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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

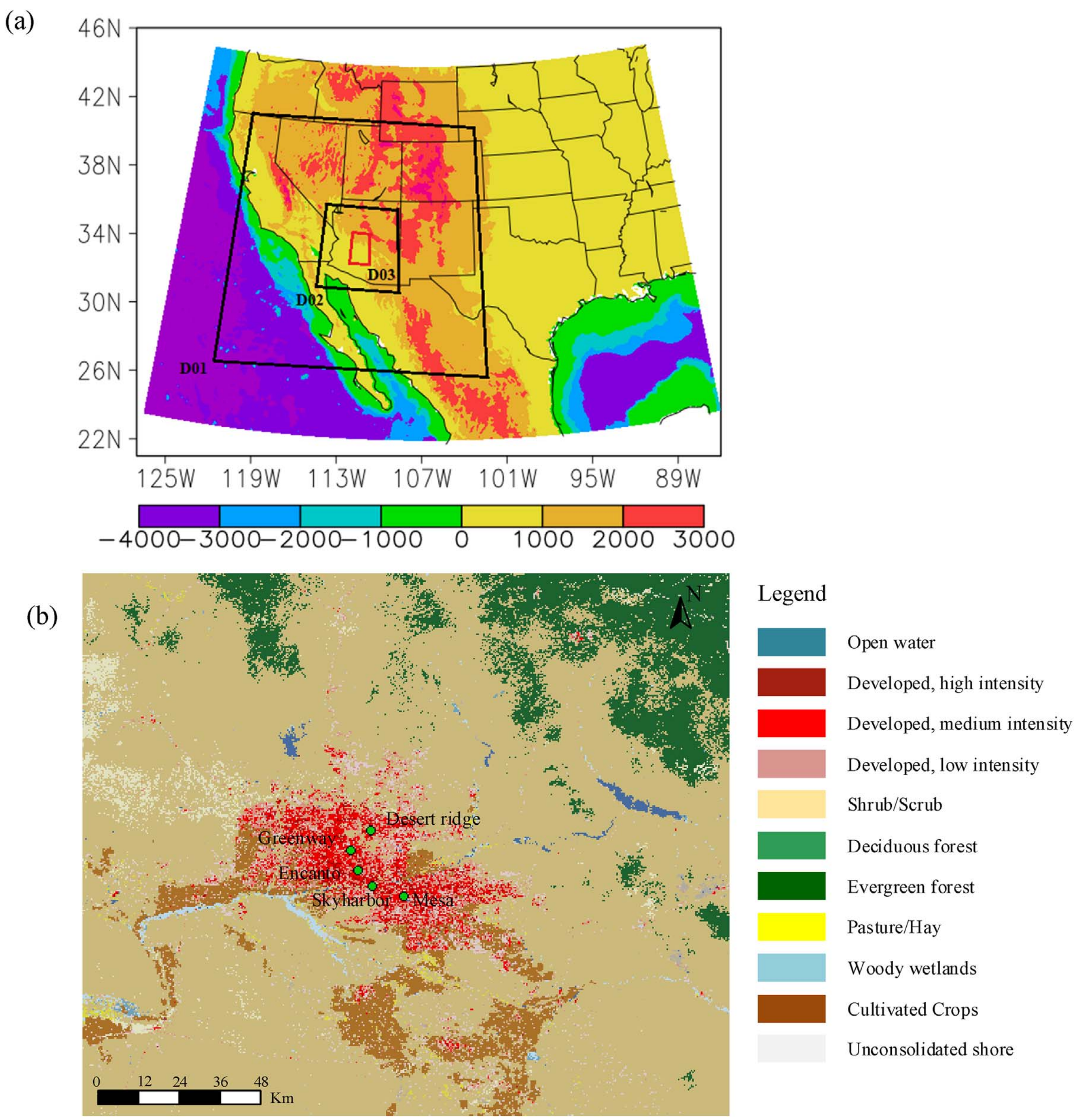

Fig. 1. Numerical experiment setup in the WRF-UCM model: (a) Geographical representation of the domain extent with elevation (in meters) overlaid; (b) Spatial variation of land use land cover (major land use categories shown in the legend) and location of ground-based meteorological stations in the inner domain.

Table 1
Summary of canopy parameters for different urban land use categories in the WRF-UCM model.

