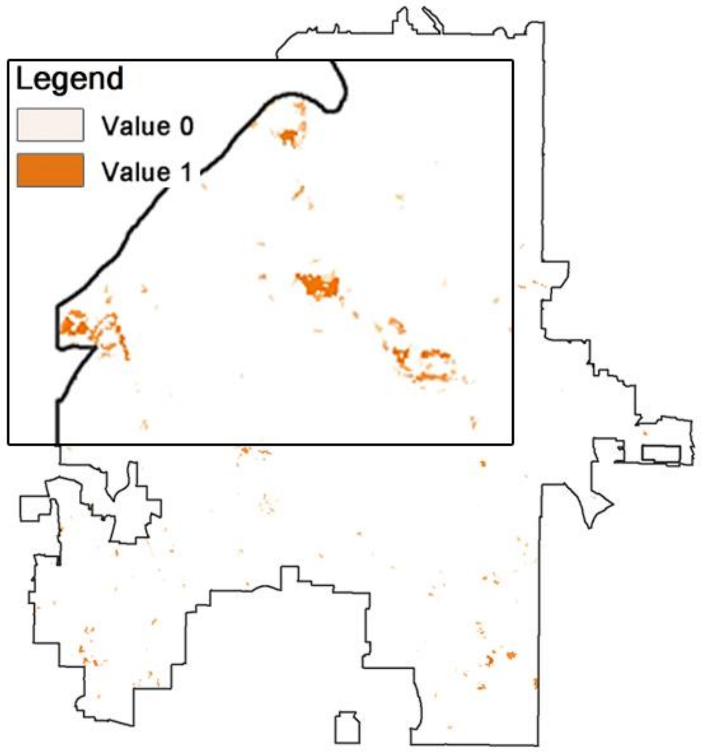

(c1) Distribution of Wetland



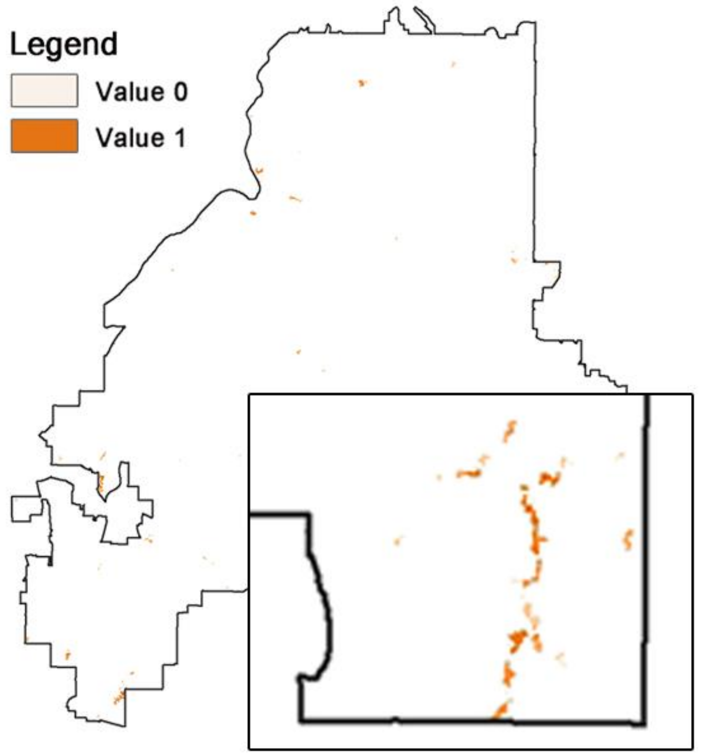

(d1) Distribution of Permeable Surface



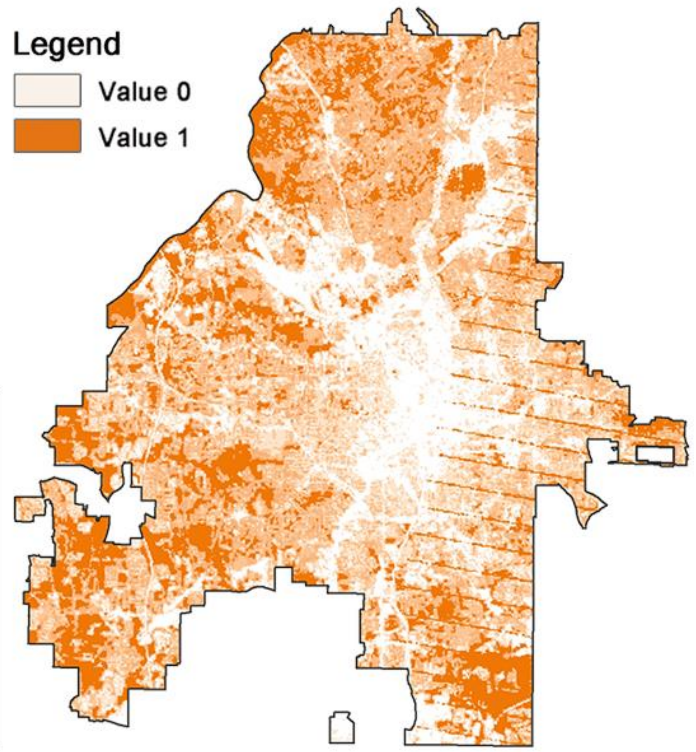

(a2) Spatial Correlation between LST and Forests




(b2) Spatial Correlation between LST and Grass Land




(c2) Spatial Correlation between LST and Wetland




(d2) Spatial Correlation between LST and Permeable Surface

Fig 4.5 Distribution of ECSM Practices and Their Spatial Correlation Values with LST. (Data Source: LULC data (2011 edition) from NLCD; Imperviousness data (2011 edition) from NLCD)

# CHAPTER 5

# PRACTICE SCENARIOS AND SIMULATIONS IN ATLANTA, GA

In the previous chapter, we learned that ECSM practices are effective for reducing Atlanta's temperatures on the city-level scale. However, many aspects of the relationship between temperature and ECSM practices remain unknown, such as which practice contributes the most to the lowering of temperatures, how the surrounding environment influences the cooling effect produced by the practices, and so on. Accordingly, the objective of this chapter is to examine the effectiveness of ECSM practices in terms of cooling the thermal environment on a neighborhood-level scale, looking at two key elements. The first is how evapotranspiration rates affect temperatures over the course of one day, while the second is which type of ECSM practice has the best cooling effect in a certain type of urban environment. The results can be used as guidance for the development of reasonable and optimal ECSM designs in the corresponding neighborhoods of Atlanta.

## 5.1 Conditions of Simulation Areas

### 5.1.1 Watersheds for Simulation

As illustrated before, the simulations were conducted in three watersheds that were selected due to having different characteristics in each of their environments. To use watershed as study unit follows the research conducted by Yang et al. (2013). They studied three watersheds, using watershed as analyzing unit, to discuss how to design with nature for multifunctional landscapes The boundaries of the watersheds in this thesis are defined by the data from the National Hydrography Dataset (NHD) from the U.S. Geological Survey (USGS). Watershed 1 is named Peachtree Creek, and its Hydrologic Unit Code (HUC) is 031300011204. Watershed 2 is Proctor Creek-Chattahoochee River with HUC of 031300020101. Watershed 3 is Utoy Creek with HUC of 031300020103. Figure 5.1 shows the location of the three watersheds. As can be seen, they extend across a large spread of land from areas in or near the city center to suburban areas near or even outside the city boundary. Peachtree Creek watershed (Watershed 1) is totally included in the City of Atlanta and covers the central urban area. Proctor Creek-Chattahoochee River watershed (Watershed 2) and Utoy Creek watershed (Watershed 3), meanwhile, are close to, but not part of, the city center and both extend outside the city boundary into the suburban zone. In this study, the simulations were conducted in the entire area of the three watersheds, including the areas outside the City of Atlanta. Although the areas outside the city boundary are lying in suburban space, they also should be included in simulation area. Stone et al. (2013) found that the land surface alteration in the suburban zones of the Atlanta region could have a statistically significant effect on the thermal environment of the urban core. Considering these findings, the ECSM practices implemented beyond the major developed urban regions may also play a critical role in improving the climate conditions. In such a situation, it was essential to conduct experiments throughout the whole coverage area of the three watersheds.

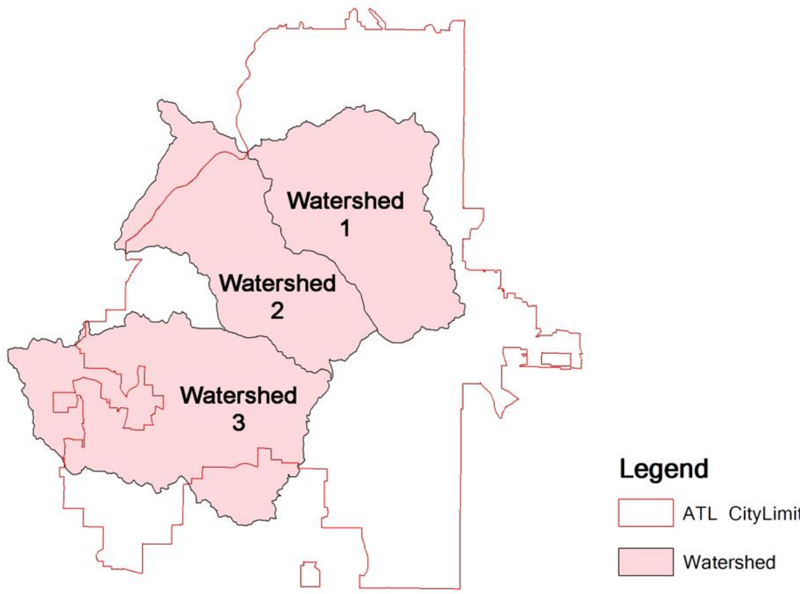



Fig. 5.1 Watersheds for Simulation

(Data Source: National Hydrography Dataset (NHD) from USGS)

### 5.1.2 Retrieve Land Cover Information

In order to examine the current land cover conditions in the three watersheds, the following process is conducted in GIS with the National Geospatial Data Asset (NGDA) Land Use Land Cover (LULC) data (2011 edition; 30-m resolution) from NLCD. This process can be expressed in 8 steps (use Watershed 1 as an example):

(1) Calculate the area of Watershed 1 by its HUC boundary and the result is 15427.25 acres.

