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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 surfaces at the parcel level from an integrated remote-sensing and GIS method utilized to model residential landscape water needs (Xie, 2009).

The primary goal of the current study is to quantify outdoor and irrigation water use using several previously-published methods and to investigate the relationship between residential water use and urban vegetation greenness surplus across a semi-arid and highly developed urban metropolis. Our work is one of the first to quantify outdoor and landscaping irrigation use during drought periods with voluntary and mandatory utility restrictions on outdoor watering. We compare two methods from the Pacific Institute (Gleick et al., 2003) that quantify outdoor use using LADWP water billing data and also utilize a remote-sensing approach inspired from Johnson and Belitz (2012) that provides landscaping irrigation estimates. We developed the remote-sensing model based on NDVI, land use and land cover products. The developed model is then used to compare the efficacy of two outdoor watering restrictions periods implemented during 2007–2010 on landscaping irrigation application. Ultimately, the developed model could be used by regional utilities as a predictive tool for landscaping irrigation budgets and to help target conservation efforts across the city.

2. Study area and conservation efforts

The city of Los Angeles has a population of approximately 3.8 million (U.S. Census Bureau, 2010) and an areal extent of around 1300 km^2. The city contains 114 neighborhoods with distinct demographic and socioeconomic characteristics (Los Angeles Times, 2010). The twelve selected neighborhoods are generally representative of the city's characteristics and were selected based on population, median household income, average household size, education level and microclimate criteria (Table 1). In response to the drought conditions, voluntary water restrictions were first implemented in June 2007 (through fiscal year (FY) 2008) to ask the customers to voluntarily reduce their water use by 10% (through rebates for water-saving devices, fixing leaks or taking shorter showers) (LADWP, 2007). In August 2008, mandatory water restrictions were enacted to prohibit waste practices (e.g. no irrigation during rain, fixing leaks) no irrigation between 9 am and 4 pm, and limiting landscape watering time up to 15 min per cycle (up to two cycles per water day) when using sprinklers or similar non-conserving techniques (spray head, bubblers, standard rotors). In June 2009, mandatory water conservation requirements were increased with more stringent water restrictions including a two-day landscaping irrigation per week limit, increased restrictions on the time and frequency of landscaping irrigation for the use of sprinklers (spray head, bubblers, standard rotors and rotary heads) and additional prohibited water-waste usage such as car washing. Price conservation measures were also enacted in June 2009 throughout FY2010 corresponding to a reduction in Tier 1 water allocation by 15% and an increase in Tier 2 rates in order to trigger higher reductions.

3. Data

3.1. Water consumption data

Monthly single-family residential (SFR) water billing and lot size data was provided by LADWP from January 1, 2000 to December 31, 2010. The initial database contained around 480 000 individual residential customers identified by census tract numbers. Less than 1% of the records (500–600 single-family customers) did not match the U.S. Postal Service ZIP code database and were removed. The LADWP reading period is bi-monthly (every 60 days) and the utilities pro-rated the data to calculate monthly water consumption. The 2000–2010 data includes the following restriction periods: 1) voluntary water conservation implemented throughout fiscal year (FY) 2008; 2) additional mandatory water waste provisions implemented in August 2008 to limit irrigation time (a fiscal year is defined as the period from July 1st of the preceding year to June 30th of the current year); and 3) increased mandatory two-day per week outdoor watering restrictions and water rates increase (increase in Tier 2 rate coupled with a 15% decrease in Tier 1 water allotment) implemented in June 2009 for FY2010 (LADWP, 2010).

The current LADWP service area includes customers residing in the city of Los Angeles and on the edge of the city boundary. However, only the census tracts contained within the city boundary were analyzed and the LADWP customer data was matched with the census residential population data in the city of Los Angeles. The final set of monthly individual customer records was aggregated to the census tract level to protect customer privacy. The aggregated list includes 855 census tracts with monthly water data for a ten-year period (from FY2001 to FY2010). The average customer lot size was calculated for each census tract. Monthly water consumption data was normalized per the number of SFR accounts or SFR customers and per average lot size area including built and vegetated areas (as it was not possible to differentiate these data from LADWP records). The GIS census tract boundary layer comes from the 2000 US Census Bureau.

3.2. Land cover data

Irrigated, non-irrigated and impervious areas across the city were selected using a land cover database derived from high resolution satellite imagery (McPherson, Simpson, Xiao, & Wu, 2011). The database was created using Quickbird imagery and aerial photography from 2002 to 2005 at high spatial resolution (<2 m pixel resolution) and identifies four primary land cover types: tree (tree and shrub), grass (green grass and ground cover), dry grass/bare soil (dry grass and bare soil), and impervious surface (includes pervious pavement) (McPherson et al., 2011). Eight golf courses and irrigated urban parks were delineated to represent irrigated areas in the city. Non-irrigated surfaces were identified in the Northern part of the city using the dry grass land cover areas and the non-irrigated fields next to airports. Impervious areas were selected in the downtown neighborhood and at airports runways. We assumed that land cover was generally static over the 10-year study period (from FY2001 to FY2010) for the delineated endmembers in the city.

3.3. Land use data

Land use data was acquired using the NOAA C-CAP 2006 (30 m) classification database. We selected the pixels in the low density development category within each census tract boundary as it primarily includes single-family residential areas. The land cover was assumed to remain static over the 10-year study period. Between 2001 and 2006, developed area in the city increased by 0.18% and impervious surface area increased by 0.41%, (NCLD, 2001, 2006; NOAA C-CAP, 2001, 2006), therefore we assumed that land use was generally static for the study period.

3.4. Vegetation indices

Urban vegetation greenness was estimated using the NASA Landsat Thematic Mapper 5 (Landsat TM 5) satellite that provides remote-sensing products at 30-m resolution every 16 days. This higher resolution data compared to NASA's Terra moderate resolution imaging spectroradiometer (MODIS) 250-m product is more appropriate to extract and map vegetation characteristics in the delineated land cover areas and census tracts. We used spectral

Table 1
Twelve focus neighborhoods and key characteristics from the U.S. Census (2000 or 2010).