Canopy parameters	Unit	High-density	Medium-density	Low-density
h (building height)	m	17.0	7.5	5.0
l_{roof} (roof width)	m	10.0	9.4	8.3
l_{road} (road width)	m	10.0	9.4	8.3
f_{urb} (urban fraction)	–	0.95	0.85	0.70
α (albedo of building materials)	–	0.16	0.18	0.18
k (thermal conductivity of building materials)	$\mathrm{W\,m^{-1}\,K^{-1}}$	1.8	1.3	1.3
C (heat capacity of building materials)	$\mathrm{MJ\,m^{-3}\,K^{-1}}$	2.8	2.1	2.1
ε (emissivity of building materials)	–	0.90	0.90	0.90
Anthropogenic heat	$\mathrm{W\,m^{-2}}$	35	30	20

range, and calibrated the model for three urban land use categories for a week from May 15 to May 22, 2012 (Table 1). After calibration the WRF-UCM model was run for May 23 to August 31, with May 23–May 31 as the spin-up period for 5 different summers.

Averaged 2-m air temperature (T_2) and 2-m dewpoint temperature (T_{d2}) from the model were compared against averaged measurements over 5 stations in Fig. 2. It is clear that predicted T_2 and T_{d2} match reasonably well with observations throughout summers from 2008 to 2012. Root-mean-square error (RMSE) and coefficient of determination (R^2) are summarized in Table 2. During the study period, the model performance is the best in 2008, and least accurate in year 2010. Overall, Table 2 indicates that the discrepancy between model prediction and observation is relatively small across all summers, with the RMSE ranging from 1.85 to 2.07 °C for T_2, and 2.80 ~ 3.91 °C for T_{d2}. The mean R^2 for T_2 and T_{d2} is 0.86 and 0.78, respectively. Predicted T_{d2} tended to have a larger error than that of T_2 when compared against in-situ measurements. To date, accurate modeling of urban hydroclimate in the monsoon season (July – September in Phoenix) remains an

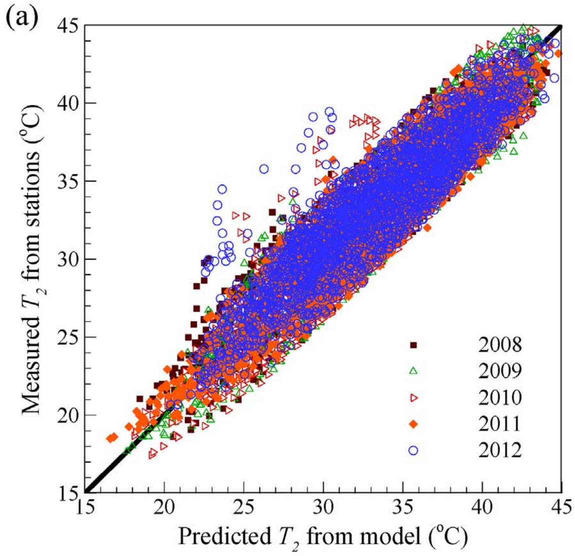

Fig. 2. Comparison of WRF-UCM model prediction in the control scenario against observation (both averaged over 5 stations in Fig. 1) in Phoenix during 2008–2012 summers: (a) 2-m air temperature, and (b) 2-m dewpoint temperature.

Table 2
Summary of root-mean-square error and coefficient of determination in comparison of model-predicted 2-m air temperature and dewpoint temperature in the control scenario against station measurements.

		2008	2009	2010	2011	2012	Mean
RMSE (°C)	T_2	1.78	1.85	2.07	1.85	2.03	1.91
	T_{d2}	2.80	2.81	3.91	3.36	3.40	3.26
R^2	T_2	0.87	0.88	0.83	0.87	0.83	0.86
	T_{d2}	0.83	0.77	0.69	0.81	0.78	0.78

ongoing challenge. In general, the agreement between model predictions and observations demonstrates the capacity of the WRF-UCM model to reproduce current hydroclimate in the Phoenix metropolitan area.

According to the Phoenix Active Management Area assessment template (http://www.azwater.gov/AzDWR/WaterManagement/Assessments/default.htm#Phoenix), urban irrigation consumed 1.49×10^8 m^3 water in 2009. Direct comparison between model-predicted summer irrigation and observation is not feasible since the seasonal irrigation data are not available. Using water meter data at Arizona State University's Polytechnic campus in 2007–2009 from the North Desert Village Neighbourhood Landscaping Experiment (https://sustainability.asu.edu/caplter/research/long-term-monitoring/north-desert-village-neighborhood-landscaping-experiment/), summer irrigation is found to be 37.76 ± 0.78% (mean ± standard deviation) of the annual irrigation for a typical mesic household and 38.82 ± 4.63% for a typical xeric household in the metropolitan Phoenix. Model-predicted summer irrigation for the entire Phoenix metropolitan area in 2008–2012 is about 51.68 ± 3.36% of the reported annual irrigation in 2009. Simulation results apparently overestimate summer water consumption compared to the experiment, which possibly exaggerate the effect of urban green infrastructure management. However, it is difficult to estimate regional urban irrigation because of the variety in timing, duration, and amount of outdoor water consumption from neighbourhood to neighbourhood. Due to this practical limitation of data

