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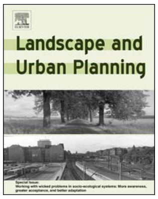

Research Paper

Planning for a sustainable desert city: The potential water buffering capacity of urban green infrastructure

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ABSTRACT

Urban green infrastructure offers arid cities an attractive means of mitigation/adaptation to environmental challenges of elevated thermal stress, but imposes the requirement of outdoor irrigation that aggravates the stress of water resource management. Future development of cities is inevitably constrained by the limited availability of water resources, under challenges of emergent climate change and continuous population growth. This study used the Weather Research and Forecasting model with urban dynamics to assess the potential water buffering capacity of urban green infrastructure in arid environments and its implications for sustainable urban planning. The Phoenix metropolitan area, Arizona, United States, is adopted as a testbed with water-saving and fully-greening scenarios investigated. Modifications of the existing green infrastructure and irrigation practices are found to significantly influence the thermal environment of Phoenix. In particular, water saving by xeriscaping ($0.77 \pm 0.05 \times 10^8\ m^3$) allows the region to support 19.8% of the annual water consumption by the projected 2.62 million population growth by 2050, at a cost of an increase in urban ambient temperature of about 1 °C.

1. Introduction

The urban heat island (UHI) effect is one of the most prominent example of anthropogenic impacts on natural environment that have been observed globally (Peng et al., 2011). Owing to the intricate relationship among economic, environmental, and social components, environmental consequences induced by UHIs impair the multisector sustainability of cities (Bulkeley & Betsill, 2005; Georgescu, Morefield, Bierwagen, & Weaver, 2014). In addition, urban climatic extremes, such as heatwaves, are projected to be exacerbated in the future (Meehl & Tebaldi, 2004). The challenge remains open and imperative for many cities around the world seeking sustainable mitigation/adaptation strategies for urban thermal environment (Georgescu et al., 2015). Incorporating emergent climatic patterns into urban landscape begins to attract more attention of urban planners (Alcoforado, Andrade, Lopes, & Vasconcelos, 2009; Eliasson, 2000). Recent decades have seen enormous efforts in developing and testing strategies for sustainable urban environments (Li, Bou-Zeid, & Oppenheimer, 2014; Santamouris, 2013; Tzoulas et al., 2007; Yang, Wang, & Kaloush, 2015; Yang, Wang, Kaloush, & Dylla, 2016). In particular, urban green infrastructure is recognized as one effective measure by both numerical studies and in-situ observations (Benedict & McMahon, 2012; Gill, Handley, Ennos, & Pauleit, 2007; Niu, Clark, Zhou, & Adriaens, 2010; Wang, Zhao, Yang, & Song, 2016).

Urban green infrastructure (e.g., lawns, shade trees, rain gardens, central parks, etc.) provides valuable ecosystem services for the built environment via shading, evaporative cooling, and esthetical effect. Yet, the watering demand of green infrastructure raises practical concerns of water resource management (Sun, Bou-Zeid, & Ni, 2014), especially for cities located in semiarid or arid environments. Under the challenge of climate change, water scarcity is becoming a widespread reality for global cities with rapid population growth (Vörösmarty, Green, Salisbury, & Lammers, 2000). Water pervades every aspect of a dynamic urban system (e.g., outdoor recreation, industrial production, residential consumption, etc.); thus its efficient management is an integral component as well as a critical challenge of urban environmental sustainability in the planning process (Brown, Keath, & Wong, 2009). While mounting evidence demonstrates the effectiveness of green infrastructure in cooling urban environments (Oberndorfer et al., 2007; Yang, Wang, Georgescu, Chen, & Tewari, 2016), only a few studies have looked into its impact on urban water resources in detail (Gober et al., 2012; Shashua-Bar, Pearlmutter, & Erell, 2009; Yang & Wang, 2015). In particular, Vahmani and Hogue (2014, 2015) found that irrigation of urban vegetation had significant impacts on energy and water cycles

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over the Los Angeles metropolitan area.

Here we selected the populous desert metropolitan area of Phoenix, Arizona as our study area. This is mainly due to: (1) land use conversion in the past decades has created a significant UHI in this region (Brazel, Selover, Vose, & Heisler, 2000; Wang, Myint, Wang, & Song, 2016), and (2) typical landscape management practices in the study area, ranging from oasis to desert landscaping, impose vastly different requirements for outdoor irrigation of green infrastructure. In the 21st century, high temperature, low precipitation, and decreased runoff result in increased aridity of the southwest United States (MacDonald, 2010). Even without significant reductions in surface water supply, projected population growth and groundwater drawdown make political decisions and actions imperative for water sustainability of Phoenix metropolitan region in 2030 (Gober & Kirkwood, 2010). Recognizing that native desert landscaping facilitates amelioration of water shortage, many cities within the metropolitan Phoenix offer financial incentives and rebates for homeowners to xeriscape their yards (City of Mesa, 2017; City of Glendale, 2017). In contrast, though the widespread adoption of water-intensive mesic landscape has adverse impacts on the long-term water sustainability, it enhances thermal comfort in the built environment over all spatial and temporal scales via evapotranspirative cooling (Song & Wang, 2016). The city of Phoenix initialized a Tree and Shade master plan in 2010 to achieve a tree canopy cover of 25% by 2030 (City of Phoenix, 2010). In water-energy-climate repercussions, the tradeoff between water conservation and UHI mitigation inevitably exerts profound impacts on multiple elements in the urban network (Grimm et al., 2008). Assessment of the water usage associated with urban green infrastructure is therefore crucial for water resource management as well as sustainable planning of the Phoenix metropolitan area.