Neighborhood	Zip code	Population 2010 (in thousands)	Average household size 2010	Number of people with a high school degree or less 2000 (in thousands)	Temperature zone (LADWP)	Median household income in 1999-dollars (in thousands) (1999)	10-fiscal year average annual single-family water use (m^3/SFR cust./year)
Florence (FL)	90003	66.3	4.2	17.8	Medium	29.5	385
Koreatown (KR)	90005	37.7	2.5	43.9	Medium	30.6	514
Leimert Park (LM.P)	90008	32.3	2.3	3.1	Medium	45.9	352
Mid-Wilshire (MD.W)	90019	64.5	2.7	8.5	Medium	58.5	461
Downtown (DW)	90021	4.0	1.6	13.5	Medium	15.0	369
Silver Lake (SL.L)	90039	28.5	2.5	8.9	Medium	54.3	359
Playa Vista (PL.V)	90045	39.5	2.4	0.8	Low	68.6	342
Pacific Palisades (PC.P)	90272	23.0	2.5	1.5	Low	168.0	827
Venice (VN)	90291	28.3	1.95	7.2	Low	67.7	307
Pacoima (PC)	91331	103.7	4.6	31.7	High	49.1	572
Reseda (RS)	91335	74.4	3.2	21.1	High	54.8	515
Sherman Oaks (SH.O)	91423	31.0	2.1	10.8	Medium	69.7	700
North Hollywood (NR.H)	91601	37.2	2.3	27.6	Medium	42.8	506

band 3 (wavelength is from 0.626 μm to 0.693 μm, red band) and band 4 (wavelength is from 0.776 μm to 0.904 μm, near-infrared band) to calculate NDVI (Rouse, 1974). Landsat images were downloaded over the study period using a cloud cover threshold below 10%, resulting in 111 images for the study period.

4. Methods

A ten-year period – from FY2001 to FY2010 – was used to estimate outdoor water consumption based on the minimum use month, average minimum use month and remote-sensing approaches.

4.1. Descriptive analysis

A descriptive analysis was undertaken for twelve representative neighborhoods using monthly time-series plots for the study period using single-family customer water consumption and NDVI data. The twelve selected neighborhoods are generally representative of the city's characteristics and were selected based on population, density, ethnicity, median household income, average household size, housing tenure, education level, immigration status and microclimate criteria. Census tracts within each neighborhood boundary were identified and median single-family water use and average NDVI were estimated for each tract. Trend analysis in monthly single-family water consumption and NDVI were conducted using a Seasonal Mann–Kendall trend test. Linear trends were estimated using the Sen's slope or Seasonal Kendall slope estimator. The Seasonal Mann–Kendall test accounts for seasonality: the test is derived for each monthly "season" (Hirsch, Slack, & Smith, 1982). The resulting slope is the median of all slopes computed from each pair of observations (Helsel & Hirsch, 2002).

4.2. Outdoor use: Minimum use month and average minimum use month models

Two existing methods described by the Pacific Institute (Gleick et al., 2003) use monthly water-billing data to estimate residential outdoor use as the residual of monthly total water use minus indoor use per single-family customer. The underlying assumptions of the two methods are that indoor use is consistent throughout the year and that the minimum use month is the best estimate of indoor water use.

Minimum use month: A monthly minimum water use is identified for each fiscal year and for each tract and is assumed to represent monthly indoor use.

Average minimum use: The average of the three lowest monthly water use records is calculated and is assumed to represent monthly indoor use.

The monthly outdoor use values were obtained from the minimum and average use methods for each fiscal year and for each tract from the initial set of 855 tracts. Finally, the ratio of outdoor use to total single-family water use was calculated.

4.3. Landscaping irrigation estimates: Remote sensing model

Our approach is based on Johnson and Belitz (2012) that was utilized to estimate the rate of urban irrigation in residential neighborhoods in the San Fernando Valley in Southern California using Landsat NDVI products and water delivery records as input. We build upon this approach to estimate landscaping irrigation patterns over 10 years at the census tract scale across Los Angeles and include differing climate conditions, including "dry" and "wet" years relative to the 30-year average precipitation in Los Angeles. We analyze the impact of the restrictions periods (voluntary and mandatory) on landscaping irrigation. We also account for individual tract-specific effects. We first describe the NDVI surplus calculations at the census tract level and then apply the model to estimate the amount of landscaping irrigation per census tract.

4.3.1. Calculation of NDVI values

To calculate NDVI values by pixel within the city from the Landsat images, the raw digital numbers (DNs) values for bands 3 and 4 were processed using the Landsat ecosystem disturbance adaptive processing system (LEDAPS) developed by Masek et al. (2006). The LEDAPS provides processed Landsat data including atmospherically-corrected surface reflectances for bands 3 and 4. The LEDAPS software was originally developed by Vermote et al. (1997) for the Terra MODIS platform using the atmospheric correction 6S radiative transfer model. Atmospheric correction minimizes the impacts of scattering and absorption by atmospheric gas and particles on measured reflectance. The NDVI values range from −1 to 1, with values close to 1 for healthy plants and around 0 for impervious, non-vegetation surfaces. The NDVI pixel values were averaged spatially in single-family areas for each census tract and for the delineated irrigated, non-irrigated and impervious surfaces.

4.3.2. Calculation of NDVI surplus

Each pixel in a Landsat image may be modeled as a linear mixture of image endmembers (Adams et al., 1995). Each image endmember is composed of a "pure" land cover type that participates in the mixed pixels in the image. Johnson and Belitz (2012) selected two endmembers to represent single-family residential land-use class targeted in this study: irrigated landscaping and impervious surfaces. In addition, this land use class is not likely to include extensive natural native vegetation that has high NDVI values and no landscaping irrigation. Previous studies have shown that Los Angeles urban vegetation, as in many semi-arid cities, is more likely to be non-native and well-watered (Bijoor, McCarthy, Zhang, & Pataki, 2012). In Los Angeles, 12% of urban land cover area is estimated to be irrigated grass and 21% is estimated to be tree canopy cover; the remaining percentage represents mostly impervious and dry grass/bare soil areas (McPherson et al., 2011).

To compute the amount of irrigation, three endmembers are needed that each represents one land cover type: irrigated landscaping, non-irrigated landscaping and impervious areas (Johnson & Belitz, 2012). The endmembers were delineated using a high resolution land cover database developed by McPherson et al. (2011) that classifies land cover types as tree, grass (green grass), dry grass/bare soil and impervious surfaces. Google Earth imagery was an additional resource used to visually check the endmembers. The irrigated landscaping endmember includes eight golf courses and irrigated urban parks identified in the tree/grass land cover type and visually checked on Google Earth. For the non-irrigated endmembers, dry grass surfaces were delineated in the Northern part of the city and in non-irrigated fields next to the Los Angeles international airport. Impervious surfaces were delineated in the Downtown area and using the Los Angeles international airport runways to constitute the impervious endmember. These endmembers were kept the same for all images and are assumed to remain invariant over time. The 30-m NDVI pixel centroids were extracted within each endmember boundary. The resulting NDVI values were averaged for each endmember land cover type (irrigated landscaping, non-irrigated and impervious) and for each Landsat image.