(2) Use the tool of "extract by mask" to acquire the raster map of land cover in the area of Watershed 1.

(3) Convert the raster map acquired in step (2) to map of polygon; and project the polygon map to the coordinate system of NAD 1983 StatePlane Georgia West (US Feet), so as to acquire the land cover map of Watershed 1.

(4) Open the attribute table of the land cover map of Watershed 1; add a field of "Area" to the table and add values to this field by "calculate by geometry".

(5) Summarize the field of "Area" by the category of land covers to acquire the area of each type of land cover in Watershed 1. The sum of areas of all the land covers is 15404.16 acres, around 20 acres missing compared with the area of Watershed 1 that calculated in step (1) for unknown reason. The spatial resolution of the original data (30 meter) that was converted to vector could be a potential explanation for the missing acreage.

(6) Add a field of "Percentage" to the summarizing table acquired in step (5). The values of this field is calculated as below:

$$\frac{area\ \ of\ \ each\ \ type\ \ of\ \ land\ \ cover\ \ (acres)}{area\ \ of\ \ Watershed\ \ 1\ \ (15427.25\ \ acres)} * 100 = Percentage$$

"Percentage" represents the fraction of each type of land cover in Watershed 1. Because of the missing 20 acres mentioned in step (5), the sum of "Percentage" in Watershed 1 is about 99.85% other than 100%.

(7) Reclassify the land covers into 6 categories: developed land, open water, barren land, forest, short vegetation and wetland. The original classification and

description of land covers are listed in Table 5.2. Developed land consists of "Developed, Open Space", "Developed, Low Intensity", "Developed, Medium Intensity" and "Developed, High Intensity". Forest includes "Deciduous Forest", "Evergreen Forest" and "Mixed Forest". Grassland is made of "Shrubland", "Herbaceous" and "Planted/Cultivated". Open water, barren land and wetland are same with the original classification and description.

(8) Calculate the percentage of land covers based on the reclassified categories.

Above steps are repeated in the other two watersheds. Then the current land cover conditions of each watershed (Table 5.1) are acquired.

Table 5.1 Current Conditions of Simulation Watersheds.

| **Watershed Name** | | **Peachtree Creek** | **Proctor Creek-Chattahoochee River** | **Utoy Creek** |
|---|---|---|---|---|
| Watershed Character | | Commercial | Low-greened Residential | High-greened Residential |
| **Land Cover Fraction** | Developed Land | 86.29% | 80.67% | 64.49% |
| | Open Water | 0.42% | 0.84% | 0.50% |
| | Barren Land | 0.03% | 0.55% | 0.02% |
| | Forest | 12.88% | 14.97% | 33.17% |
| | Grassland | 0.17% | 2.44% | 1.27% |
| | Wetland | 0.06% | 0.27% | 0.38% |
| Total Acres of Watershed | | 15427.25 | 15226.70 | 22361.60 |

Data Source: LULC data (2011 edition; 30-m resolution) from NLCD

Table 5.2 Classification Description of Land Covers in LULC Dataset (Data Source: cited from NLCD)

| Class\ Value | Classification Description |
|---|---|
| Water | **Open Water**- areas of open water, generally with less than 25% cover of vegetation or soil. |
| | **Perennial Ice/Snow**- areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover. |
| Developed | **Developed, Open Space**- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. |
| | **Developed, Low Intensity**- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units. |
| | **Developed, Medium Intensity** -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units. |
| | **Developed High Intensity**-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover. |
| Barren | **Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover. |
| Forest | **Deciduous Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change. |
| | **Evergreen Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage. |
| | **Mixed Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover. |
| Shrubland | **Dwarf Scrub**- Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation. |
| | **Shrub/Scrub**- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions. |
| Herbaceous | **Grassland/Herbaceous**- areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing. |
| | **Sedge/Herbaceous**- Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra. |
| | **Lichens**- Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation. |
| | **Moss**- Alaska only areas dominated by mosses, generally greater than 80% of total vegetation. |
| Planted/Cultivated | **Pasture/Hay**-areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation. |
| | **Cultivated Crops** -areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled. |
| Wetlands | **Woody Wetlands**- areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |
| | **Emergent Herbaceous Wetlands**- Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |

As shown in Table 5.1, Watershed 1 is a typical environment with a commercial character and a large percentage of developed areas while it has the least amount of green space (including forests, grassland and wetland) of all three sites. In fact, almost no grassland exists within this watershed. Watershed 2, as a low-greened residential zone, has a relatively smaller proportion of developed land surface and a slightly greater amount of forests and grasslands. Finally, the high-greened residential site of Watershed 3 has the highest amount of green space and the lowest proportion of developed land cover. There is a roughly equal amount of green land surface and acres covered by developed land in this watershed. In addition, the vegetated portion is almost double each of the other two watersheds, with around 99% of the green space consisting of trees. Despite their variations, all three watersheds have land cover of open water bodies, barren land, grassland and wetland. Therefore, the major elements of the land surface in these watersheds are developed spaces and trees. The abundance of the latter is the result of a raft of policies and actions initiated by various organizations and the city government after 1996 to prevent their decline.

**5.2 ECSM Practice Scenarios**

We created five scenarios based on the type of primary ECSM practice used in design and applied them to each of the three watersheds using LUMPS (Table 5.3–5.7). To make the scenarios more practical, the land surfaces covered by buildings in the developed spaces had to be kept unaltered, as it is nearly impossible to recreate the construction environment in practice. Therefore, all modifications when using ECSM practices were implemented in areas of roofs above buildings, impervious pavement, barren areas, and green spaces. In Scenario 1, we considered the use of ecoroofs as Atlanta's primary strategy to mitigate UHI. In this first scenario, ecoroofs with a proportion of 15% of the entire land cover in each watershed were produced on the tops of buildings. In this case, the total percentage of green space increased by 15% due to the ecoroofs, while the fraction of the rest remained unchanged. In Scenario 2, we simulated the city using ECSM that was oriented by the practice of installing non-canopy green parks. This scenario replaced 15% of the land surface with non-canopy grasslands by exchanging all barren land with the corresponding amount of impervious covers in developed land. In this situation, grasslands would become another major element of green space in addition to trees. The proportion of grassland would be even greater than that of the trees in Watersheds 1 and 2, but would still be smaller in Watershed 3. To achieve this objective in practice, our main recommendation is to replace superfluous impermeable pavement in squares and parks with turf. Besides its potential to improve thermal comfort, grassland also provides more pleasant entertainment spaces than concrete and is more conducive to activities such as walking, jogging, or simply relaxing in a park. In addition, as grassland is fairly open and easily accessible for humans, it can be applied in a broad range of public spaces so long as it does not disrupt the movement of pedestrian and vehicles. With this in mind, a 12" strip of concrete cut from a sidewalk, a buffer space for municipal facilities, or a concrete apron around buildings are other options to be considered alongside grasses. Although the cooling effect of the increased grass surface may vary due to the resultant different sizes and shapes, the results of the simulation will not be influenced as the inputs are only related to the proportion of land cover. Then, in Scenario 3 we used trees as the main strategy to improve the thermal comfort of citizens. This scenario increased land surface that is under the coverage of forests by 15%, with a reduction in barren land and impervious areas. In terms of land cover proportions, Scenarios 2 and 3 are similar as they involve the same amount of increased green space and reduced barren land and impervious pavement in developed space. However, they may have varied results in terms of the cooling effect, since their essential difference in surface humidity conditions is determined by the characteristics of trees and grasses. In addition, the increased proportion of grassland in Scenario 2 and that of the tree canopy in Scenario 3 are both effected by the reduction in barren land and impervious pavement to the same percentages; therefore, it is necessary to examine which of them has the better cooling effect in the same situation. However, the reduction of barren land and impervious pavement in developed space are not the only two options for bolstering the proportion of land covered by tree canopy. In fact, the planting of trees on grassland and the introduction of bioretention facilities are also highly appropriate strategies. Scenario 4 assumes that permeable pavement will become the leading ECSM practice in the city of Atlanta. Here, the proportion of impervious areas is reduced by 15%, to be replaced by permeable pavement; the remaining land surfaces are unmodified. In this scenario, the essential factor is the use of permeable pavement materials. According to the experiment conducted by Li et al. (2014), pavement materials, excepting sand which has greater amounts of air voids and higher permeability, have higher evaporation rates on their surface. Therefore, asphalt and concrete pavements in parks, parking lots, or pedestrian paths can be replaced by gravel materials and fine sand. Finally, in Scenario 5, the objective is to primarily use bioretention facilities to exert an evaporative cooling effect on the urban area. To transform 15% of the total land surface into such facilities, 10% of the grassland would be redeveloped as bioretention basins and swales; all the barren land would be converted into bioretention facilities; and 5% of impervious areas in developed space (such as concrete open gutters and superfluous impervious pavement in squares or parks) would be redeployed as bioretention cells and swales along streets or sidewalks; the rest would be transferred from the tree canopy. In this simulation, as the land cover that could be used for bioretention facilities is extremely limited, nearly half of the trees in Watershed 3 and almost all trees in Watersheds 1 and 2 would be eliminated. In fact, it is not necessary to remove trees when applying bioretention facilities; it is more practical to integrate them. The reason for eliminating trees in this research is that forested bioretention facilities would be counted in the category of forest in the simulations. In this scenario, the green space is dominated by bioretention facilities.

