Energy and Buildings 107 (2015) 335–344

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Optimizing urban irrigation schemes for the trade-off between energy and water consumption

Jiachuan Yang, Zhi-Hua Wang*

School of Sustainable Engineering and the Built Environment, Arizona State University, PO Box 873005, Tempe, AZ 85287-3005, USA

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form 29 July 2015
Accepted 22 August 2015
Available online 24 August 2015

Keywords:
Building energy efficiency
Energy-water trade-off
Environmental sustainability
Urban canopy model
Urban irrigation

ABSTRACT

Irrigation of green spaces in cities helps to reduce thermal stress and building energy consumption in hot seasons, but requires an intricate balance between energy and water resource usage. While the objective for agricultural irrigation is focused on the yield of produces, urban irrigation needs a new paradigm. In this study, a cutting-edge urban canopy model is applied to assess the impact of a variety of controlled irrigation schemes for Phoenix. Results show that by increasing surface moisture availability for evapotranspiration, urban irrigation has a cooling effect on the built environment throughout the year. Maximum reduction in canyon air temperature can be more than 3 °C in summer as compared to the condition without irrigation. Among all investigated schemes, the soil-temperature-controlled irrigation is the most efficient in reducing the annual building energy consumption and the total cost. The total annual saving depends on the controlling soil temperature for irrigation activation, and can be up to about \$1.19 m^{-2} wall area as compared to the current irrigation practice. In addition, the scheme can substantially enhance outdoor thermal comfort of pedestrians in summers.

1. Introduction

From 1984 to 2004, global energy use has been growing at an average annual rate of 2%, with the developing countries experiencing higher increasing rates [1]. At present, urban areas account for 67–76% of global energy use [2], with the percentages expected to increase under future urban expansion. Within the cities, buildings are the dominant energy consumers. Around 40% of the total final energy consumption in the United States and the European Union is in the building sector [3,4]. In recent years there has been a growing concern about the energy consumption as it is the largest contributor to global CO_2 emissions, which is the leading cause of climate change [2]. To reduce greenhouse gas emissions and to slow down the depletion of non-renewable energy resources, a number of studies and initiatives have been carried out during the past decades to cut back building energy consumption, including usage of reflective materials [5], deployment of green roofs [6], introducing new building design requirements [7], and improving operation efficiency of building services [8].

While numerous means for reducing building energy consumption have been investigated, the impact of various urban irrigation schemes on building energy efficiency has been less explored. Building energy consumption in cities is closely related to environmental temperatures [9], on which irrigation has cooling effects by increasing the supply of surface moisture for evapotranspiration. Irrigation-induced cooling on near-surface temperature over agricultural land has been extensively documented in both observational [10] and modeling [11,12] studies. In summers, daily maximum air temperature over 100% irrigated area can be 5 °C cooler than that over non-irrigated area in California [12]. On the other hand, though the importance of irrigation in modeling urban energy and water budget has been increasingly recognized [13,14], the explicit impact of irrigation on urban environmental temperature and building energy consumption has rarely been studied. Irrigation of private gardens consumes 16–34% of the total water supplied to an urban area, let alone the water used for irrigating large open space such as public parks and golf courses [15]. For residential areas within the city of Los Angeles, nearly 225×10^6 m^3 of water was used for irrigation per year [16]. Such amount of irrigation can increase evapotranspiration and cool the urban environment considerably, leading to significantly lower cooling load, especially in densely built areas.

Under the challenge of future climate change, water becomes a more precious resource in cities [17]. Current irrigation practices in most cities are scheduled between sunset and sunrise in order to avoid rapid moisture loss. However, from an energy saving perspective, irrigation should be conducted during daytime as evaporative cooling is driven by available solar radiation at the

* Corresponding author.
E-mail address: zhwang@asu.edu (Z.-H. Wang).

http://dx.doi.org/10.1016/j.enbuild.2015.08.045
0378-7788/

surface. In this case, irrigating urban vegetation leads to improved building energy efficiency, albeit the trade-off and balance between water and energy resources need to be carefully measured. Different from agricultural irrigation whose objective is mainly on the yield of produces [18], urban irrigation apparently needs a new paradigm by considering the environmental sustainability of cities (e.g. mitigate urban heat islands and save building energy consumption).

It is therefore imperative to understand the relationship between water and energy consumption in the urban environment to develop an optimal urban irrigation scheme. In this study a state-of-the-art urban canopy model is employed [19–21], with realistic representation of urban hydrological processes, to identify the environmental impact of urban irrigation in the Phoenix metropolitan area. A variety of uncontrolled and controlled irrigation schemes is investigated, including (1) daily constant scheme, (2) soil-moisture-controlled scheme, and (3) soil-temperature-controlled scheme. Considering the seasonal variation of meteorological conditions and irrigation demands, the net saving of individual scheme is quantified at an annual scale. The trade-off between water and energy consumption is quantified by adopting the combined monetary saving as a measure of environmental co-benefit. The indirect benefit of irrigation on outdoor thermal comfort of pedestrians is also discussed.