To compute the NDVI values in the targeted single-family land use areas within each census tract, we utilized the NOAA C-CAP 30-m land cover database. The single-family land-use pixels classified in the low intensity development category were selected in each census tract. The 30-m NDVI pixel centroids were extracted from the single-family areas in each census tract and each Landsat image. The resulting NDVI values were spatially averaged for each census tract. Similar to Johnson and Belitz (2012), NDVI in single-family areas is represented as a two-endmember model (Eq. (1)):

$$\mathrm{NDVI}_{\mathrm{tract}}(t) = F_{\mathrm{irr,tract}}(t) \times \mathrm{NDVI}_{\mathrm{irr}}(t) + (1 - F_{\mathrm{irr,tract}}(t)) \times \mathrm{NDVI}_{\mathrm{imp}}(t) \quad (1)$$

where $\mathrm{NDVI}_{\mathrm{tract}}(t)$ is the average NDVI value for single-family areas within each tract and each Landsat image, $F_{\mathrm{irr,tract}}(t)$ is the portion or "fraction of irrigated landscaping" in each single-family tract area and for each image, $\mathrm{NDVI}_{\mathrm{irr}}(t)$ is the irrigated landscaping endmember and $\mathrm{NDVI}_{\mathrm{imp}}(t)$ is the impervious endmember. $F_{\mathrm{irr,tract}}(t)$ is computed from Eq. (1) in single-family areas within each tract and for each image using the averaged NDVI values per endmember and tract.

The NDVI values from irrigated landscaping areas are expected to remain constant over time as they are maintained by residential irrigation. The NDVI values from non-irrigated landscaping areas follow precipitation patterns. The difference in NDVI between the two endmembers called "NDVI surplus" is related to the amount of irrigation and defined as (Johnson & Belitz, 2012) (Eq. (2)):

$$\mathrm{NDVIsurplus}(t) = \mathrm{NDVI}_{\mathrm{irr}}(t) - \mathrm{NDVI}_{\mathrm{nonirr}}(t) \quad (2)$$

where $\mathrm{NDVIsurplus}(t)$ is the NDVI surplus between the irrigated landscaping endmember and the non-irrigated landscaping endmember for each Landsat image.

The last step involves multiplying the NDVI surplus by $F_{\mathrm{irr,tract}}$ representing the portion of irrigated landscaping in single-family areas within each tract and for each image (Eq. (3)):

$$\mathrm{NDVIsurplus}_{\mathrm{tract}}(t) = \mathrm{NDVIsurplus}(t) \times F_{\mathrm{irr,tract}}(t) \quad (3)$$

where $\mathrm{NDVIsurplus}_{\mathrm{tract}}$ is the NDVI surplus calculated in single-family areas for each census tract and each image. A total of 220 Landsat images were possible over the 10 years of the study period. We utilized a final 111 images after quality controlling for cloud cover. The 111 images were then interpolated to monthly values using a piecewise cubic Hermite algorithm. This variable is then used as an input in the relationship with monthly single-family water use normalized per customer and lot size.

4.3.3. *Development of the relationship between NDVI surplus and single-family water use*

A non-linear mixed effects exponential model was developed to predict the relationship between NDVI surplus in single-family areas and single-family water use (in mm/SFR customer/month) at the census tract level. This method is based on the approach developed by Johnson and Belitz (2012) that includes these two variables. The current study aims to apply the previously-developed model to a larger study domain using the key variables first selected by Johnson and Belitz (2012). Other socio-economic variables influence residential water use and outdoor use. Therefore, we further analyzed the relationship between NDVI surplus and other socio-economic variables (income, ethnicity, household size, household type, housing tenure). The socio-economic variables were collected using the 5-year American community survey at the census tract level (2005–2009).

Single-family water use was lagged by one month as a one-month lag was observed between NDVI and water inputs (Szilagyi et al., 1998). The final model equation is (Eq. (3)):

$$\begin{aligned}\mathrm{SFRwateruse}_{\mathrm{tract}}(t-1) = b_{\mathrm{tract}} \times \exp(&k_{\mathrm{tract}} \times \mathrm{NDVIsurplus}_{\mathrm{tract}}(t) \\ &+ m \times \mathrm{restriction} \times \mathrm{NDVIsurplus}_{\mathrm{tract}}(t))\end{aligned} \quad (4)$$

where $\mathrm{SFRwateruse}_{\mathrm{tract}}(t-1)$ is monthly single-family water use in mm/household/month lagged by one month, b_{tract} is the constant tract-specific intercept, $\mathrm{NDVIsurplus}_{\mathrm{tract}}$ is monthly NDVI $\mathrm{surplus}_{\mathrm{tract}}$ in single-family areas within each tract, "restriction" is a dummy variable interacting with NDVI surplus for the fiscal years FY2008, FY2009 and FY2010 during which residential irrigation restrictions were implemented. The model dummy variable controls for the overall impact of restrictions on residential irrigation.

The non-linear mixed effects model was selected in order to account for omitted variables specific at the census tract level. Possible tract-level specific variables might include socio-demographic or building characteristics (building age for example). Other models were tested (such as simple linear regression) that produced lower R^2 values. A few outlier tracts (17) were identified and were removed to improve the normality of residuals and reduce uncertainty in the model; these tracts had with very low total water consumption (under 20 mm/hsld/month, lower water use than the other tracts for total water consumption) and under 10 customers per tract. The final model was run for 710 tracts across the city at the monthly time scale over a ten year period (FY2001–FY2010). We also controlled for heteroskedasticity and serial correlation of the residuals. The serial correlation issue was solved by de-trending the monthly water use and NDVI data for each tract: the difference term between the monthly mean and the annual mean per tract was computed and subtracted from the monthly values for each tract.