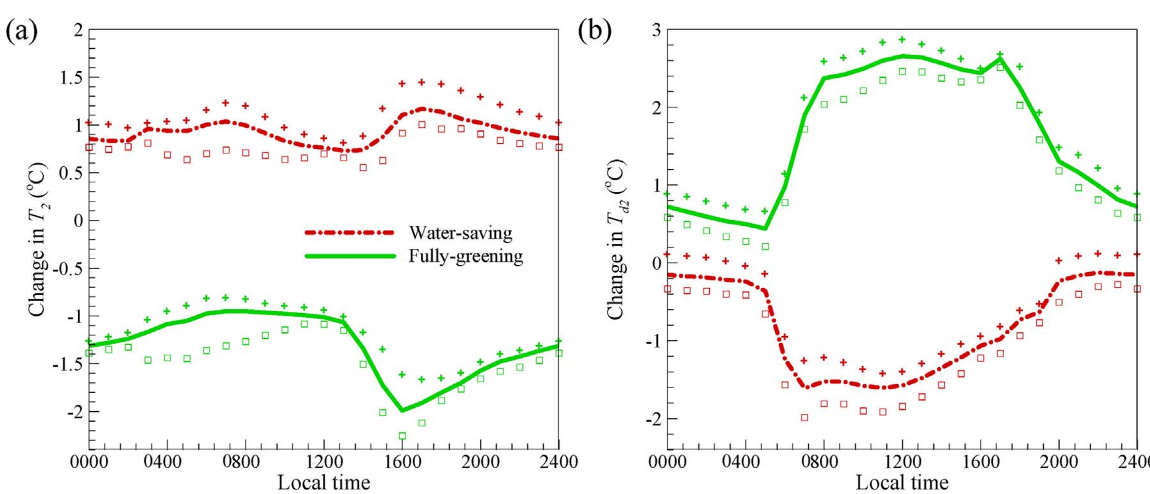

Fig. 3. Simulated difference between hypothetical scenarios and the control scenario in the WRF-UCM model averaged over the Phoenix metropolitan area: (a) 2-m air temperature, and (b) 2-m dewpoint temperature. The lines represent the mean difference over summers from 2008 to 2012, while "+" and "□" denote upper and lower bounds of the simulated difference among studied summers.