2. Numerical simulations

2.1. Irrigation schemes

Here the Phoenix metropolitan area is selected as the study area. The simulation period was one entire calendar year, 2012. Phoenix has a population of more than 1.5 million in 2013, and is the sixth most populous city in the United States [22]. Located in a semi-arid environment, Phoenix has a tremendous demand for cooling compared to other cities [23], thus providing a large potential for building energy saving through optimizing irrigation schemes [24]. In Phoenix, xeric and mesic are two typical vegetated residential landscapes. Xeric sites usually comprise drip-irrigated, low water-use native and/or desert-adapted plants, while mesic sites mainly consist of turf grass and shade trees [25]. Though xeric landscaping helps to conserve water resource, mesic landscaping provides valuable environmental services by, e.g. reducing urban warming and improving stormwater management, and is esthetically appealing [26].

A schematic of irrigation in the urban canopy layer is shown in Fig. 1. Focusing on irrigation of mesic neighborhoods, four different urban irrigation schemes are tested for Phoenix. Scheme 1 is the baseline case with no irrigation during the entire simulation period. Scheme 2 is a daily constant scheme that represents current irrigation practice over mesic residential landscapes in Phoenix. Daily irrigation amount is estimated by dividing monthly irrigation data from an in situ measurement by the number of days in each month [27]. Following a previous study, irrigation is scheduled at 8 pm local time every day in this scheme [28]. Sensitivity analysis finds that the irrigation time at night has limited impacts on model results. Scheme 3 is a soil-moisture-controlled scheme proposed as a potential urban irrigation paradigm. The idea is to maintain soil moisture at a certain level to keep evaporative cooling effective all the time. Whenever the moisture content of top soil layer (θ_{top}) drops below a critical value, irrigation is carried out to increase the moisture. The amount of irrigation each time is set to be the same as that in the daily constant scheme. Scheme 4 is similar to the soil-moisture-controlled scheme but uses the soil temperature as the controlling variable. Targeted on reducing urban environmental temperature during hot periods, the scheme activates urban irrigation once the temperature of top soil layer exceeds a threshold value. Each time the irrigation amount also equals to the daily irrigation amount of Scheme 2. During prolonged daytime period of hot summers, this scheme may easily lead to over irrigation. To avoid waste of water resource, the irrigation amount is then regulated by either the daily irrigation amount of Scheme 2 or the difference between θ_{top} and saturated soil moisture, whichever is smaller. For cool to cold months where soil temperature is consistently lower than the threshold value, essential irrigation is conducted to maintain soil moisture above the wilting point to support biological functions of mesic vegetation.

Volo et al. [29] have conducted a comparative analysis of the impact of irrigation scheduling at both mesic and xeric sites in Phoenix. Typical wilting point for mesic site is found to be from 0.15 to 0.24. In this study, the lower bound value 0.15 is used as the wilting point and the upper bound value 0.24 is used as the controlling moisture for the soil-moisture-controlled irrigation scheme. Residual and saturated soil moisture is set to be 0.10 and 0.50. With respect to the threshold soil temperature for irrigation activation in the soil-temperature-controlled scheme, a value of 22 °C is adopted as the first step to illustrate performance of the scheme.

2.2. Model evaluation

To quantify the impact of urban irrigation, an integrated modeling framework that physically resolves energy and water transport in the urban environment is needed. Here a state-of-the-art urban canopy model (UCM) developed by Wang et al. [19–21] is used. The model features detailed description of hydrological processes over natural and engineered surfaces, sub-facet heterogeneity, and analytical solutions to heat diffusion equations. Capability of the model has been validated by field measurements under different climate conditions [28]. Detailed computational processes of the model can

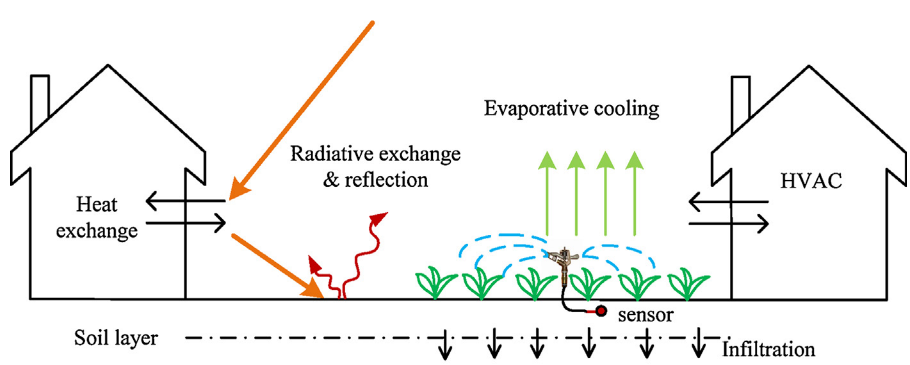

Fig. 1. A schematic of lawn irrigation in residential areas. The two-dimensional “big canyon” representation is adopted to represent the urban area with the longitudinal dimension (canyon length) much larger than the planar dimensions (building height and road width).