Table 5.3 Land Cover Fractions in Scenario 1 – Ecoroof

| **Watershed Name** | | **Peachtree Creek** | **Proctor Creek-Chattahoochee River** | **Utoy Creek** |
|---|---|---|---|---|
| Watershed Character | | Commercial | Low-greened Residential | High-greened Residential |
| **Land Cover Fraction** | Developed Land | 86.29% | 80.67% | 64.49% |
| | Ecoroof | +15.00% | +15.00% | +15.00% |
| | Open Water | 0.42% | 0.84% | 0.50% |
| | Barren Land | 0.03% | 0.55% | 0.02% |
| | Forest | 12.88% | 14.97% | 33.17% |
| | Grass Land | 0.17% | 2.44% | 1.27% |
| | Wetland | 0.06% | 0.27% | 0.38% |
| Total Acres of Watershed | | 15427.25 | 15226.70 | 22361.60 |

Note: ecoroof is included in developed land. (Data Source: altered based on Table 5.1)

Table 5.4 Land Cover Fractions in Scenario 2 – Non-canopy Green Parks

| **Watershed Name** | | **Peachtree Creek** | **Proctor Creek-Chattahoochee River** | **Utoy Creek** |
|---|---|---|---|---|
| Watershed Character | | Commercial | Low-greened Residential | High-greened Residential |
| **Land Cover Fraction** | Developed Land | 71.32% (-14.97%) | 66.22% (-14.45%) | 49.51% (-14.98%) |
| | Open Water | 0.42% | 0.84% | 0.50% |
| | Barren Land | 0.00% (-0.03%) | 0.00% (-0.55%) | 0.00% (-0.02%) |
| | Forest | 12.88% | 14.97% | 33.17% |
| | Grass Land | 15.17% (+15%) | 17.44% (+15%) | 16.27% (+15%) |
| | Wetland | 0.06% | 0.27% | 0.38% |
| Total Acres of Watershed | | 15427.25 | 15226.70 | 22361.60 |

Note: the decrease in developed land represents converting impervious pavement into grassland. (Data Source: altered based on Table 5.1)

Table 5.5 Land Cover Fractions in Scenario 3 – Trees

| **Watershed Name** | | **Peachtree Creek** | **Proctor Creek-Chattahoochee River** | **Utoy Creek** |
|---|---|---|---|---|
| Watershed Character | | Commercial | Low-greened Residential | High-greened Residential |
| **Land Cover Fraction** | Developed Land | 71.32% (-14.97%) | 66.22% (-14.45%) | 49.51% (-14.98%) |
| | Open Water | 0.42% | 0.84% | 0.50% |
| | Barren Land | 0.00% (-0.03%) | 0.00% (-0.55%) | 0.00% (-0.02%) |
| | Forest | 27.88% (+15%) | 29.97% (+15%) | 48.17% (+15%) |
| | Grass Land | 0.17% | 2.44% | 1.27% |
| | Wetland | 0.06% | 0.27% | 0.38% |
| Total Acres of Watershed | | 15427.25 | 15226.70 | 22361.60 |

Note: the decrease in developed land represents converting impervious pavement into trees. (Data Source: altered based on Table 5.1)

Table 5.6 Land Cover Fractions in Scenario 4 – Permeable Pavement

| **Watershed Name** | | **Peachtree Creek** | **Proctor Creek-Chattahoochee River** | **Utoy Creek** |
|---|---|---|---|---|
| Watershed Character | | Commercial | Low-greened Residential | High-greened Residential |
| **Land Cover Fraction** | Developed Land | 86.29% | 80.67% | 64.49% |
| | Impervious Pavement | -15.00% | -15.00% | -15.00% |
| | Permeable Pavement | +15.00% | +15.00% | +15.00% |
| | Open Water | 0.42% | 0.84% | 0.50% |
| | Barren Land | 0.03% | 0.55% | 0.02% |
| | Forest | 12.88% | 14.97% | 33.17% |
| | Grass Land | 0.17% | 2.44% | 1.27% |
| | Wetland | 0.06% | 0.27% | 0.38% |
| Total Acres of Watershed | | 15427.25 | 15226.70 | 22361.60 |

Note: altering impervious pavement into permeable pavement is conducted in the area of developed land. (Data Source: altered based on Table 5.1)

Table 5.7 Land Cover Fractions in Scenario 5 – Bioretention Facility

| **Watershed Name** | | **Peachtree Creek** | **Proctor Creek-Chattahoochee River** | **Utoy Creek** |
|---|---|---|---|---|
| Watershed Character | | Commercial | Low-greened Residential | High-greened Residential |
| **Land Cover Fraction** | Developed Land | 81.99% (-4.3%) | 76.67% (-4.0%) | 61.29% (-3.2%) |
| | Open Water | 0.42% | 0.84% | 0.50% |
| | Barren Land | 0.00% (-0.03%) | 0.00% (-0.55%) | 0.00% (-0.02%) |
| | Forest | 2.23% (-10.65%) | 4.76% (-10.21%) | 21.51% (-11.66%) |
| | Grass Land | 0.15% (-0.02%) | 2.20% (-0.24%) | 1.15% (-0.12%) |
| | Wetland | 0.06% | 0.27% | 0.38% |
| | Bioretention Facility | +15.00% | +15.00% | +15.00% |
| Total Acres of Watershed | | 15427.25 | 15226.70 | 22361.60 |

(Data Source: altered based on Table 5.1)

## 5.3 Simulation Results

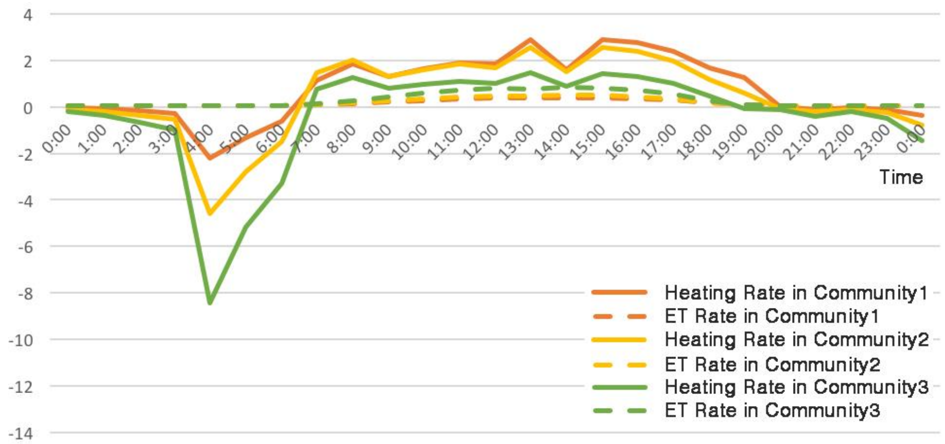
### 5.3.1 Cooling Effect and Evapotranspiration

In this section, we will examine the hourly change of evapotranspiration and heating rates during one day (24 hours) in different scenarios and watersheds (Figure 5.3). The available hourly meteorological data for this research were collected during July and August 2016 and were provided by the College of Agriculture and Environmental Sciences at the University of Georgia. We used the data from July 25$^{th}$ to conduct simulations, as it was the hottest day in Atlanta during this period according to the University of Georgia Weather Network. In Figure 5.3, it can be seen that the air becomes warmer when the heating rates are positive numbers, while the temperature lowers when said rates are lower than zero. Therefore, the negative numbers of heating rates imply a cooling effect in this analysis, with the lower the rate, the larger the effect. There is a sharp drop in the heating rate around 3 to 7 a.m. in every line chart, which may be caused by the unusual reduction in wind speed within this period (Figure 5.2). Despite this, Figure 5.3 indicates that there is a positive correlation between evapotranspiration rate and atmospheric heating rate during the entire day, as both of them rise and fall at closely aligned times. However, this is more likely to be a result of the fluctuation of solar radiation, which increases around 7 a.m. and reduces around 8 p.m.; a broadly similar effect is seen with the fluctuation of the heating and evapotranspiration rates. This may be reasonable in some sense, since solar radiation determines the amount of heat provided for evapotranspiration and heating the atmosphere.

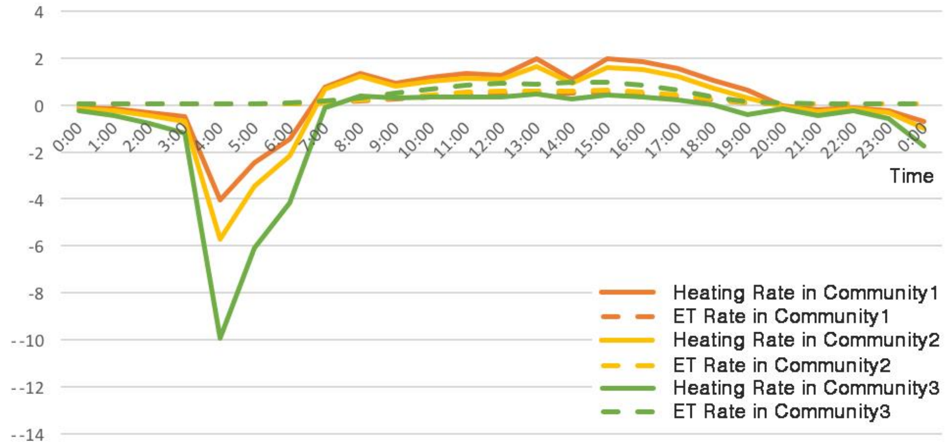

Fig 5.2 Hourly Wind Speeds During July 25th, 2016
(Data Source: College of Agriculture and Environmental Sciences, University of Georgia)

In contrast, we found an inverse relationship between evapotranspiration and heating rate; the higher the evapotranspiration rate, the lower the heating rate. In every scenario, all the heating rates in Watershed 3 are the lowest with the highest evapotranspiration rates, while the situations in Watershed 1 are the opposite. Meanwhile, when the overall evapotranspiration rates increase in any one of the three watersheds, the heating rates will simultaneously decline, as will the time period when heating occurs. Watershed 3's heating rates always become less than zero at the earliest time, around 6 p.m., which signals the start of the cooling effect. In addition, this phenomenon is more obvious in situations with more humid land surfaces, such as Scenarios 3 and 5. In Scenario 3, the time when the cooling effect begins in Watershed 3 is closer to 3 p.m., while the effect is in place throughout the whole day in Scenario 5. The effects on the heating periods in Watersheds 1 and 2 in different scenarios are similar, but not as apparent as that in Watershed 3. Finally, higher evapotranspiration rates could also lower the range of fluctuation of heating rates during a day, leading to more stable air temperatures. This is in line with the theories reviewed earlier, in that temperatures are more stable in more humid environments such as forests and wetlands.