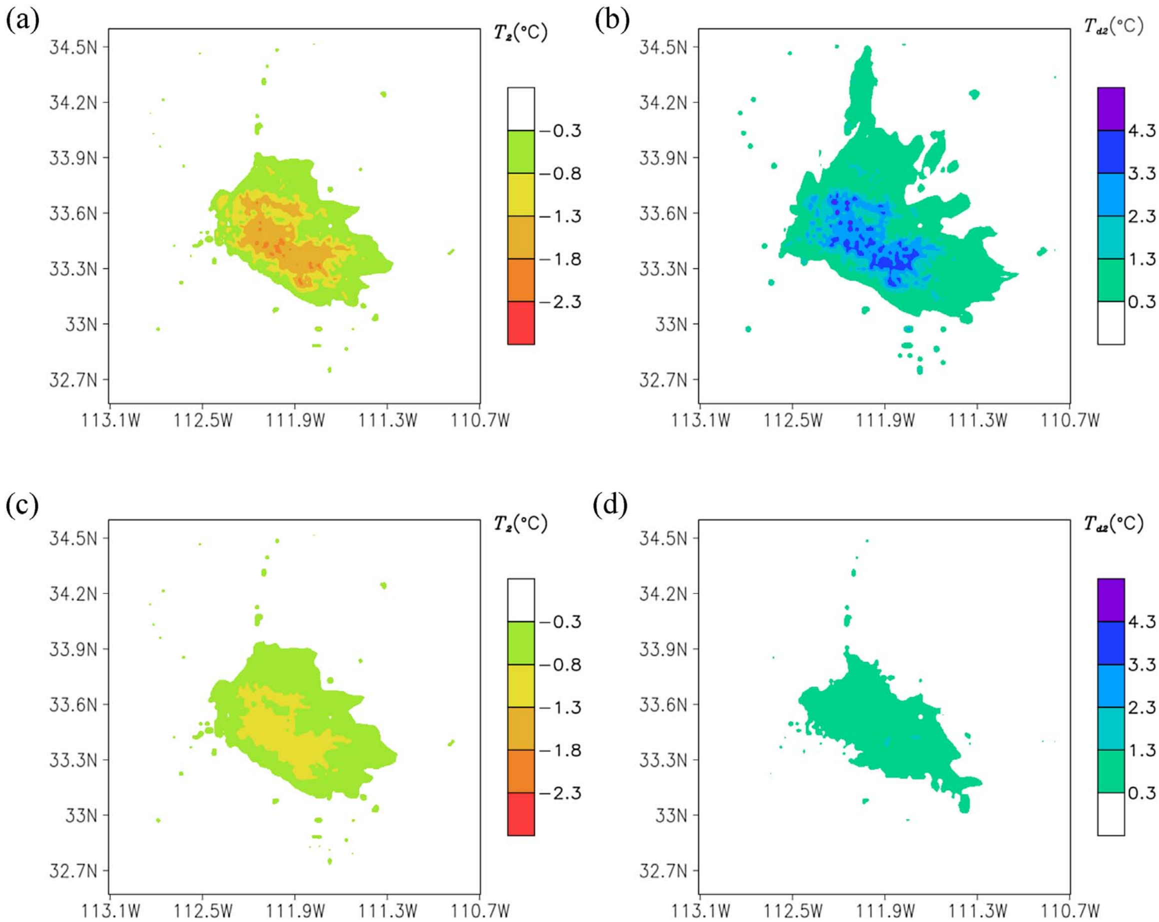

Fig. 4. Simulated mean difference between the control and the fully-greening scenarios in the WRF-UCM model over 2008–2012 summers: (a) 2-m air temperature at 1400 local time, (b) 2-m dewpoint temperature at 1400 local time, (c) 2-m air temperature at 0200 local time, and (d) 2-m dewpoint temperature at 0200 local time.

availability, the estimated summer irrigation in the control scenario is adopted as a reference for subsequent analysis.

4. Regional climate modeling

4.1. Hydroclimatic impacts

With different irrigation schedules and green infrastructure types, the two simulated hypothetical scenarios exhibit distinct hydroclimatic responses in the study area. As compared to the control case, the fully-greening scenario (with ample irrigation and enhanced evapotranspirative cooling during daytime), as shown in Figs. 3(a) and 4(a), induces urban cooling, with a maximum reduction of 2.0 °C for T_2 and an increase of 2.7 °C for T_{d2}, respectively. The reduction in air temperature has significant implications for building energy consumption; whereas a life cycle analysis of the water-energy nexus determines an optimal urban irrigation scheme (Yang & Wang, 2015). The nocturnal cooling of air temperature, in comparison, is lower than the daytime counterpart (Fig. 4(c)), as the energy source for evapotranspiration diminishes. The fully-greening scenario has a relatively homogeneous effect over the Phoenix metropolitan area (Fig. 4), as the areal fraction of green roofs (roof area divided by the total area of roof and road) is set the same across three urban land use categories (Table 1). On the other hand, the self-supportive xeriscaping infrastructure with no irrigation leads to consistently higher T_2 (Figs. 3(a), 5(a) and (c)) and lower T_{d2} (Figs. 3(b) and 5(b)) with reduced water consumption. The south-eastern part of the metropolitan area, consisting mainly of low-density residential neighbor, experiences a greater change in hydroclimate than other areas (Fig. 5). This is due to the smaller fraction of impervious surface and larger coverage of ground vegetation. It is noteworthy that simulated mean daytime maximum temperature of summers from 2008 to 2012 in the control case is about 38.4 °C, where the additional warming of about 1.2 °C by xeriscaping (mean daytime maximum temperature reaches 39.6 °C in the water-saving case) is a critical factor in heat-related morbidity and mortality (Golden, Hartz, Brazel, Luber, & Phelan, 2008), especially for citizens without access to air conditioning systems.

Despite the annual variability caused by meteorological conditions, hydroclimatic impacts of hypothesized urban green infrastructure scenarios are relatively steady (Fig. 3). In both water-saving and fully-greening scenarios, the mean difference between the upper and the lower bounds is about 0.3 in T_2 and 0.4 °C in T_{d2}. Over the diurnal cycle, the irrigated mesic green infrastructure provides a stronger cooling effect (1.21 °C) than the xeriscaping scenario provides in warming (0.92 °C). Difference between the control and water-saving cases indicates that existing urban green infrastructure and irrigation schemes play a crucial role in regulating the current hydroclimate of the Phoenix metropolitan area. In addition, to achieve the improved thermal comfort in the fully-greening scenario, deployment of green roofs across entire metropolitan area will require extensive engineering and maintenance efforts (Bianchini & Hewage, 2012).