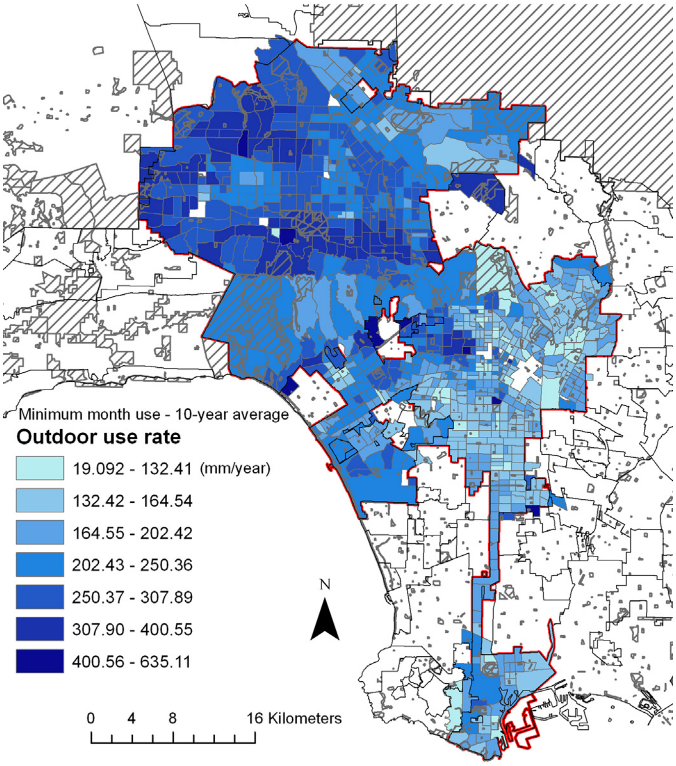

Fig. 1. Average outdoor use rate (in mm/year) over 10 years using the minimum month use method.

The b constant in the exponential model is assumed to represent water used for purposes other than landscaping irrigation, including household indoor use and outdoor usage such as pool and dry-weather runoff (it is the intercept estimated when NDVI surplus is equal to zero). The exponential term contributes to water used for landscaping irrigation in single-family households, which is related to the NDVI surplus variable. This equation form was adjusted from the initial model equation found by Johnson and Belitz (2012). In their study, the water use component excluding landscaping irrigation is a separate constant added to the exponential term. This original model was tested and not selected as it did not represent a good fit over the ten year study period.

5. Results and discussion

The following section presents results from the minimum use month and average minimum use methods (applied on the total set of 855 tracts) and compares our results with previously-published values (including DeOreo et al., 2011 and Mayer and DeOreo, 1999). It also describes the landscaping irrigation results from the developed remote-sensing model, including water use and NDVI surplus analysis (applied on 710 tracts as explained above in the methods section).

5.1. Outdoor use estimates: Minimum month and average minimum month models

The 10-year average outdoor use rate for the minimum use month model has a mean of 213 mm/year (27.3% of total single-family water use) and ranges from 19 to 635 mm/year (Fig. 1, Table 2). The median value for the minimum month method is equal to 199 mm/year and the standard deviation is equal to 71 mm/year. Higher outdoor use values are located in the Northern part of the city and Coastal tract neighborhoods while lower values are observed for census tracts located in the Downtown area.

The average minimum month model provides similar results: the 10-year average outdoor use rate has a mean of 211 mm/year (27% of total single-family water use) and ranges from 18 to 630 mm/year (Table 2). The median value for the average minimum month method is equal to 196 mm/year and the standard deviation is equal to 70 mm/year. For both methods, high outdoor water use values are positively related with high vegetation indices in the northern arid part of the city and in the coastal tract neighborhoods (correlation (r) between average annual outdoor use and NDVI in single-family areas equal to 0.47 significant at $p < 0.05$). The outdoor use values calculated using the minimum use and average minimum use methods in Los Angeles are similar to California Department of Water Resources (CDWR, 2005) estimates (232 mm/year in 2004) but are generally lower than estimates found in previous studies which range from 384 to 980 mm/year (Table 1). DeOreo et al. (2011)'s outdoor use estimate averages 384 mm/year representing 56.8% of total single-family water use in Los Angeles. LADWP estimates that 54% of total single-family water use is for outdoor purposes, combining data from wastewater flow, minimum month and landscape ET requirements. Previous studies support that these methods likely underestimate actual outdoor use and have relatively high uncertainties (DeOreo et al., 2011; Gleick et al., 2003; Mayer and DeOreo, 1999). This uncertainty primarily comes from the fact that many single-family customers still irrigate during winter months. Johnson and Belitz (2012) calculated that landscaping irrigation accounts for 1/3 of total water delivery during winter months in the San Fernando Valley in Southern California.

5.2. Irrigation use: Remote-sensing NDVI model

5.2.1. Descriptive time-series analysis

Monthly time-series of single-family water use and NDVI were first analyzed to identify trends and correlations in the selected study neighborhoods (Figs. 2 and 4). Single-family water use time-series normalized per household and lot size reveals seasonal variability correlated with the precipitation patterns over the 10 years (correlation r between −0.49 and −0.61 significant at $p < 0.05$). A decrease in single-family water use is observed during the winter months followed by an increase during the summer months (Fig. 2). On average, monthly single-family water use ranges from 54.8 mm/hsld/month to 72.9 mm/hsld/month across the selected neighborhoods over 10 years. After the voluntary conservation period, mandatory water waste provisions and more stringent mandatory water restrictions went into place (in June 2007, August 2008 and June 2009 respectively), single-family water use was observed to decrease (from FY2008 to FY2010). The Seasonal Mann–Kendall trend test performed on monthly single-family water use per neighborhood confirms the presence of a downward and statistically significant trend for all selected neighborhoods for FY2008–FY2010 (significant at $p < 0.05$) with average slope equal to a decrease of 5 mm/year (or 7.5% of average single-family water use) over a year for the selected neighborhoods.

Non-irrigated areas identified in Los Angeles follow seasonal precipitation patterns (Fig. 3). Higher NDVI values are observed in the winter months and lower NDVI values in the summer months. NDVI for non-irrigated endmember ranges from 0.130 to 0.523. NDVI for irrigated landscaping endmember remains relatively stable over 10 years with an average NDVI equal to 0.507. Impervious surfaces have smaller NDVI values that are relatively constant over 10 years. The average NDVI value for the impervious endmember is equal to 0.057.