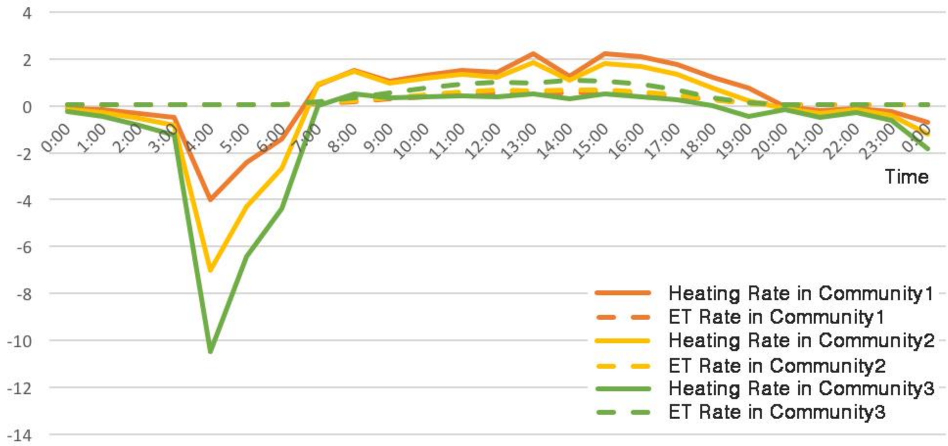
In short, all the ECSM practices in these five scenarios are beneficial in terms of increasing evapotranspiration rates in the three watersheds, which will enhance the cooling effect by lowering heating rates, shortening the heating period, and providing a more stable thermal environment.



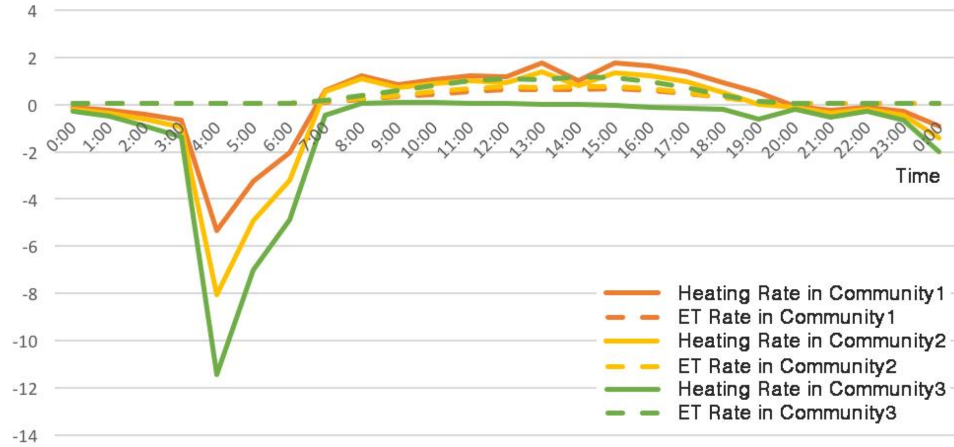

(a) Current



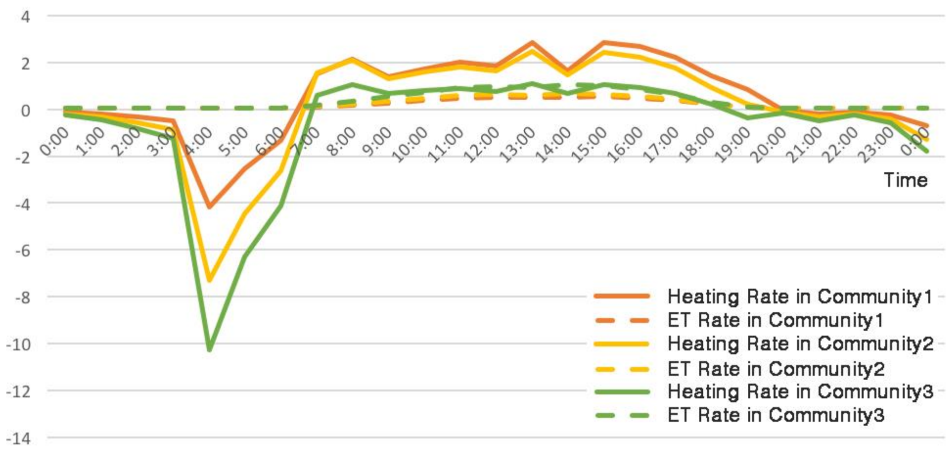

(b) Scenario 1 – Ecoroof



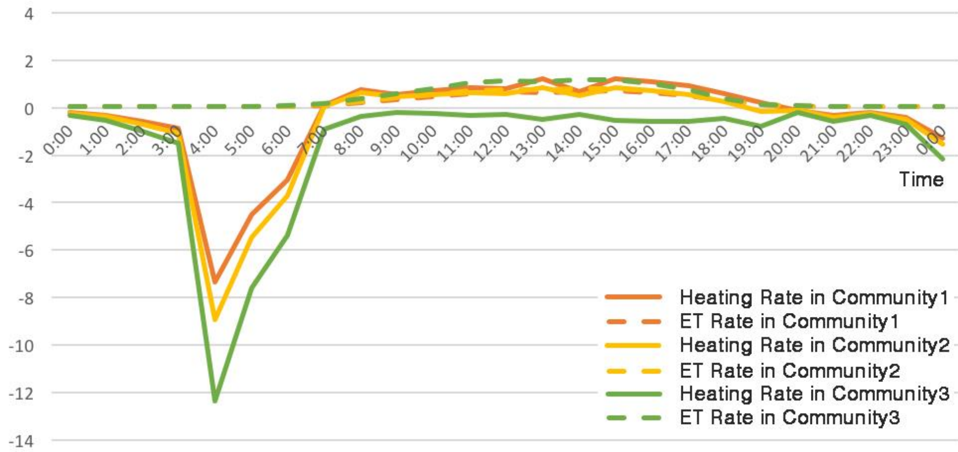

(c) Scenario 2 – Non-canopy Green Parks




(d) Scenario 3 – Trees




(e) Scenario 4 – Permeable Pavement




(f) Scenario 5 – Bioretention Facility

Fig 5.3 Hourly Evapotranspiration (ET) Rate (mm/h) and Heating Rate (℃/h) on July 25th, 2016, in the three watersheds under five scenarios. In this figure, red lines represent Watershed 1; yellow lines represent Watershed 2; green lines represent Watershed 3; solid lines represent heating rates; and dashed lines represent evapotranspiration rates.

(Data Source: current data were from the College of Agriculture and Environmental Sciences, University of Georgia; simulated data in the five scenarios were computed by the LUMPS model.)

### 5.3.2 Scenarios and Cooling Effectiveness

In this section, the cooling effectiveness of ECSM practices in different scenarios is examined in two dimensions. The first regards determining which practices are more effective in which kind of watershed in a certain scenario; the second relates to establishing which practice or scenario has a greater cooling effect within a certain kind of watershed. Table 5.8–5.10 shows the simulation results of the basic casein three aspects, mean evapotranspiration rate, heating rate, and evaporative cooling efficiency, during July 25$^{th}$, 2016, as computed by the data of current conditions. Mean evapotranspiration rate and heating rate were directly acquired through the LUMPS model; evaporative cooling efficiency was gained by dividing the mean evapotranspiration rate by mean cooling rate (inverse number of mean heating rate), which means the cooling produced per unit of evapotranspiration and water requirement for each unit of decreased temperature. Table 5.8–5.10 also lists the change in the three aspects from the basic case under the five scenarios, while the extent of the changes in different watersheds and scenarios is compared in Figure 5.4–5.6. In addition, the cooling effectiveness of ECSM practices is examined from two perspectives: the ability to reduce heating rate and to increase cooling efficiency. In general, all five scenarios produced a positive evaporative cooling effect across all three watersheds with increased evapotranspiration rates, lowered heating rates, and enhanced evaporative cooling efficiencies. However, the highest cooling effect and cooling efficiency was garnered in Scenario 5 (bioretention facility) while Scenario 4 (permeable pavement) scored lowest in both aspects.

Table 5.8 Evapotranspiration (ET) Rate (mm/h) Under Five Scenarios

| Watershed | ET rate | Change in ET rate from basic case | | | | |
|---|---|---|---|---|---|---|
| | Basic Case | S1 | S2 | S3 | S4 | S5 |
| 1 | 0.160 | 0.048 | 0.068 | 0.095 | 0.048 | 0.105 |
| 2 | 0.193 | 0.048 | 0.068 | 0.097 | 0.049 | 0.110 |
| 3 | 0.302 | 0.052 | 0.081 | 0.113 | 0.063 | 0.123 |

Note: the ET rates used in this table are the mean ET rates on July $25^{th}$, 2016; S refers to scenario.

Table 5.9 Heating Rate (℃/h) Under Five Scenarios

| Watershed | Heating rate | Change in heating rate from basic case | | | | |
|---|---|---|---|---|---|---|
| | Basic Case | S1 | S2 | S3 | S4 | S5 |
| 1 | 0.783 | -0.520 | -0.417 | -0.734 | -0.202 | -1.165 |
| 2 | 0.442 | -0.476 | -0.534 | -0.824 | -0.330 | -1.119 |
| 3 | -0.383 | -0.545 | -0.575 | -0.875 | -0.325 | -1.168 |

Note: the heating rates used in this table are the mean heating rates on July 25th, 2016; S refers to scenario.

Table 5.10 Cooling Efficiency Under Five Scenarios

| Watershed | EC Efficiency | Change in EC Efficiency from basic case | | | | |
|---|---|---|---|---|---|---|
| | Basic Case | S1 | S2 | S3 | S4 | S5 |
| 1 | -4.892 | 3.628 | 3.283 | 4.699 | 2.095 | 6.334 |
| 2 | -2.294 | 2.436 | 2.645 | 3.614 | 1.833 | 4.528 |
| 3 | 1.267 | 1.355 | 1.231 | 1.761 | 0.674 | 2.386 |

Note: the cooling efficiency is the ratio of cooling rate (inverse number of heating rate) to evapotranspiration rate; this represents the amount of cooling per unit of evapotranspiration; S refers to scenario.