4.2. Potential water buffering capacity

The potential water buffering capacity of urban green infrastructure is estimated as the difference of water usage between the water-saving (xeriscaping) and the fully-greening scenarios. To completely replace xeriscaping by mesic/oasis landscape with green roofs, approximately

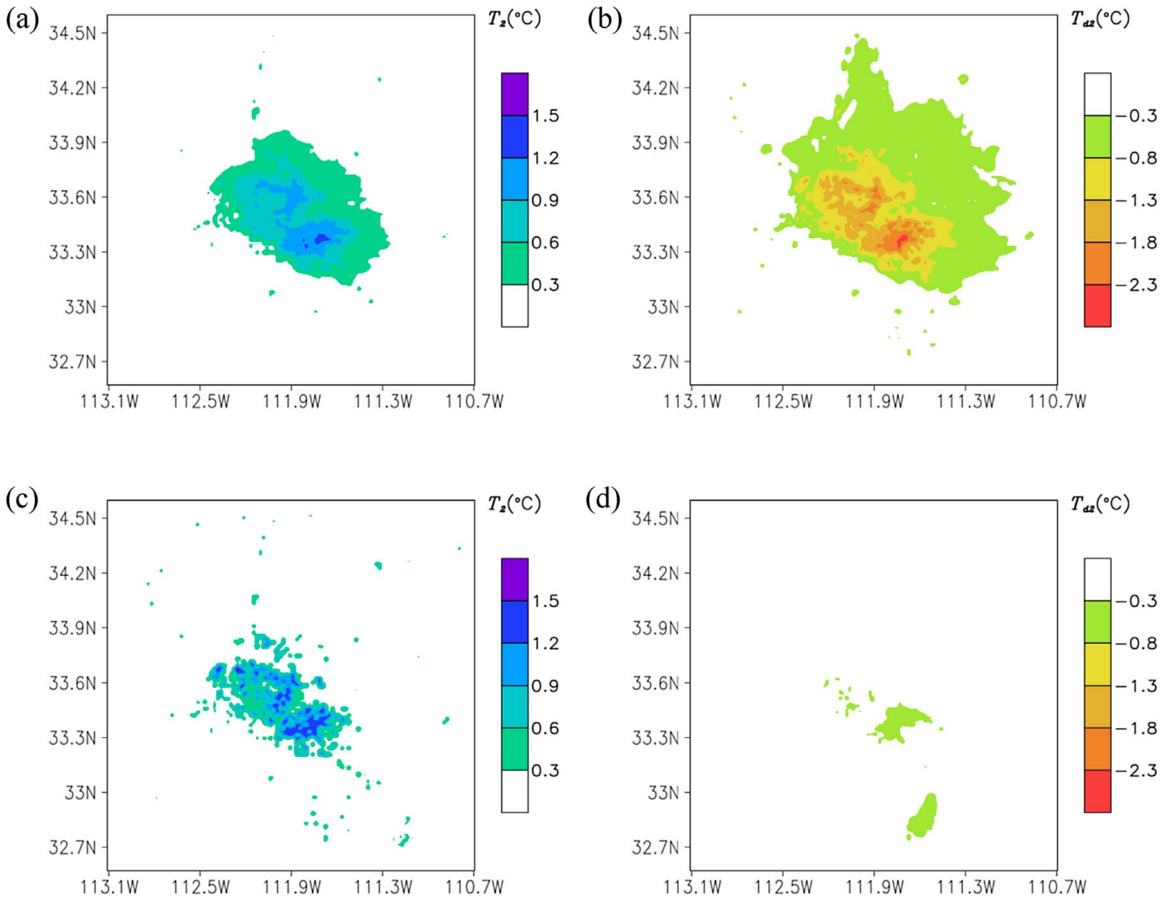

Fig. 5. Simulated mean difference between the control and the water-saving scenarios in the WRF-UCM model over 2008–2012 summers: (a) 2-m air temperature at 1400 local time, (b) 2-m dewpoint temperature at 1400 local time, (c) 2-m air temperature at 0200 local time, and (d) 2-m dewpoint temperature at 0200 local time.

176 mm depth of outdoor irrigation per unit Phoenix urban area (i.e. inner domain) is consumed on average in the summer (Fig. 6(a)). Summing over the entire Phoenix metropolitan area, mean demand of outdoor irrigation amounts to 3.62×10^8 m^3 of water (Table 3). As the urban green infrastructure is not over-irrigated, most of the irrigation water is converted to humidity via evapotranspiration and creates cooling benefits for the built environment. Despite spatial variability within the urban matrix, the potential water buffering capacity per unit urban area is relatively constant over the metropolitan Phoenix, owing to the substantial water consumption related to the rooftop green infrastructure. Irrigation water consumption in the fully-greening scenario (with green roofs) is about five times as the irrigation water consumption in the control case (green infrastructure only at the ground level, see Table 3). Fig. 6(b) shows that the standard deviation of difference in irrigation depth per summer between the fully-greening and water-saving scenarios ranges from 0 to 20 mm during 2008–2012. This suggests that the estimated potential water buffering capacity of urban green infrastructure is relatively insensitive to summer meteorological conditions in the study area, as the variation ($\sim$10 mm) is only about 5% of the mean ($\sim$176 mm).