The NDVI surplus time-series reveals a seasonal pattern over 10 years for single-family land use areas in the selected neighborhoods (Fig. 4). High NDVI surplus values are observed during summer months and lower values during winter months and are correlated

Table 2
Comparison of outdoor use estimates from Los Angeles water billing data with estimates of outdoor use including a CDWR estimate of outdoor use, DeOreo et al. (2011), Mayer and DeOreo (1999) and Grimmond et al. (1996). Outdoor use rate: depth of water applied over entire lot size area (mm/year), except for Mayer and DeOreo (1999) study for which outdoor use estimates are over irrigable area. Outdoor use estimates from billing data are averages over 10 years. Salvador et al. (2011) study provides applied irrigation water use in the Zaragoza region in Spain, which has a semi-arid climate with similar annual average precipitation (average precipitation of 337 mm in Zaragoza compared to 396 mm in Los Angeles).

Method	Outdoor use rate (mm/year)
	Outdoor use estimates from billing data
Minimum use (over entire lot size area)	213 (standard deviation = 69.7)
Average minimum use (over entire lot size area)	211 (standard deviation = 68.9)
	Outdoor use estimates for comparison
CDWR (estimate WY 2004)	232
DeOreo et al. (2011) (Los Angeles, 2005–2008 estimates) (over entire lot size area)	384
Mayer and DeOreo (1999) (San Diego, CA) (over irrigable area)	841
Mayer and DeOreo (1999) (Phoenix, AZ) (over irrigable area)	980
Mayer and DeOreo (1999) (Las Virgenes, CA) (over irrigable area)	914
Salvador et al. (2011) (Spain) (over entire lot size area)	1276–1378
Hunt et al. (2001) (Irvine, CA) (over entire lot size area)	1764
Grimmond et al. (1996) (Los Angeles) (over entire lot size area)	482–500

with seasonal precipitation patterns (correlation r between −0.27 and −0.54 significant at $p < 0.05$). High positive NDVI surplus values indicate that residential vegetation maintained by irrigation is greener than non-irrigated vegetation that follows precipitation pattern. Average monthly NDVI surplus ranges from 0.071 to 0.174 across the selected neighborhoods over 10 years. The Seasonal Mann–Kendall trend test performed on monthly NDVI surplus per neighborhood revealed a statistically significant downward trend over FY2008–FY2010 for the neighborhoods (significant at $p < 0.05$) except for two neighborhoods: Silver Lake (SLL) does not have a statistically significant trend and Playa Vista (PLV) has a positive trend. The average slope across the selected neighborhoods is equal to a decrease of 0.0072 (or 3% of average NDVI surplus) over a year.

5.2.2. Correlation of NDVI surplus with socio-economic variables

We tested the correlation of NDVI surplus with socio-economic variables to better understand which variables are captured by NDVI surplus. Income is correlated with NDVI surplus with a correlation equal to 0.58 ($p < 0.05$), showing that a greener landscape and higher income are related. The percent Hispanic or Latino origin residents per tract is negatively correlated with NDVI surplus ($r = -0.57$, $p < 0.05$). NDVI surplus has a lower correlation with average household size ($r = 0.35$, $p < 0.05$). This lower correlation may be due to the fact that households with a greener landscape and higher irrigation volume have a larger proportion of total water use being for irrigation compared to water used for indoor purposes. Household composition exhibits a lower correlation with NDVI surplus: the percent of households with one or

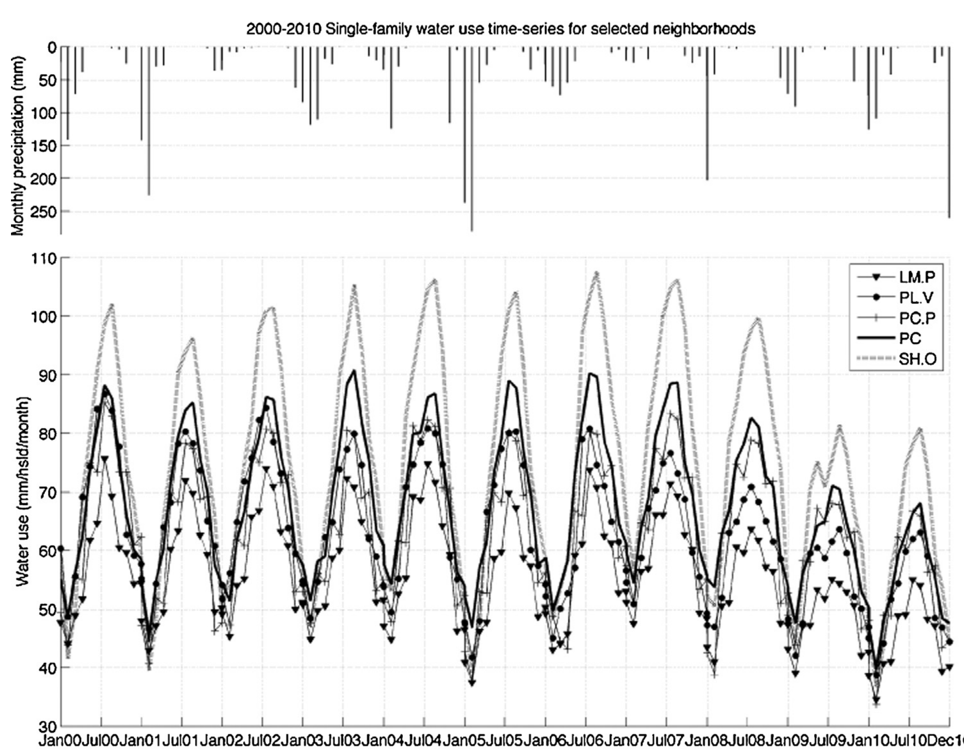

Fig. 2. Time-series plot of median single-family water use in mm per single-family customer per month over FY2001–FY2010 for the selected neighborhoods with precipitation (mm) on the inverse bar plot.