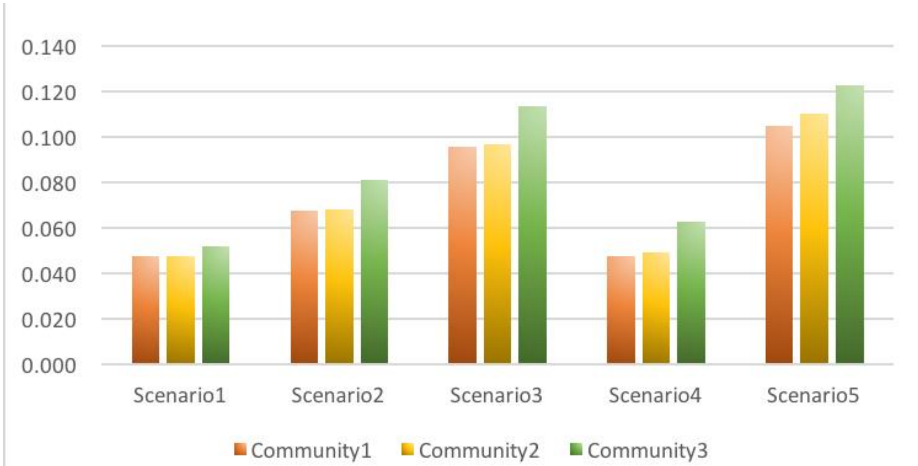



Fig 5.4 Increased Evapotranspiration Rate (mm/h) Under Five Scenarios

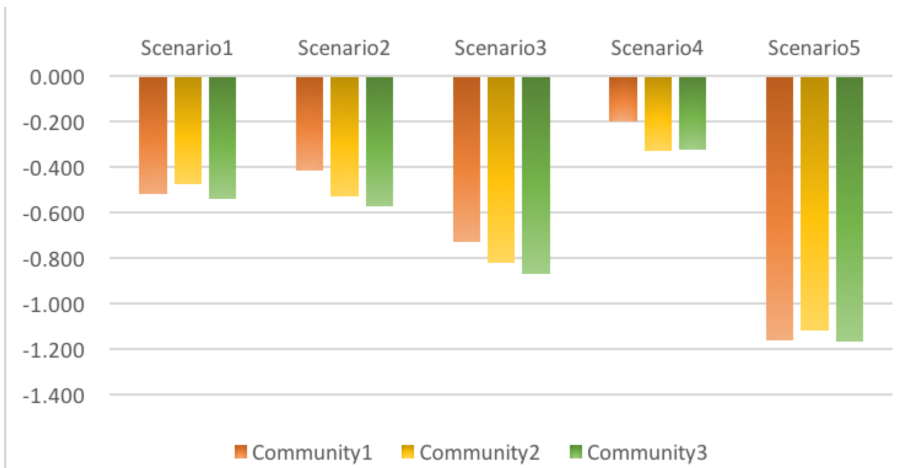



Fig 5.5 Decreased Heating Rate (℃/h) Under Five Scenarios

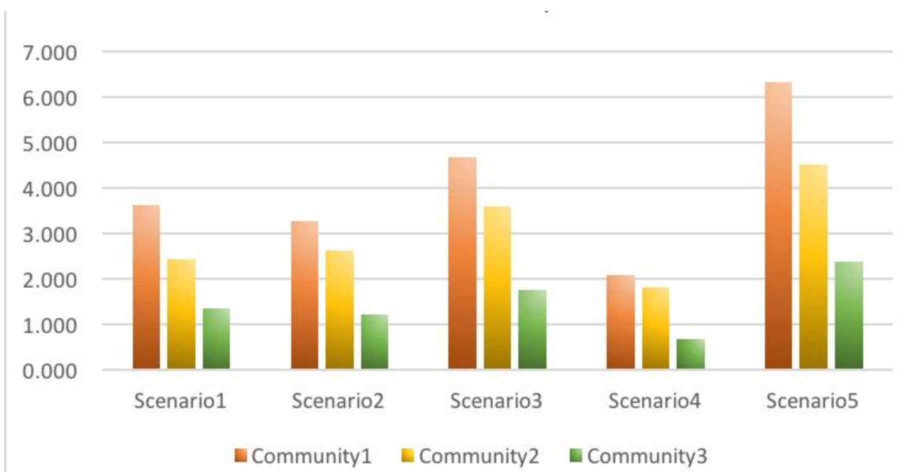



Fig 5.6 Increased Cooling Efficiency (℃/mm) Under Five Scenarios

In Scenario 1, the ecoroofs increased the proportion of green space by 15% in all three watersheds while reducing the percentage of conventional rooftops by the same amount. The additional green roofs provided a moderate evaporative cooling effect, compared to the current heating rate in the basic case. It was also seen that all three watersheds experienced a similar cooling effect from the ecoroofs. However, the cooling efficiency was enhanced to the greatest extent in the commercial neighborhood (Watershed 1), while it was altered the least in the high-greened residential neighborhood (Watershed 3). This indicates that ecoroofs require less water to reduce air temperatures in commercial spaces, which contain fewer vegetative land surfaces. Therefore, ecoroofs are most suitable for application in urban commercial areas, although their cooling effect in commercial watershed is slightly lower than in high-greened residential neighborhoods.

Scenario 2 was focused on cooling the urban thermal environment using non-canopy green parks. In this scenario, an additional 15% land cover of green space was acquired by converting barren land and impervious pavement to grassland. Similarly to Scenario 1 (ecoroof), this practice also offers a moderate evaporative cooling effect in general. However, the reduced heating rates among the three watersheds in this scenario are not as close as in Scenario 1. The most reduced heating rate was in Watershed 3, the high-greened residential watershed, while the lowest reduction was seen in Watershed 1, the commercial watershed. Therefore, from the perspective of creating a greater cooling effect, non-canopy parks are most suitable for residential watersheds with rich plant life. However, the increased cooling efficiency in this scenario successively declined in the sequence of Watershed 1, 2, 3. Therefore, in the interests of increasing cooling efficiency and saving water, it is more reasonable to apply non-canopy parks in commercial watersheds that are usually dry and lack water for evapotranspiration due to the sparseness of vegetation.

In Scenario 3 the urban land cover was altered by increasing the number of trees. The addition of 15% more land cover under the tree canopy produced a substantial cooling effect, which was just lower than the cooling created by Scenario 5 (bioretention facility). Comparing Scenario 2 (non-canopy green parks) and Scenario 3 (trees), the reduced heating rate of the latter is nearly as twice that of the former in each watershed. Moreover, not only the cooling ability, but also the increased cooling efficiency, is much higher in the scenario of trees than in the scenario of non-canopy green parks. Therefore, planting more trees would be a much more effective practice than adding grassland in regards to increasing evaporative cooling in any kind of watershed.

The proposal of Scenario 4 was to replace impervious pavement with permeable pavement, which was the least effective strategy in terms of both reducing heating rate and increasing cooling efficiency among the five scenarios; as such, its results were much less impressive. The reason for this may be that there was no increase in the proportion of green space compared with the current land cover conditions. Based on this, we can conclude that permeable pavement could be a supplemental strategy for enhancing the evaporative cooling effect, alongside the other ECSM practices.

In Scenario 5, an additional 15% land cover was converted into bioretention facilities from barren land, grassland, and impervious pavement; this scenario produced the most obvious reduction in heating rate and growth in cooling efficiency. As with Scenario 1 (ecoroof), the reduced heating rates in this scenario across the three watersheds were fairly close to each other, while the highest increase in cooling efficiency was seen in Watershed 1, the commercial watershed. Based on these results, a bioretention facility would have the greatest cooling effect in commercial urban areas where vegetation is sparse at present, although it could provide a considerable cooling effect for all three kinds of watersheds.

The above results indicate that different types of ECSM practice should be developed when focusing on different kinds of watersheds. In Watershed 1 (the commercial watershed), which is highly developed (86.43%) with little vegetation (13.15%), the total reduction in heating rate was slightly lower than in the other two watersheds, while the increase in cooling efficiency was notably higher in all five scenarios, especially 1 (ecoroof), 3 (trees), and 5 (bioretention facility). Comparing the practices in these three scenarios, bioretention facility had the greatest cooling effectiveness in this commercial watershed, while ecoroof had the worst. Therefore, in the interest of effecting greater reductions in air temperature with less water, bioretention facility is the most desirable option for commercial watersheds, followed by trees, with ecoroof being the least effective. In Watershed 2 (the low-greened residential watershed), which had relatively less developed space (80.89%) and a small proportion of vegetation (18.27%), a bioretention facility (in Scenario 5) and trees (in Scenario 3) were the two most effective practices for temperature reduction, as shown in Figures 5.5 and 5.6. Meanwhile, the cooling effectiveness of the ecoroof in Scenario 1 and non-canopy green parks in Scenario 2 was distinctly average. Finally, Watershed 3 (the high-greened residential watershed) had the lowest proportion of developed land cover (64.63%) among the three watersheds and a percentage of green space (34.87%) that was approximately twice those of its two neighbors. The cooling efficiency in this watershed was considerably lower than in the other two for all five scenarios. This indicates that the possible reduction of temperatures produced by ECSM practices in this kind of neighborhood is subtle compared with the other two kinds of watersheds, when they are provided with the same evapotranspiration rate. The basic mean evapotranspiration rate in Watershed 3 was 0.302 mm/h, which is almost double that in the other two neighborhoods (0.160 mm/h in Watershed 1; 0.193 mm/h in Watershed 2). In addition, Watershed 3 required twice as high an evapotranspiration rate as needed in Watersheds 1 and 3 to reduce per degree of temperature. This result may be related to the highly vegetated land surfaces in Watershed 3. As this large proportion of green space would produce a basic case with high evapotranspiration, watersheds with abundant plant life usually have a humid environment. This high humidity may impede the efficiency of the evapotranspiration's cooling in some way; for example, Gober et al. (2010) found that cooling efficiency will decline as the wet fraction of land surface increases. Therefore, the cooling efficiency of ECSM practices will decline as a greater proportion of land is covered with vegetation. In this situation, it is not advisable to apply ECSM practices to their fullest extent to reduce temperatures in those neighborhoods with plentiful plants, in terms of cooling efficiency and reduction of water loss.

# CHAPTER 6

# DISCUSSION AND CONCLUSIONS

## 6.1 ECSM Practices and Human Comfort

This chapter describes the results of simulations to provide guidance for designing ECSM practices from the perspective of maximizing evaporative cooling effectiveness. The simulation results show that either a remarkable reduction in temperature or a notably high cooling efficiency can reduce air temperature of Atlanta. But reduction in air temperature does not guarantee a comfortable thermal environment. As demonstrated in section 2.1 in Chapter 2, many parameters affect thermal comfort, including air temperature, humidity, radiant energy received or emitted by the body, wind speed, and people's adaptability to different conditions, as well as their activities, age, clothing, and culture. ECSM practices can mainly affect human comfort according to two parameters—air temperature and humidity—and they may produce different influences on thermal comfort when applied in environments with different characteristics. In this case, bioclimatic analysis is required to evaluate the relationship between thermal comfort and external climate produced by the different ECSM practices in Scenarios 1, 2, 3, 4, and 5. Such analysis aims to identify desirable combinations of ECSM practices to meet human needs related to thermal comfort under specific climatic and environmental conditions.