The variability between the xeric and mesic green infrastructure leads to markedly different hydroclimatic patterns in the desert city (Fig. 7). By converting a hypothetical water-saving city to a fully-greening one, metropolitan center of Phoenix receives a significant

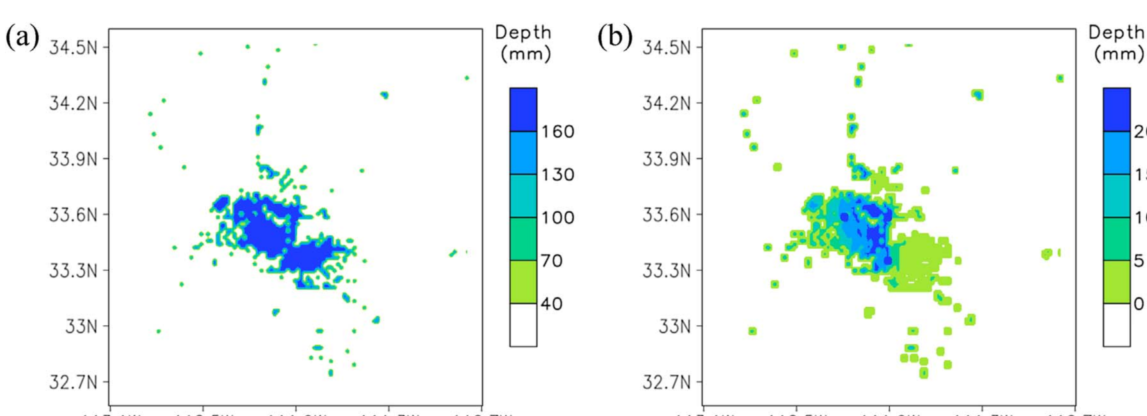

Fig. 6. Simulated difference in irrigation depth per summer between the fully-greening and the water-saving scenarios in the WRF-UCM model over 2008–2012 summers: (a) mean, and (b) standard deviation.

Table 3
Water usage and corresponding hydroclimatic condition of the Phoenix metropolitan area in different simulated scenarios. Values before and after ± denote the mean and standard deviation over 2008–2012 summers.

Case name	Irrigation amount (m^3)	Cumulative ET (mm)	Daytime mean T_2 (°C)	Daytime mean T_{d2} (°C)	Nighttime mean T_2 (°C)	Nighttime mean T_{d2} (°C)
Control	$0.77 \pm 0.05 \times 10^8$	84.4 ± 6.1	35.28 ± 0.47	8.97 ± 0.83	31.07 ± 0.36	11.42 ± 1.06
Water-saving	0	13.8 ± 2.7	36.19 ± 0.63	7.66 ± 0.71	31.99 ± 0.43	11.14 ± 0.84
Fully-greening	$3.62 \pm 0.31 \times 10^8$	161.9 ± 10.6	33.71 ± 0.31	11.18 ± 1.12	30.22 ± 0.27	11.97 ± 1.30

cooling benefit, while the maximum change occurs in the southeast part of the city. The cooling of T_2 and the warming of T_{d2} at 1400 local time can be more than 2.7 (Fig. 7(a)) and 5.3 °C (Fig. 7(b)), respectively. This effect generally diminishes with increasing distance from the metropolitan center. Via the urban-rural air circulation, the planning of urban green infrastructure alters the hydroclimate of surrounding rural areas. The prevailing wind generates a more evident difference in the northern and eastern outskirts of the Phoenix metropolitan. Contrasting green infrastructure strategies also have evident effects on the nighttime urban thermal environment. Without the radiative energy supply, evapotranspirative cooling of green infrastructure is not effective to the extent that the increase in T_{d2} at night is much smaller than that in daytime (Fig. 7(d)), and the signature of cooling in 2-m air temperature is consequently dampened in nighttime. The spatial patterns of differences in T_2 and T_{d2} provide evidences of the potential variability of regional hydroclimatic responses to the landscape planning.

5. Implications to water source management

Water resource management in urban networks necessitates complex tradeoffs among social, economic, and environmental components. Previous studies of urban green infrastructure have largely focused on unraveling the environmental-economic tradeoff (e.g., water vs. electricity consumption), leaving implications to the environmental-social nexus comparatively less explored. To illustrate the environmental-social tradeoff, here we quantify the water usage required by urban green infrastructure as equivalent to the population to be supported by the same amount of water. Within the Phoenix metropolitan area, residential water consumption can be vastly different across cities (Arizona Department of Water Resources, 2010). Scottsdale, one of the wealthiest cities in the state, has large-lot residential estates and a per capita annual water use of about 302 m^3 in 2009. In contrast, high population density in other cities (Glendale, Gilbert, Chandler, Mesa, Phoenix, and Tempe) leads to an annual water use of 148–178 m^3 per resident in 2009. In compact communities with housing density of 37–74 units per hectare, per capita annual water use can be as low as 75 m^3 per person (Gober & Kirkwood, 2010). As latest information after 2010 is not available, in this study we assume that emergent population in this region maintains a similar lifestyle as residents in high-density cities during 2009, with a minimum water consumption of 148 m^3 per person annually.