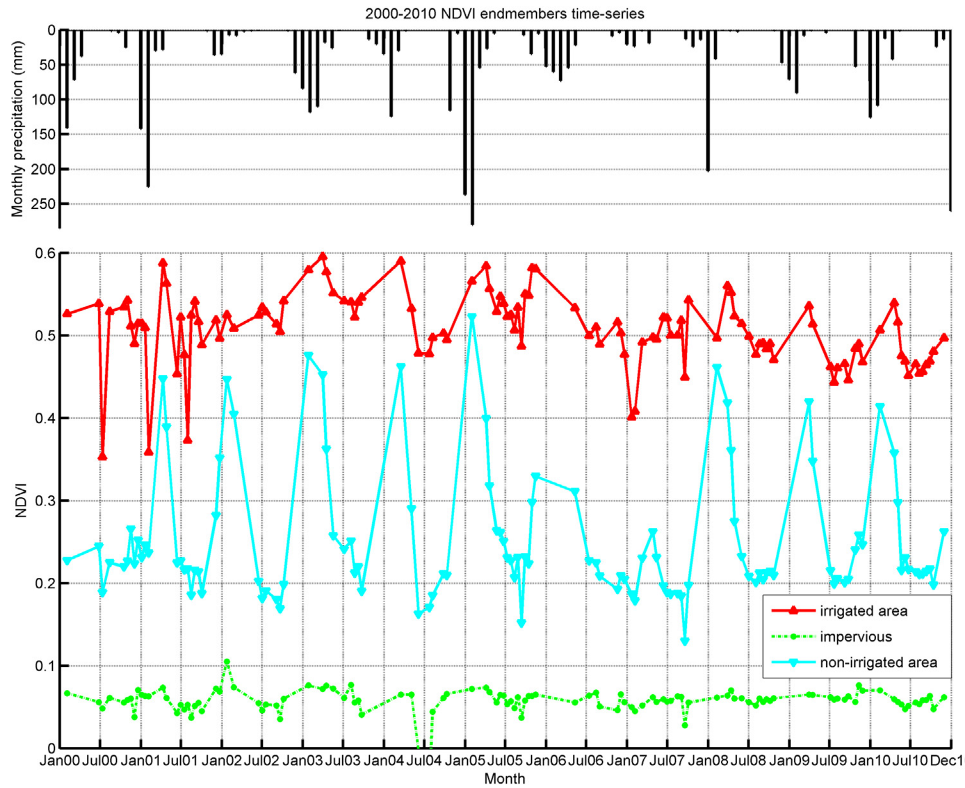

Fig. 3. NDVI time-series for the three endmembers: irrigated landscaping, impervious and non-irrigated landscaping areas from 2000 to 2010 with precipitation (mm) on the inverse bar plot (precipitation data is from the Downtown LA station).

more people under 18 years and NDVI surplus have a correlation of −0.32 ($p < 0.05$). The percent of households with one or more people over 60 years and NDVI surplus have a correlation equal to 0.30 ($p < 0.05$). The percent of owner-occupied housing units is also correlated with NDVI surplus (correlation $r = 0.48$, $p < 0.05$). Therefore, the NDVI surplus value captures income and ethnicity effects that also impact residential water use. It also captures variations in weather conditions as it is built on the difference in NDVI between irrigated and non-irrigated areas over time.

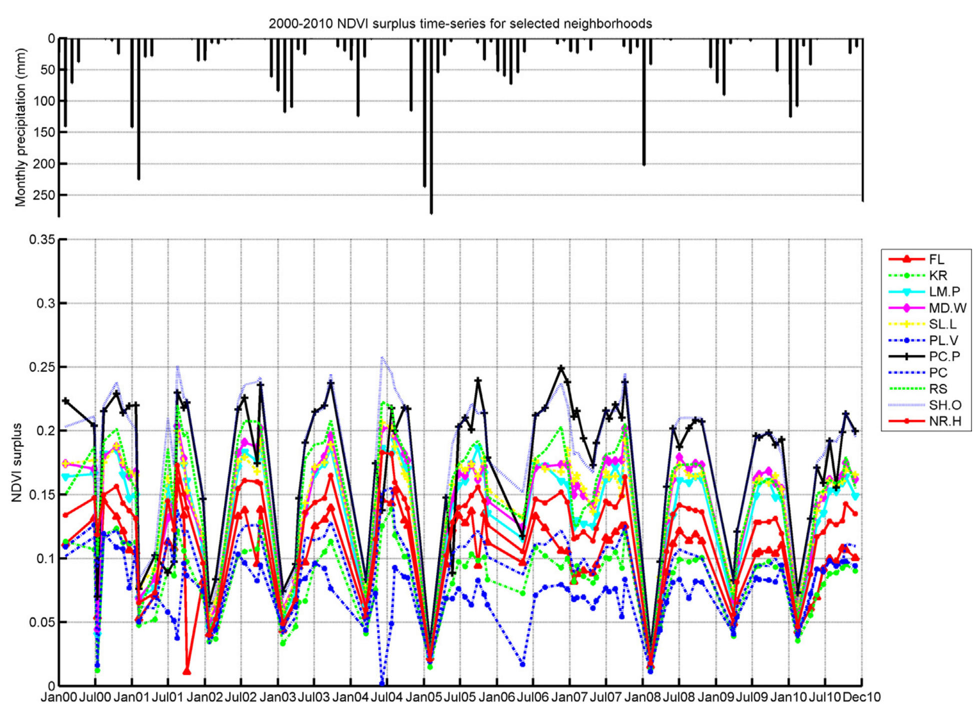

Fig. 4. Time-series plot of average NDVI surplus for the selected neighborhoods from 2000 to 2010 with precipitation (mm) on the inverse bar plot.

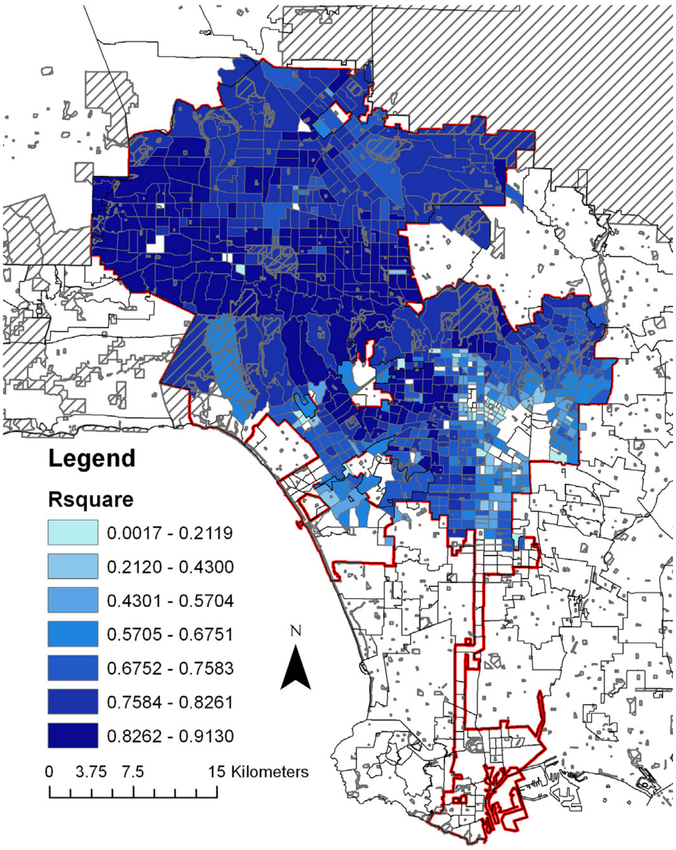

Fig. 5. R^2 results from single-family water vs. NDVI surplus exponential regression at the Census tract level.