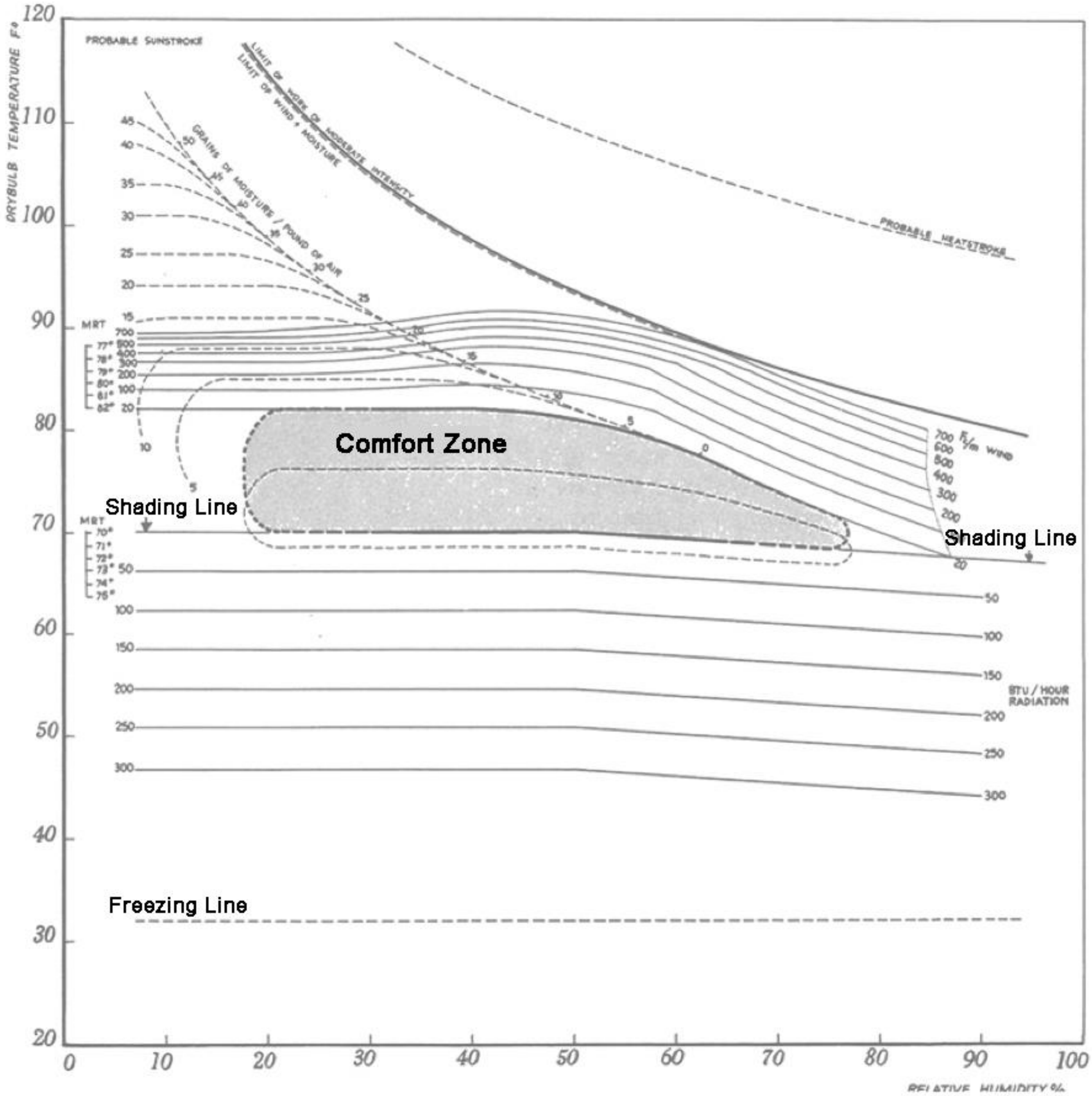



Fig. 6.1 Bioclimatic Chart (BC) for U.S. Moderate Zone Inhabitants

(Source: Olgyay and Olgyay, 1963).

The relationship between thermal comfort and its associated elements can be portrayed in the “bioclimatic chart” (BC) developed by Victor Olgyay in 1963; this is used for assessing passive cooling methods without mechanical assistance (Robinette, 1972). As shown in Figure 6.1, the BC defines a general comfort zone that is suitable for most people most of the time. As Olgyay (1992) illustrated, the plotted points on the chart are determined by air temperature and relative humidity. If a plotted point falls within the comfort zone, this indicates a comfortable thermal condition. In contrast, if the plotted point falls outside of the comfort zone, corrective measures are needed to improve the thermal conditions, thereby moving the plotted point into the comfort zone. If the point is below the comfort zone, additional solar radiation is needed; if it is above this zone, additional air movement is required. If it is to the left of the comfort zone, additional moisture is necessary; if it is to the right, dehumidification is needed. This BC will be extremely helpful in assessing the thermal comfort conditions under different scenarios determined according to different major ECSM practices.

Atlanta’s climate in the summer can be described as relatively hot and humid, with lower wind speed, compared to the climatic conditions of the other three seasons. Using data from Weatherbase, Table 6.1 presents the monthly climatic conditions for Atlanta in the past 20–51 years. Comparing the temperatures for June, July and August, almost every day during this period had an average temperature of above 80°F. The maximum average temperature during summer is 89.1°F while the minimum one is 68.2°F.

Table 6.1 Monthly Climatic Conditions of Atlanta in The Past 20–51 Years

(a) Average temperature (°F) in the past 30 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 43.3 | 47.2 | 54.3 | 62 | 70.1 | 77.3 | 80.2 | 79.4 | 73.5 | 63.3 | 54 | 45.3 |

(b) Average high temperature (°F) in the past 30 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 52.3 | 56.6 | 64.6 | 72.5 | 79.9 | 86.4 | 89.1 | 88.1 | 82.2 | 72.7 | 63.6 | 54 |

(c) Average low temperature (°F) in the past 30 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 34.3 | 37.7 | 44.1 | 51.5 | 60.3 | 68.2 | 71.3 | 70.7 | 64.8 | 54 | 44.5 | 36.5 |

(d) Average number of days above 80°F in the past 30 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| —— | —— | 1.3 | 6.5 | 16.7 | 26 | 29.8 | 29.4 | 19.9 | 5.2 | 0.4 | —— |

(e) Average number of days Above 70°F in the past 30 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.8 | 2.6 | 10.6 | 19.4 | 28.5 | 29.6 | 31 | 30.9 | 28.6 | 20.6 | 8.2 | 1.8 |

(f) Average relative humidity (%) in the past 20 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 66.2 | 64.1 | 61.1 | 62.2 | 67 | 69.7 | 71.6 | 72 | 70.1 | 69.6 | 67.8 | 68 |

(g) Average morning relative humidity (%) in the past 51 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 79 | 77 | 78 | 78 | 82 | 84 | 88 | 89 | 88 | 84 | 81 | 80 |

(h) Average evening relative humidity (%) in the past 51 years

| JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 56 | 50 | 48 | 45 | 49 | 53 | 57 | 56 | 56 | 51 | 52 | 56 |

Note: The above data are from Weatherbase.

This indicates that for the most of summer, temperature is above the comfort zone, while a few minimum values may be located below this area. In terms of relative humidity, the average morning relative humidity in summer is 87%, while the average for evening is 55%. Furthermore, based on the climatic data provide by Atlanta Station, the highest relative humidity in a day is usually evident in the morning, while the lowest relative humidity occurs in the afternoon; the average afternoon relative humidity is calculated to be 28%. Based on these results, the relative humidity conditions are mostly distributed in the right portion of the comfort zone, with a few values are plotted outside and to the right of this area. This means that the humidity is generally relatively high during summer, and it is not far from exceeding the comfort zone.

Integrating the above analysis, Figure 6.2 highlights the BC for Atlanta; and the red line represents the mean high and low temperatures with the corresponding relative humidity values during summer. Almost the entire red line—the values for temperature and relative humidity—is plotted to the upper right of the comfort zone. This indicates that a high amount of wind is necessary to counteract the high temperatures and vapor pressure. Moreover, all the data are above the shading line, which demonstrates that shading devices are crucial in summer to block the solar radiation received by the body.

