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Research Paper

Estimation of residential outdoor water use in Los Angeles, California

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HIGHLIGHTS

- Outdoor use is quantified using water billing data methods and remote-sensing model.
- Traditional methods based on billing data underestimate outdoor use in Los Angeles.
- A remote-sensing model is implemented based on vegetation and land cover products.
- The modeled irrigation estimates were validated with previous outdoor use studies.
- Landscaping irrigation represents 54% of single-family water use in the city.

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ABSTRACT

The current study analyzes existing methods for estimating outdoor use and landscape irrigation in highly developed residential areas across Los Angeles. Outdoor use was estimated using three methods: two methods described by the Pacific Institute and a third approach that utilizes remotely sensed vegetation and water billing data. Monthly individual water use records were provided by the Los Angeles Department of Water and Power (LADWP) for 2000–2010. This period includes voluntary and mandatory restrictions due to drought conditions across the state. Records were aggregated to the census tract level to protect customer privacy. The two Pacific Institute methods, which are based on water billing data, generally underestimate outdoor use due to assumptions that the lowest water consumption month represents indoor use, which is likely not the case in Los Angeles. The remote-sensing model developed between single-family water use and the Landsat normalized difference vegetation index (NDVI) surplus performed well in greener areas of the city and indicates that landscape irrigation use represents 54% of total single-family water use. The model also predicts an average decrease in landscaping irrigation of 6% and by 35% during voluntary and mandatory restrictions, respectively. Voluntary conservation and mandatory waste restrictions were less effective for higher income groups in the city, while more stringent pricing and non-pricing mandatory restrictions in FY2010 had similar effects across income groups. Study results contribute to a better understanding of the partitioning of Los Angeles residential water use and can be utilized to evaluate pricing structures and target water conservation efforts.

1. Introduction

Residential water use is the largest urban water use category, with single-family water use noted to represent half of urban water consumption in California (2000) (CDWR, 2005; DeOreo et al., 2011; Gleick et al., 2003). A recent study by DeOreo et al. (2011) notes that residential outdoor use in Southern California is twice as high as in Northern California and represents a significant portion of household water budget (65% of average daily water use in Southern California study sites based on household logged water records and flow trace analysis) (DeOreo et al., 2011). The DeOreo study of single-family water use includes several water agencies across California from Sonoma County Water Agency to San Diego Water Authority including the Los Angeles Department of Water and Power (LADWP). It is important to note that most cities in California's Central Valley do not yet have residential water meters, thus studying residential water use in California is generally restricted to the major coastal metropolitan areas. It is evident that

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outdoor water use has the largest potential for water conservation. Recent work highlights that residential outdoor use in California can be reduced by 25% to 40% with improved management practices and increased use of available irrigation technology (Gleick et al., 2003). The difficulty resides in quantifying and predicting outdoor water use for which current approaches entail significant uncertainties related to heterogeneous land cover characteristics, water consumption metering, climate, and availability of data (Gleick et al., 2003).

A range of methods has been developed to estimate residential outdoor use. Early methods developed by Costello and Jones (1994) and Costello, Matheny, & Clark (2000) focused on landscape coefficients and estimated irrigation requirements based on the landscape characteristics and reference evapotranspiration (ETo). The landscape coefficient (K_L) is the product of three factors including species, density and microclimate conditions based on field observations (Costello and Jones, 1994 and Costello et al., 2000). The landscape method is difficult to apply at regional and longer temporal scales as it requires data for each plant species within heterogeneous urban landscapes. Previous studies have implemented this method at the household level, producing reasonable estimates of landscaping irrigation requirements that also account for effective precipitation and irrigation system efficiency (DeOreo et al., 2011; Domene, Saurí, & Parés, 2005; Haley, Dukes, & Miller, 2007; Salvador, Bautista-Capetillo, & Playán, 2011). The landscape method is particularly challenging to apply to Southern California as the region has high floral biodiversity, perhaps some of the highest in the nation, due to its benign climate (Pincetl, Gillespie, Pataki, Saatchi, & Saphores, 2012; Pincetl et al., 2013). Based on this approach, Al-Kofahi, VanLeeuwen, Samani, & St Hilaire (2011) proposed an approach that integrates different types of residential tree, shrubs and grass to estimate a water budget for homeowners' residential landscape in Albuquerque, New Mexico.

A second category of methods relies on the formulation of urban water balance models. Grimmond et al. (1986, 1996) and Grimmond and Oke (1986) estimated urban water budget coupled with an energy balance approach to evaluate human impacts in urbanized areas. The model relies on the partition of the urban domain into three surfaces: impervious, pervious irrigated and pervious non-irrigated. The developed model can be run from daily to annual time scales but requires climate data, land cover characteristics, surface retention capacities, soil storage capacity, field capacity, water use data (for the imported water supply component), water storage conditions and surface aerodynamic characteristics for evapotranspiration, many of which are difficult to obtain in highly urbanized areas (Grimmond, Oke, & Steyn, 1986; Grimmond and Oke, 1986).