5.2.3. NDVI surplus vs single-family water use

The non-linear exponential model was first applied to each individual tract in the city over the 10 year period to assess the distribution of the b and k coefficients in Eq. (4). The b coefficient (intercept) follows two distinct distributions: the first normal distribution has a mean of 26.5 mm/hsld/month with standard deviation equal to 6.41 mm/hsld/month and includes 61% of the tracts. For the second group, 39% of the tracts also follow a normal distribution with a mean equal to 41.3 mm/hsld/month and standard deviation equal 15.38 mm/hsld/month. Two non-linear mixed effects models were implemented to reflect these two different coefficient distributions. The final equations for the two models are:

$$\mathrm{SFRwateruse}_{\mathrm{tract}}(t-1) = 25.9 \times \exp(6 \times \mathrm{NDVIsurplus}_{\mathrm{tract}}(t) + 0.050 \times \mathrm{restriction} \times \mathrm{NDVIsurplus}_{\mathrm{tract}}(t)) \quad (5)$$

$$\mathrm{SFRwateruse}_{\mathrm{tract}}(t-1) = 39.1 \times \exp(5.1 \times \mathrm{NDVIsurplus}_{\mathrm{tract}}(t) - 0.110 \times \mathrm{restriction} \times \mathrm{NDVIsurplus}_{\mathrm{tract}}(t)) \quad (6)$$

The mean value for the b intercept is 25.9 mm/hsld/month (with a standard deviation equal to 4.2 mm/hsld/month) for the first group (61% of the tracts) (Eq. (5)) and 39.1 mm/hsld/month (with a standard deviation equal to 16 mm/hsld/month) for the second group (39% of the tracts) (Eq. (6)). The value for the mean k coefficient is 6 with a standard deviation of 1.4 for the first group and mean of 5.1 with a standard deviation of 2.4 for the second group. All the estimated coefficients are statistically significant at $p < 0.05$ (Table 3). Note that the estimated coefficient for the interaction variable with NDVI surplus is positive for the first group and negative for the second group, indicating that the 3-year watering restrictions may have different impacts on the tracts. However, this

Table 3
Summary of the remote-sensing model coefficients.

Non-linear mixed effects model	Eq. (5)	Eq. (6)
Mean intercept b (mm/hsld/month)	25.9[a]	39.1[a]
Mean coefficient k (mm/hsld/month)	6[a]	5.1[a]
Interaction variable (NDVI surplus and restrictions)	0.05[a]	−0.11[a]
N (tracts)	433	277
Overall R^2	0.721	

[a] Denotes significance at $p < 0.05$.

does not reflect the response at the individual tract level. Results from both equations (Eqs. (5) and (6)) are highlighted (Figs. 5 and 6) to analyze the overall performance of the model and landscaping irrigation estimates across the city.

5.2.4. Performance of the NDVI model

The R^2 value indicating the performance of the model was calculated for each tract to compare the actual and simulated water use values (Fig. 5). The mean R^2 value is equal to 0.721 and ranges from 0.0017 to 0.913 with a standard deviation equal to 0.169 (Fig. 5). Higher values are observed in the northern arid part of the city as well as in tracts surrounding the Santa Monica Mountains and Griffith Park area (Fig. 5). The correlation between the R^2 values and household income is equal to 0.43 (significant at $p < 0.05$), showing a moderate correlation between model R^2 and income patterns. The model R^2 appears to coincide with vegetation greenness patterns: the correlation between R^2 values and average annual NDVI in single-family areas for each tract is equal to 0.58 and significant at $p < 0.05$. Hence, the NDVI model performs better in greener landscape areas.

According to the derived model, single-family water use can be divided into two terms: a constant value b (intercept) and the exponential term related to NDVIsurplus, which represents landscaping irrigation. Hence, the b intercept is the volume of water used for purposes other than landscaping irrigation and we assume that it

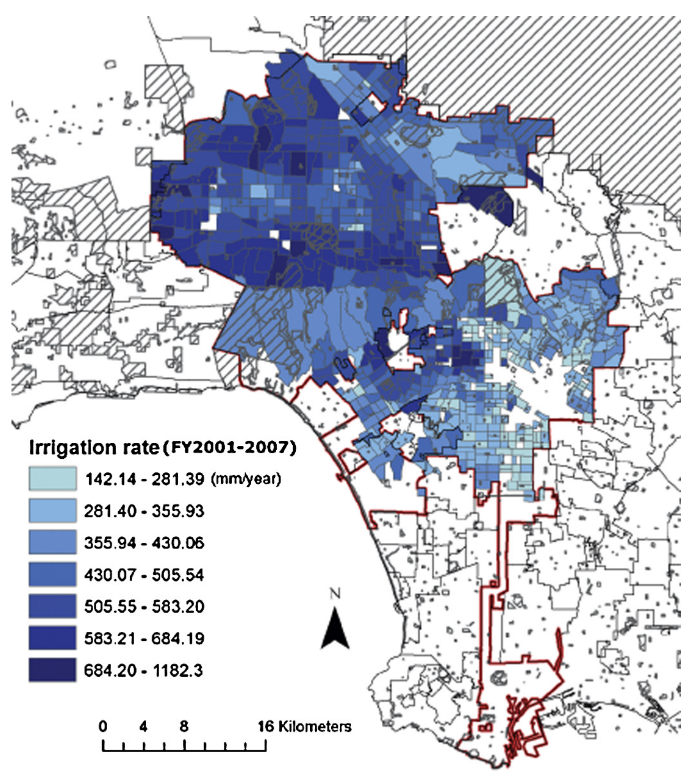

Fig. 6. Average landscaping irrigation rate (in mm/year) for the FY2001–FY2007 period from single-family customers at the Census tract level.