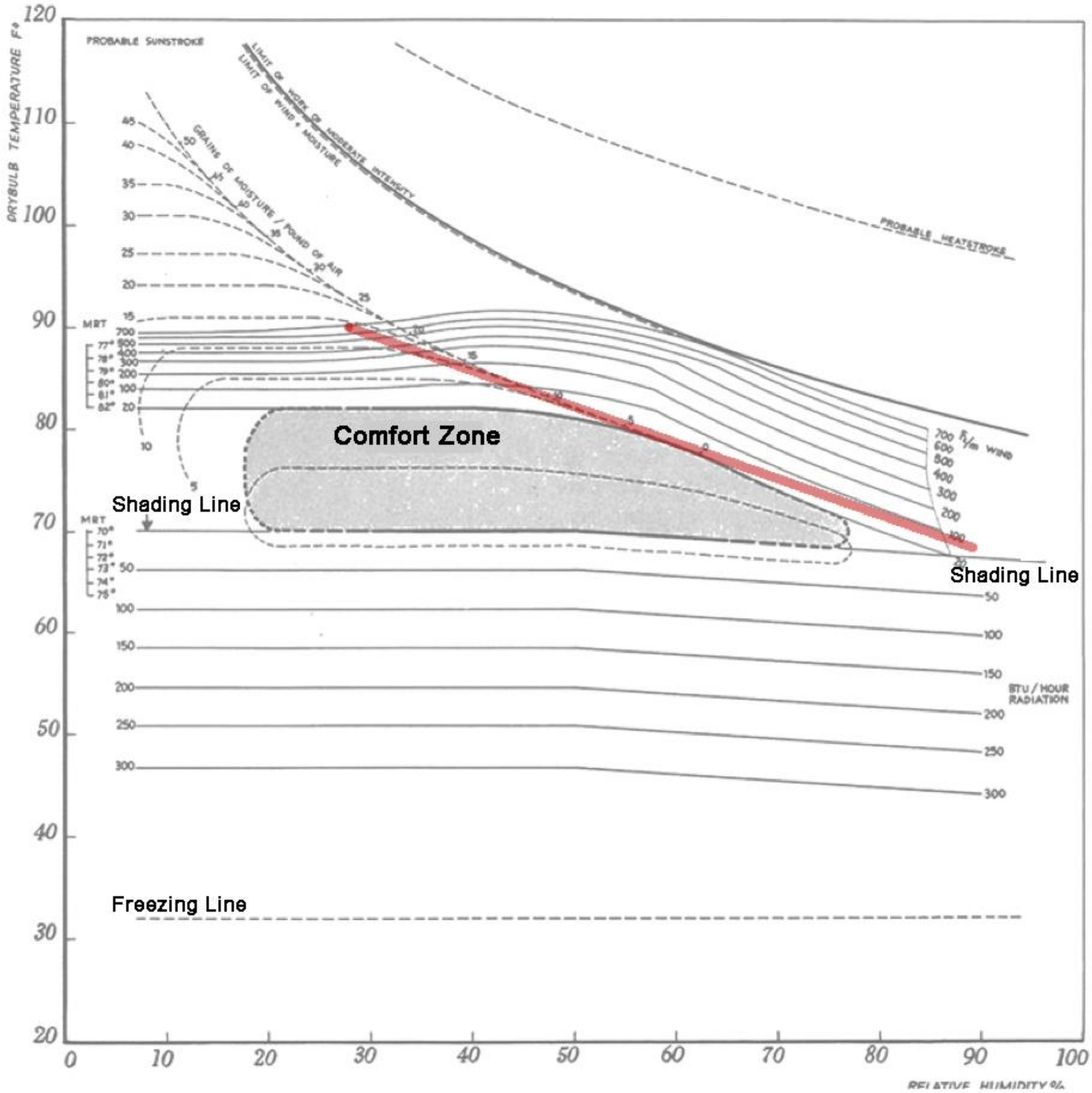



Fig. 6.2 Bioclimatic Chart (BC) for Atlanta, GA

(Source: Olgyay and Olgyay, 1963).

Table 6.2 Basic Climate Conditions from 8:00 to 24:00

| | Watershed 1 | Watershed 2 | Watershed 3 |
|---|---|---|---|
| **Mean air temperature (°F)** | 90.81 | 88.01 | 77.67 |
| **Mean ET rate (mm/h)** | 0.21 | 0.26 | 0.41 |

Note: The mean air temperatures and evapotranspiration (ET) rates are calculated from the simulation results of the LUMPS model, under the current situation without any ECSM practices.

Table 6.3 Major Environmental Characteristics of Watersheds

| | Watershed 1 | Watershed 2 | Watershed 3 |
|---|---|---|---|
| **Developed space** | 86.43% | 80.89% | 64.63% |
| **Green space** | 13.15% | 18.27% | 34.87% |

Note: The proportions of developed space and green space are computed on GIS based on the land cover data from the National Land Cover Dataset (NLCD).

It should be noted that the temperature and relative humidity will not be evenly distributed across Atlanta because of different environments, such as land cover, building density, and form of constructions. Thus, the abovementioned climatic conditions are useful in explaining the overall situation of Atlanta, but they cannot represent the specific climatic conditions at the neighborhood level. The climates in Watershed 1 – commercial space, Watershed 2 – low-greened residential space, and Watershed 3 – high-greened space are distinct to some extent.

Based on the simulation results, Table 6.2 lists the average temperature and evapotranspiration rate during the period from 8:00 to 24:00 under the basic scenario (i.e., the current situation without adding ECSM practice). It is important to realize that the temperatures and evapotranspiration rates used in this table are computed results rather than measured ones. The usefulness of this table would be enhanced if real data were included. Despite this issue, we can learn about the climate characteristics in each type of watershed from Tables 6.2 and 6.3. Watershed 1 – commercial space and Watershed 2 – low-greened residential space have similar climatic features, including a relatively high average temperature of approximately 90°F and a relatively low evapotranspiration rate of about 0.2 mm/h. Meanwhile, the mean temperature in Watershed 3 – high-greened residential space is around 77°F, with an evapotranspiration rate that is twice that of the other two watersheds. This indicates that neighborhoods that are broadly developed with few plants, such as Watersheds 1 and 2, usually produce a hotter and drier climate compared with those with fewer constructed areas and more plentiful vegetation. According to this result, Figure 6.3 portrays the possible ranges of temperature and relative humidity for the three types of watersheds by dividing them into Sections 1 and 2 (Section 1 represents Watershed 1 and 2; Section2 represents Watershed 3). As 82°F is the highest temperature in the comfort zone, this temperature with its corresponding relative humidity of 50% on the BC for Atlanta is used as a division point for the two sections.

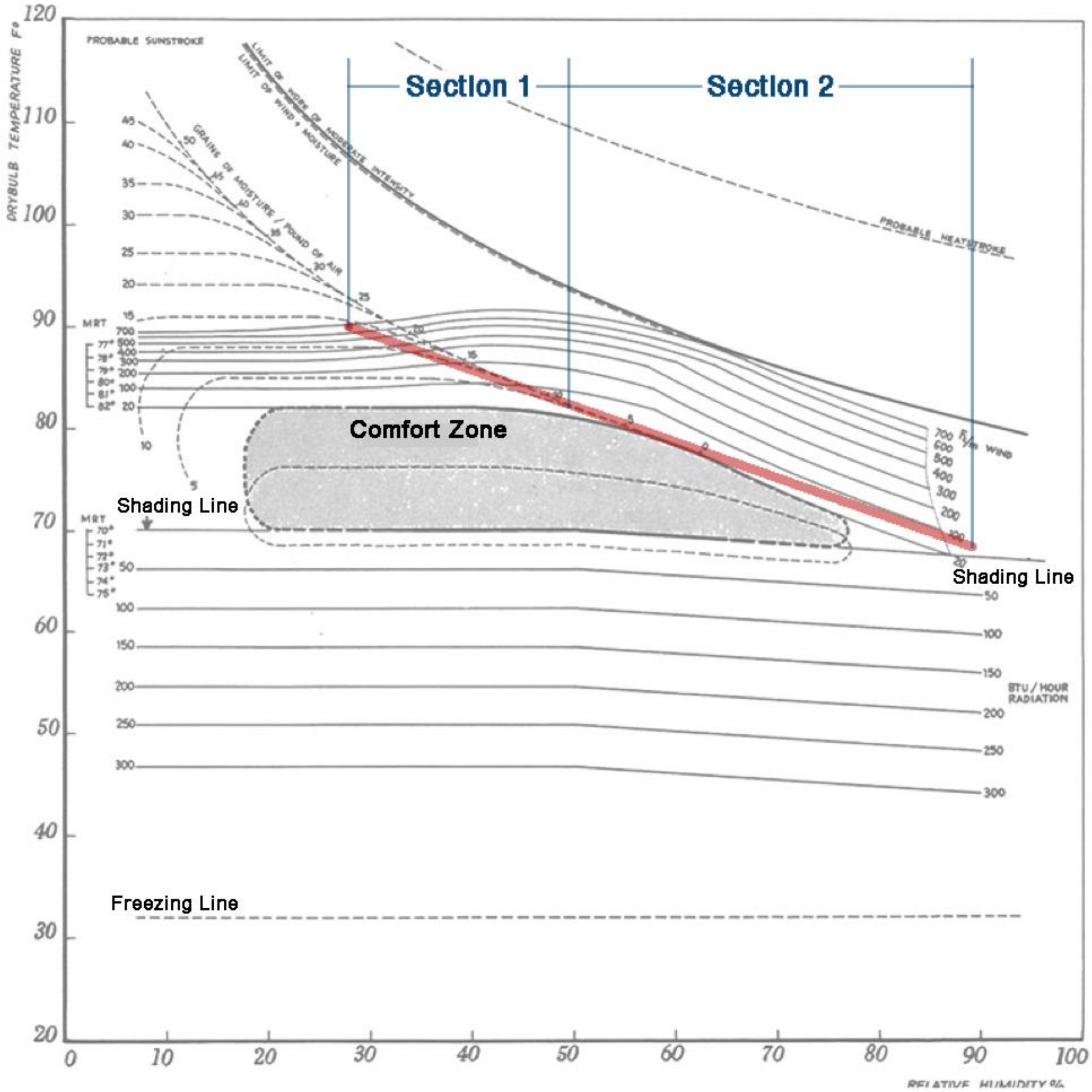



Fig. 6.3 Bioclimatic Chart (BC) for Atlanta, GA, Divided into Sections 1 and 2

(Source: Olgyay and Olgyay, 1963).

Section 1 represents the potential climatic conditions of Watersheds 1 and 2 (commercial and low-greened residential watersheds), which have high temperature values (above 82°F) and relatively low humidity (below 50%). This demonstrates requirements for more moisture in the air, higher wind speed, and shading devices to achieve a comfortable thermal environment for humans. However, as all the relative humidity values in this section lie within the comfort zone and the line of this section is extremely close to the borderline of increasing air moisture (Figure 6.3), a slight increase in humidity is enough in this case, and the greatest air moisture cannot be higher than 15 grains of moisture per pound of air. Thus, any increase in the proportion of green space in Watershed 1 and 2 should be limited. In contrast, the higher wind speed plays a more important role than the higher air moisture in this section. According to the BC for Section 1, the top wind speed should reach 700 fpm (i.e., 3.556 m/s) to improve the thermal comfort. As the average wind speed during summer is above 7.1 m/h (i.e., 624.8 fpm; 3.17 m/s) according to Weatherbase, the primary strategy for wind speed is to refrain from blocking any more air movement.

For Watershed 1 – commercial space, the best two ECSM practices to increase air moisture are trees and bioretention facilities, with an increase in the evapotranspiration rate of around 0.1 mm/h under Scenarios 3 and 5. As it is necessary to increase air moisture slightly based on the climatic conditions in Watershed 1, the additional application of these two kinds of ECSM practices should be kept to a low proportion. Furthermore, considering the necessity of enhancing wind speed, the distribution of the trees should be carefully designed to avoid impeding air movement. As the wind generally moves from northeast to southwest across Atlanta during summer (Weatherbase), and Watershed 1 is located in the northeastern quadrant of whole city, sparsely and linearly arranged trees are encouraged in this watershed to avoid blocking winds flowing to the southeast. The final issue is shading, and the only ECSM practice that can provide shading is trees. In this case, the proportion of trees in Watershed 1 should be increased to an appropriate degree. Consequently, it is necessary to add some more bioretention facilities, as the increased trees for shading may be enough to meet the slight need for increased air moisture.