Urban irrigation is also not routinely incorporated in urban hydrologic models including land surface models (LSMs) which are commonly used for longer term climate and ecosystem impact studies. Micro-scale urban water models have been employed to better understand runoff and landscape irrigation processes (Xiao, McPherson, Simpson, & Ustin, 2007). Xiao et al. (2007) developed an urban water model at the residential parcel scale based on physical parameters to evaluate the impact of best management practices on landscaping irrigation. Vahmani and Hogue (2013) developed an irrigation module within the coupled Noah-SLUCM (single layer urban canopy model) to assess residential irrigation and the impact on urban meteorological processes at the block level in Los Angeles.

Several studies have also used total and indoor water use to derive outdoor use estimate as a residual (DeOreo et al., 2011; Endter-Wada, Kurtzman, Keenan, Kjelgren, & Neale, 2008; Grimmond, Souch, & Hubble, 1996; Syme, Shao, Po, & Campbell, 2004). There are different models used to estimate indoor use, including water billing data and direct measurement through household logged water data and flow trace analysis (DeOreo et al., 2011; Mayer and DeOreo, 1999). Total water use is generally obtained from water billing data or logged water records from these same studies. These methods evolved due to the lack of indoor-outdoor metering information. Few places in the U.S. require dual metering, thus determining the apportionment of water use between indoor and outdoor use remains difficult.

The Pacific Institute (Gleick et al., 2003) developed minimum use month and average minimum use methods for regions of California which can be applied using monthly water use billing data. The assumption underlying both aforementioned methods is that indoor use remains consistent throughout the year (non-seasonally dependent). This hypothesis was tested in the Mayer and DeOreo (1999) study which showed there were no statistically significant differences in indoor use between different seasons in the cities selected in warmer and cooler climates (except for Tampa, FL). For the minimum use month method, the month with the minimum water use is identified for each year as indoor use and the difference between the minimum value and each monthly water use value represents outdoor use. The same approach is used for the average minimum use method: the average of the three lowest water consumptions is computed to be equal to indoor use and outdoor use is calculated as the residual. However, the estimation of indoor use using the minimum use month in semi-arid climates generally includes some residential irrigation and overestimates indoor use (Gleick et al., 2003; Mayer and DeOreo, 1999). Several studies have shown that the minimum and average minimum use methods underestimate outdoor use in warmer and more arid climates in cities such as San Diego, CA, Scottsdale, AZ, Phoenix, AZ, Tempe, AZ and Las Virgenes, CA (DeOreo et al., 2011; Gleick et al., 2003; Mayer and DeOreo, 1999). Thus, the advancement of these types of methods needs to be designed with specific consideration of climate zones. Data loggers installed on household water meters provide records used in flow trace analysis in studies at the household level, allowing more accurate estimates of indoor and outdoor use (DeOreo et al., 2011; Mayer and DeOreo, 1999). This approach is limited by the duration of the logging period as annual and outdoor consumption totals are difficult to estimate for data collected over small logging periods. However, logged water use data is often combined with billing records to obtain more accurate total and residential outdoor use estimates (Mayer and DeOreo, 1999).

More recent approaches involve the use of remote-sensing vegetation indices to estimate urban irrigation which is a significant part of the outdoor water budget in many semi-arid cities. The normalized difference vegetation index (NDVI) is a measure of the photosynthesis activity of plants and has been shown to be strongly related to evapotranspiration (Keith, Walker, & Paul, 2002; Li, Lu, Yang, & Cheng, 2012; Szilagyi, 2002). Results from Keith et al. (2002) demonstrate the relationship between maintained high NDVI values and increased water use during moderate and severe drought conditions in domestic and agricultural water use categories. In addition, Szilagyi, Rundquist, Gosselin, & Parlange (1998) found strong correlation between monthly mean NDVI and one month-lagged evaporation in a natural prairie water-limited environment (study area consisted of a natural mixed-grass species). Szilagyi (2002) confirmed the existence of a strong correlation between monthly NDVI and areal evapotranspiration in a prairie domain with areal evapotranspiration being lagged by one month. Kondoh and Higuchi (2001) also found a strong relationship between NDVI and daily evapotranspiration rate during the growing season in a grassland area. Finally, Johnson and Belitz (2012) estimated urban irrigation rate from the relationship between evapotranspiration and NDVI surplus calculated as the difference between irrigated landscaping NDVI and non-irrigated landscaping NDVI values. They also found a strong exponential relationship between water delivery and NDVI surplus ($R^2 = 0.94$) over a 2-year period (Johnson & Belitz, 2012). NDVI can also be used to estimate vegetated