Towards this end, we used the Weather Research and Forecasting (WRF) model coupled with an advanced urban canopy model (UCM), to assess projected water consumption of urban green infrastructure in the Phoenix metropolitan area. Our primary objective is to quantify the potential water buffering capacity, i.e. the possible range of variability in the water resource demand of urban green infrastructure using a framework, in a way that integrates geophysical modeling and policy uncertainty in the Phoenix metropolitan area. Simulated water consumption for outdoor irrigation and corresponding hydroclimatic condition related to individual green infrastructure scenarios are expected to be highly informative for analysts in urban planning via moderating between the maximum possible degree of temperature change along with the amount of water usage.

2. Model description and setup

The advanced research version 3.4.1 of the Weather Research and Forecasting model, an integrated land-atmosphere framework developed by the National Center for Atmospheric Research, was used for numerical simulations in this study. The WRF model features multiple parameterization options to represent physical processes in the land-atmosphere system (Skamarock & Klemp, 2008), and hence has been widely tested over major metropolitan areas around the world, ranging from weather predictions to regional water resources (Chen et al., 2011). Enabled by a recent model development (Yang, Wang, Chen et al., 2015), water and heat transport inside the urban canopy were modeled using a new single-layer urban canopy model with consideration of hydrological processes. The previous study (Yang & Wang, 2015) was conducted in an offline setting where the UCM is employed as a stand-alone model, whilst the current study is online by coupling land surface processes with atmospheric dynamics.

To avoid the boundary effect, a domain of 1856 km × 1856 km centered at the Phoenix metropolitan area was used for the numerical simulation. A nested domain configuration (Fig. 1(a)) was used to output high-resolution results around metropolitan Phoenix with incorporation of large-scale meteorological forcing. The outer, middle, and inner domains had a resolution of 32 km, 8 km, and 2 km, respectively. Spatial variation of land use/land cover in the inner domain (Fig. 1(b)) was represented using the National Land Cover Database 2006 (Fry et al., 2011; Wickham et al., 2013). In this database, urban land use is divided into three categories, namely, high intensity, medium intensity, and low intensity, respectively. Building height and fraction of impervious surface increase with the intensity of urban land use. For every urban grid, fractions of impervious surface (f_{urb} in Table 1) and ground green infrastructure add up to unity. Shrub/scrub (named as “open shrubland” in the WRF model) is the dominant land use type surrounding Phoenix. This land use/land cover features low water use native shrubs (e.g., agave, cactus, etc.) and short trees (e.g., mesquite, acacia constricta, etc.), and is representative of xeric landscape in the southwestern United States (Volo, Vivoni, Martin, Earl, & Ruddell, 2014; Yabiku, Casagrande, & Farley-Metzger, 2008).

We simulated three scenarios with the WRF-UCM model: (1) the control case: mixed ground green infrastructure (cropland/natural vegetation mosaic) representing the current urban practice of landscape management with daily irrigation in the Phoenix metropolitan area; (2) the hypothetical water-saving scenario, i.e. current ground green infrastructure is xeriscaped (open shrubland) with no irrigation; and (3) the fully-greening scenario: 100% coverage of green roofs (short-grass) and current ground green infrastructure replaced by mesic landscaping (grassland), both irrigated daily. Water-saving and fully-greening scenarios are extreme scenarios that are unlikely to be accomplished in practice, and are useful in estimating theoretical limits of the regional impact of urban green infrastructure. Following a previous study (Yang, Wang, Georgescu et al., 2016), irrigation is scheduled at night and the daily amount is equal to an increase in moisture of a 0.4 m thick soil layer to a threshold value where transpiration will not be limited by the water availability. Irrigation is applied only to the green infrastructure in urban grids and not to those in rural areas.

Simulations were conducted for the summer (June, July, and August), a season which necessitates frequent irrigation to compensate for heat-induced rapid soil water loss through evapotranspiration. The Final Operational Global Analysis data, available on a 1° x 1° resolution with a 6-h temporal frequency since 1999, were obtained from the National Centers for Environmental Prediction (https://rda.ucar.edu/datasets/ds083.2/) to drive the simulations. To reduce the sensitivity of model results to inter-annual variability of meteorological conditions, each scenario was repeated for 5 years (2008–2012) to better estimate the average impact of different green infrastructure strategies on the metropolitan Phoenix.

3. Model evaluation

Performance of the WRF-UCM model in capturing the local hydroclimate was evaluated against field measurements obtained by ground-based stations within the Phoenix metropolitan area. Hourly observations of air temperature and dewpoint temperature were collected from 4 Arizona Meteorological Network (https://cals.arizona.edu/azmet/) stations including Phoenix Encanto (33.479° N, 112.096° W), Phoenix Greenway (33.621° N, 112.108° W), Mesa (33.387° N, 111.867° W), and Desert Ridge (33.733° N, 111.967° W). In addition, in-situ measurements at the Skyharbor International Airport (33.428° N, 112.004° W) were used. Dewpoint temperature was included in this study since our focus is not merely on temperature but on the energy-water nexus in regional hydroclimate. In Phoenix, previous studies had estimated the input parameters of a typical residential neighbor (Chow, Volo, Vivoni, Jenerette, & Ruddell, 2014; Yang, Wang, Georgescu et al., 2016) and different land use classes (Yang, Wang, Kaloush et al., 2016) for urban canopy models using remote sensing technique and in-situ measurement. In the WRF-UCM model, input parameter space for each urban land use type is specified by users, where variability within individual types is largely neglected to maintain computational efficiency. We adopted the reported parameters and adjusted them within a physical