As for Watershed 2 – low-greened residential space, it is in the same section of the BC for Atlanta as Watershed 1 – commercial space. Thus, the requirements for corrective measures to create a comfortable thermal environment are similar. Specifically, the appropriate policies for ECSM practices in this watershed include a moderate proportion of increased tree canopy to provide shading and contribute to increasing air moisture, some added ecoroofs, green parks with grasslands and permeable pavement as supplemental measurements, and no increase in bioretention facilities to prevent the humidity from becoming too high for humans. Furthermore, this watershed is located in the northwestern quadrant of Atlanta, and as mentioned above, the wind direction is northeast to southwest. This indicates that trees in this watershed should be distributed sparsely or linearly to comply with the wind direction throughout the area except the northeastern corner.

Section 2 of the bioclimatic chart for Atlanta represents the general climatic conditions of Watershed 3 – high-greened residential space; here, the climatic conditions partially overlap with the upper-right boundary of the comfort zone. This is a result of the high relative humidity, which ranges from 50% to 87%, while the entire temperature values remain within the comfort zone. This situation indicates that a small amount of improvement is required. As the average summer wind speed of 7.1 m/h (i.e., 624.8 fpm; 3.17 m/s) is already well above the least required wind speed, it is not necessary to consider enhancing the comfort of the thermal environment through increased air movement. Therefore, the major strategy to bring thermal conditions into the comfort zone in this watershed involves dehumidification. In this case, some of the ECSM practices that are highly effective in increasing the evapotranspiration rate should be replaced with moderately effective ones. This means that the following measures are recommended: (1) no more trees or bioretention facilities should be added, and the current proportion of land covered by these two elements (33.57%) is at the highest suitable level for Watershed 3; (2) a reasonable percentage of trees and bioretention facilities should be replaced with ecoroofs, non-canopy green parks, and permeable pavement. Furthermore, based on the LULC data from the NLCD, a large fraction of trees in Watershed 3 consists of forests. Densely growing trees in forests represent a major cause of high-level air moisture. Hence, another potential strategy to reduce humidity in Watershed 3 is to slightly lessen the density of trees.

### 6.2 Application Strategies of ECSM Practices in Atlanta, GA

From the perspective of reducing air temperature, the results of the simulations indicate that the two best ECSM practices are bioretention facilities and trees, which will be most effective for cooling in all types of urban zones in the City of Atlanta. However, when considering the effects of these measures on thermal comfort for humans, the reasonable application strategies for ECSM practices vary depending the type of urban zone.

Watershed 1, the commercial zone around the city core, is highly developed; a proportion of 86.43% of this area is developed, with only 13.15% representing vegetated land. This watershed is hot and somewhat humid during summer. In this kind of urban zone of Atlanta, thermal comfort can be achieved via moderately increased humidity with high wind speeds. The primary strategy among the five major ECSM practices is to increase the landcover from trees due to their unique advantage in providing shading, as well as their powerful ability to increase the evapotranspiration rate and reduce air temperature. One principle of this strategy is a moderate increase in tree canopies, which will serve to avoid the relative humidity becoming too high for thermal comfort. Also the addition of bioretention facilities having longer term surface water storage are not encouraged in this kind of urban space, while rapid infiltration practices are acceptable. The other principle is to arrange the trees sparsely or linearly to avoid blocking air movement from the northeast to southwest. Furthermore, ecoroofs, non-canopy green parks, and permeable pavement can serve as supplemental strategies. They can be applied across a relatively broader area than trees because of their comparatively low potential for increasing humidity. Among these three ECSM practices, the most recommended is using ecoroofs, as the urban commercial zone is usually densely constructed, with abundant spaces above building tops and limited land surface for vegetation.

Watershed 2, the low-greened residential zone, has been developed slightly less than the commercial neighborhood in Watershed 1, with 80.89% developed land and 18.27% vegetated land. It has similar climatic conditions to Watershed 1 in summer, as it is relatively hot with a low amount of humidity. Therefore, the primary strategy and principles concerning the ECSM practice of tree planting are generally same as those for the commercial zone as well as the use of rapid-infiltration bioretention. However, there is a slight difference in the supplemental strategies of ecoroofs, non-canopy green parks, and permeable pavement. Among these three practices, non-canopy green parks are more suitable than ecoroofs, in contrast to the proposal for urban commercial area. One reason for this is that there are few public spaces on the roofs of buildings in the residential zone, which is much more private than the commercial zone. So the available space for applying ecoroof is limited. The other reason is the better cooling effect and cooling efficiency of non-canopied green parks than ecoroofs in this kind of watershed, according to the simulation results in Chapter 5.

Watershed 3, representing the high-greened residential area in Atlanta, has a proportion of developed land of 64.63% and a percentage of green space of 34.87%. This kind of urban zone is much less constructed and more vegetated than Watersheds 1 and 2.

Correspondingly, it has comfortable temperatures but high air moisture, which is a bit too humid for humans. In this case, the major approach to acquiring thermal comfort is dehumidification. Primarily, we recommend increasing the percentage of ecoroofs, non-canopy green space, and permeable pavement to reduce the moisture evapotranspired into the air slightly at street level. Among these three practices, use of non-canopy green space is most encouraged, as this not only has the best cooling effectiveness compared with the other two measures, but will also represent a welcomed public space in the residential zone for outdoor entertainment and social activities. Furthermore, slight lessening of the tree density in forests within this kind of urban zone is another potential option.

### 6.3 Challenges in Applying ECSM practices

Generally, the ECSM practices are effective in cooling the atmosphere. However, some of them may increase the heating effect instead of cooling. One study conducted by Stone and Norman (2006) in Atlanta found that a tree canopy decreased UHI effects, while grass cover increased them, at least compared to forested vegetation. Three parks in Tel Aviv were compared in another study (Potchter et al., 2006). Here, the researchers study found that a grass park with few trees tended to be warmer during the day compared to its surroundings than the other two parks, which had greater tree cover. They suggested that this effect resulted from a combination of the shade from buildings in the surrounding areas and heat release from decomposition in the grass. Therefore, the application of ECSM practices cannot guarantee a cooler thermal environment.

Another element that may weaken the cooling effect of ECSM practices is plant health. Urban trees are also faced with high heat and radiation loads (Oke et al., 1989), as well as high vapor pressure deficits, which can constrain stomatal conductance (Chen et al., 2011) and can lead to leaf senescence (Munn-Bosch and Alegre, 2004), thereby restricting transpiration. In this situation, it is critical to choose the most appropriate tree species to promote cooling while also ensuring tolerance to current and future climate conditions.

The choice of tree species and density of tree planting are important issues in the context of ECSM practices and sustainable water management (Peters et al., 2010). Peters et al. (2010) assessed tree transpiration among dominant tree species in a suburban neighborhood and found that evaporative responses to climate change in urban ecosystems are likely to depend in part on species composition.

As most of the Atlanta region's anticipated 2025 built area is already in place, changes in future development will serve to offset continued growth rather than reducing the UHI generated at present. Given this observation, the most effective practice-oriented ECSM strategies for reducing total regional warming must address both existing and future development (Stone and Norman, 2006).

The last challenge that must be considered in the application of ECSM practices is underground water. Simulations by Holman-Dodds et al. (2003) suggested that certain spatial arrangements for bioretention basins could adequately replicate predevelopment runoff. However, simulations by Gobel et al. (2004) illustrated that the recharge may exceed predevelopment conditions and cause water table encroachment. It is reasonable for urban managers to be concerned about infrastructure when considering watershed restoration through bioretention basins. Restoring the hydrological process of the surface infiltration of stormwater will create unknown subsurface conditions in the built environment, including potentially the mounding of water tables, destructive buoyancy, and frost-heave forces on roads and subsurface pipes or foundations (Endreny, 2008). Therefore, as always, each site should receive careful study and planning before installation of ECSM practices.

### 6.4 Future Research

The simulations in this thesis to estimate the cooling effects of ECSM practices on air temperatures only can be used as guidance. Further research is required to gain a deeper, more comprehensive understanding of these practices. Several limitations of this study, which open up prospective avenues for future research, are described below.

First, only one set of meteorological data was used for simulations, and the outputs correspondingly represent the results for only July 25$^{th}$, 2016. If more data could be included, results would give a better overall picture of the conditions. It is always necessary to conduct simulations with more sets of data.

Second, the analysis in this research mainly focused on the proportion and amount of different land surfaces produced by varied ECSM practices at the watershed and city levels; it did not take the arrangement of constructions and vegetation into account, and such characteristics would influence micrometeorological conditions, such as wind speeds and directions, at the site level. Moreover, the cooling effective of installing the same ECSM measures may vary with the specific urban topographic characteristics, such as street orientation, shade provided by the surrounding buildings, and the forms and sizes of parks (Gulyás et al., 2006; Gill, 2006). We expect to examine the cooling effect of ECSM practices in different formations of arrangement.

Most importantly, the simulations and analysis in this research did not include the irrigation system or water requirement for evapotranspiration. Increases in water availability through irrigation were identified by Oke and McCaughey (1983) to enhance daytime evapotranspiration rates by 40% in a suburban neighborhood in Vancouver, Canada. Moreover, Shashua-Bar et al. (2009) found that a combination of irrigated grass and trees was the most effective in cooling, whereas vegetation alone achieved the highest cooling efficiency per amount of water used. When including irrigation and water requirements in simulations, the results may offer a more comprehensive reference for ECSM practices. Furthermore, Pataki et al. (2011b) warned that large-scale tree planting may place additional pressure on already constrained water supply systems due to irrigation requirements. The best ECSM practice in terms of irrigation should provide low-energy, decentralized stormwater storage and a fit-for-purpose water supply for use in landscape irrigation. In addition, it should complement centralized supplies to avoid a tradeoff between water consumption and urban climate degradation. Meanwhile, the capacity to meet irrigation needs through stormwater harvesting will vary in different cities with the regional climate and the city's water-demand regime.

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