In addition, the population capacity in each scenario can be readily

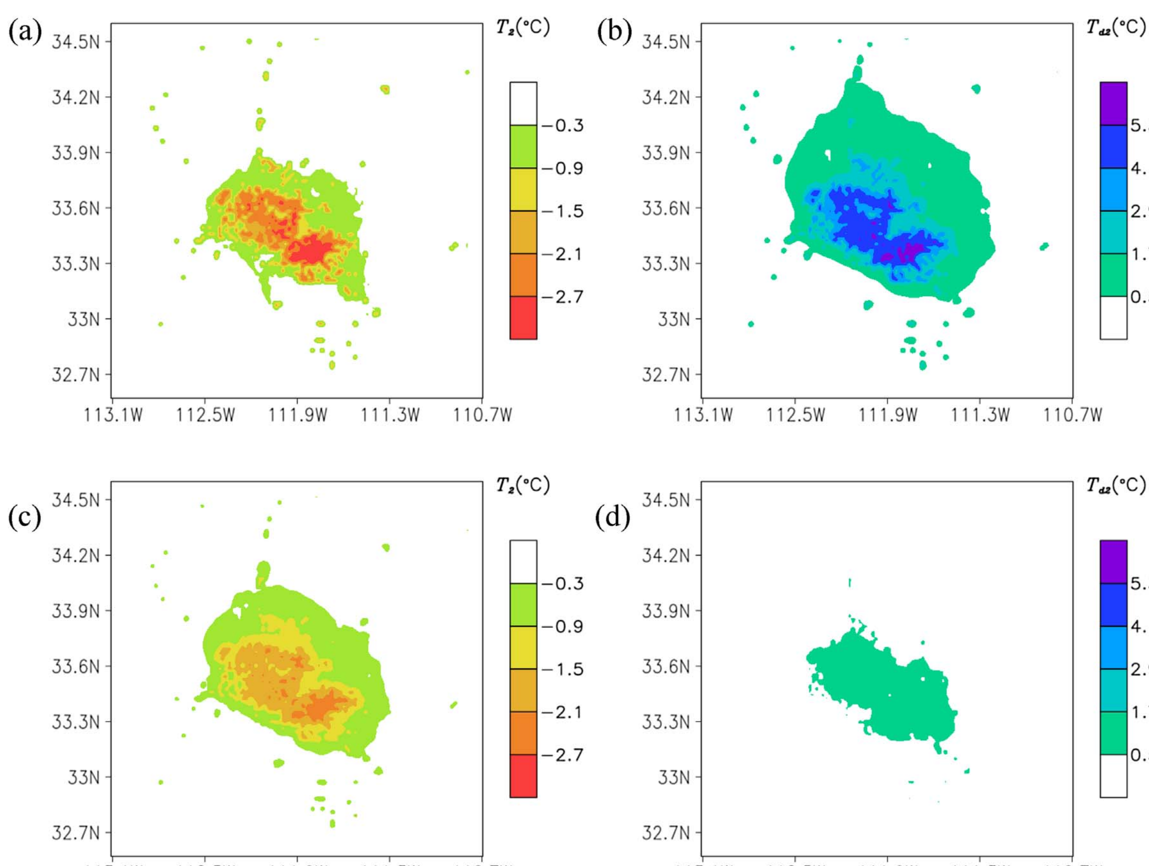

Fig. 7. Simulated mean difference between the fully-greening and the water-saving scenarios in the WRF-UCM model over 2008–2012 summers: (a) 2-m air temperature at 1400 local time, (b) 2-m dewpoint temperature at 1400 local time, (c) 2-m air temperature at 0200 local time, and (d) 2-m dewpoint temperature at 0200 local time.

derived by dividing the irrigation water use (Table 3) by the per capita water consumption in the study area (148 m^3). It is found that the irrigation water saving by xeriscaping is able to support the demand of 0.52 million new residents, which is about 19.8% of projected population growth (2.62 million) by 2050 (Arizona Department of Administration, 2015). This number is in good agreement with previous findings (Gober & Kirkwood, 2010) from a water supply and demand model (using WaterSim) that changes in lifestyle would allow the region to avoid a water shortage. In contrast, the fully-greening city requires an excessive amount of irrigation water, equivalent to the annual water consumption of 1.93 million residents, which is about 73.7% of the demand of emerging population in the projected medium growth series (Arizona Department of Administration, 2015).

6. Discussions

Municipal water demand in the Phoenix metropolitan area is projected to increase by 0.46–1.21 $\times 10^9$ m^3 between 2006 and 2025, depending on the amount of projected population growth (Arizona Department of Water Resources, 2010). The Arizona Department of Water Resources plans to increase supply from Colorado River (1.92–5.13 $\times 10^8$ m^3) and groundwater (1.12–5.47 $\times 10^8$ m^3) to meet this demand. Previous studies unanimously predicted that runoff in the Colorado River basin will reduce by 10–30% in the changing climate (Barnett & Pierce, 2009). Consequently, groundwater becomes the only reliable source to compensate for the deficit in water supply. Under this circumstance, the influence of reduced irrigation water ($0.77 \pm 0.05 \times 10^8$ m^3) for the water-saving scenario or the increase in water demand ($3.62 \pm 0.31 \times 10^8$ m^3) for the fully-greening case will be substantial for the magnitude of groundwater extraction. The state of Arizona has devoted great efforts to preserving groundwater resource after the passage of Groundwater Management Act in 1980. Nevertheless, a continuous groundwater overdraft has continued in this region (Arizona Department of Water Resources, 2010), so that any future modification on green infrastructure should carefully examine the impact on groundwater.

It is worth pointing out that green infrastructure in this study refers to short vegetation with small canopies due to the lack of representation of urban trees in the WRF-UCM model. Simulated regional hydroclimatic changes in different scenarios are therefore attributed to the modifications of landscape water-energy transport by short vegetation. Shade trees (not included in this study), for example, are popular for urban xeriscaping. With less water use, trees provide a significantly lower evapotranspirative cooling than short grass (Shashua-Bar, Pearlmutter, & Erell, 2011). They however reflect more downward radiation via large canopies and subsequent shading can effectively cool the air temperature. In addition, trees intercept radiative energy exchange between urban surfaces (i.e., walls and road) and reduce the heat storage inside the canyon, which is a primary cause of nighttime urban heat islands (Wang & Li, 2017). Though many studies found that tall trees have a higher cooling efficiency than short vegetation in the urban environment for both daytime and nighttime (Shashua-Bar et al., 2011; Shiflett et al., 2017; C. Wang et al., 2016; Z.H. Wang et al., 2016), some reported that tree canopies can retain heat at night (Gillner, Vogt, Tharang, Dettman, & Roloff, 2015; Huang, Li, Zhao, & Zhu, 2008). Parameterization of urban trees has been implemented into urban canopy models (Wang, 2014; Ryu, Bou-Zeid, Wang, & Smith, 2016) and its incorporation with the integrated WRF-UCM model is currently underway. Combined with an experimental dataset, the enhanced numerical tool will enable a better investigation of urban energy-water nexus.

In addition, this study is limited by the availability of latest dataset mainly in two ways. First, a considerable gap exists between the NLCD 2006 data used for model simulation and the current land use condition in 2017. If the expansion of Phoenix metropolitan area since 2006 is included, the impact of different green infrastructure plans is expected to be slightly greater than the current estimation. Second, per capita water use in this study is adopted from reports in 2010, when the city of Phoenix has experienced an increasing in water use efficiency and the per capita residential consumption dropped about 25% from 2002 to 2009 (City of Phoenix, 2011). It is reasonable to speculate that the water consumption per capita has been further reduced since 2009, with application of more incentivized water-saving strategies in many cities. This will lead to larger population growth capacity, supported by the water saving from xeriscaping, as compared to the current study, or create a better buffer if the population increase does not happen.

7. Concluding remarks

Despite the inherent uncertainties associated with the modeling approach, our analysis quantifies the potential water buffering capacity of urban green infrastructure in the Phoenix metropolitan area and its hydroclimatic and social implications. Such information is crucial for the long-term water sustainability under the challenge of future climate change and population growth. The adoption of complete xeriscaping land use significantly reduces the vulnerability of water shortage induced by the projected population growth in the region; notwithstanding the intensive summertime urban thermal environment in the semiarid region will be further exacerbated. The environmental-social tradeoff demonstrated in this study can be considered in the blueprint of cities to help landscape management in prioritizing urban development strategies in the water-energy nexus. With the potential water buffering capacity of urban green infrastructure in mind, the dilemma is still left to be solved by decision makers by accounting for how much the cost of water resource in order to sustain a cooler environment, or *vice versa*. An integrated tool incorporating intricate relationships among social, economic, and environmental activities is essential for advancing sustainable water management in the contemporary landscape of semi-arid and arid conurbations.

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