Table 4
Comparison of landscaping irrigation rate (in mm/year) from NDVI model with other irrigation rate and evapotranspiration (ET) estimates including Moering (2011), Johnson and Belitz (2012), Mayer and DeOreo (1999). Net ET requirement estimates for Mayer and DeOreo (1999) study are for turf grass areas. Moering (2011)'s ET estimate is for irrigated park in Los Angeles. Vahmani and Hogue (2013) ET estimate is simulated grass ET. Irrigation estimates from NDVI model are averages over the given period assuming volume of water used for other purposes than irrigation is kept constant. Salvador et al. (2011) study provides irrigation requirements in the Zaragoza region in Spain, which has a semi-arid climate with similar annual average precipitation (average precipitation of 337 mm in Zaragoza compared to 396 mm in Los Angeles). Note: For 57 tracts, the model produced negative values for FY2010 due to low R^2 values (below 0.4) relative to all the other tracts; these values were not accounted for in Table 2.

Method	Irrigation rate (mm/year)
Remote-sensing model	*Irrigation estimates from NDVI model (actual or expected)*
FY2001–FY2007	439 (standard deviation = 132)
FY2008–FY2009 (voluntary conservation and mandatory water waste provisions)	412 (6% decrease) (standard deviation = 140)
FY2010 (mandatory restrictions + pricing measure)	285 (35% decrease) (standard deviation = 98)
	Irrigation estimates for comparison
Moering (2011)	1200
Johnson and Belitz (2012) (1997 estimates)	114–541
Salvador et al. (2011) (Spain)	502–599
Vahmani and Hogue (2013)	759
Mayer and DeOreo (1999) (San Diego, CA)	1118
Mayer and DeOreo (1999) (Phoenix, AZ)	1864
Mayer and DeOreo (1999) (Las Virgenes, CA)	1222

remains constant for the study period. This assumption was also used by Johnson and Belitz (2012) to compute the average amount of water used for purposes other than irrigation in the San Fernando Valley over three years. Previous studies assumed constant indoor use (Mayer and DeOreo, 1999; Endter-Wada et al., 2008; Syme et al., 2004). Mayer and DeOreo (1999) calculated indoor use in two different periods in different cities and showed no significant difference in indoor use. They assumed in their outdoor use analysis that indoor use remained constant throughout the year. We also compared our indoor use estimates with those found in previous studies.

The *b* value was multiplied by the average lot size per tract to obtain the volume of water for household indoor uses and other consumption not related to the landscape and to compare with other previously-found values. The mean *b* value is equal to 667 L/hsld/day, which matches relatively well (583 L/hsld/day) with the volume of water used for purposes other than irrigation in Johnson and Belitz (2012). To some extent we can also compare this value to indoor use values found by Mayer and DeOreo (1999) and DeOreo et al. (2011). The resulting value of 667 L/hsld/day is comparable with indoor use of 589 L/hsld/day found in San Diego, CA and 771 L/hsld/day in Las Virgenes, CA (Mayer and DeOreo, 1999). The DeOreo et al. (2011) study showed indoor use for the LADWP area equal to 685 L/hsld/day, which is also relatively close to our estimate.

5.2.5. NDVI model irrigation estimates

Finally, landscaping irrigation is estimated by subtracting the *b* value from total single-family water use for each individual tract. The landscaping irrigation rate was expressed for FY2001–FY2007, and the expected landscaping irrigation was calculated for FY2008–FY2009 (voluntary water conservation and beginning of mandatory water waste provisions) and FY2010 (mandatory two day-per week irrigation restrictions coupled with water rates increase and decrease in water allotment). As mentioned previously, we assumed that water consumption for purposes other than landscaping irrigation remains constant over the study period and that in this case, water reductions would occur primarily in landscaping irrigation. We acknowledge that other variables may influence indoor and outdoor consumption. The current study focused on the impact of restrictions on landscaping irrigation through the NDVI surplus variable and the interaction term in the model (Eq. (4)) to quantify what would be the expected reduction in irrigation due to restrictions only. We then ran predictions to estimate the expected reduction in irrigation in response to restrictions.

For the FY2001–FY2007 period, the average landscaping irrigation estimate of 439 mm/year is well within the range of values published by Johnson and Belitz (2012) (114–541 mm/year) and comparable to irrigation values from Salvador et al. (2011) (Table 4). Our values are slightly lower than evapotranspiration (ET) estimates found in an irrigated park in Los Angeles or for turf grass areas (from 759 mm/year to 1864 mm/year) (Mayer and DeOreo, 1999; Moering, 2011). The difference between our irrigation estimates and values published from these previous studies can be explained by potential difference in the types of urban landscape plants and also by the fact that we used the entire lot size area instead of the vegetated surface area to calculate the volume of irrigation per area. The average expected landscaping irrigation estimates for the two restrictions periods considered are equal to 412 and 285 mm/year, for FY2008–FY2009 and increased mandatory restrictions in FY2010 respectively. This shows a potential large decrease in landscaping irrigation due to increased mandatory restrictions in FY2010 (35% decrease relative to the FY2001–FY2007 period) compared to 7% decrease due to outdoor watering restrictions in FY2008–FY2009, highlighting the effectiveness of mandatory restrictions (including two-day irrigation per week, water rates increase and decrease in water allotment), rather than voluntary conservation and limited water waste provisions in FY2008–FY2009, in reducing landscaping irrigation.

Across the city, landscaping irrigation during FY2001–FY2007 ranges from 142 to 1182 mm/year per tract with an average of 439 mm/year and a standard deviation of 132 mm/year (Fig. 6). Higher landscaping irrigation is located in the Northern and warmer parts of the city and in the tracts bordering the Santa Monica Mountains while lower values are observed in the Downtown area. This pattern is similar to spatial trends in total water use and greenness level. Landscaping irrigation volume is also strongly correlated with income across the city (correlation (r) of 0.71 significant at $p < 0.05$). Landscaping irrigation is negatively correlated with the percent of residents with Hispanic or Latino origin per tract (r of −0.51, $p < 0.05$). This may be due to a different landscape type or different water use habits. We also noticed that income and the percent of residents with Hispanic or Latino origin per tract are related (r of −0.65, $p < 0.05$). Correlation with the average household size is also negative (r of −0.21, $p < 0.05$). However, landscaping irrigation is related to household composition; being correlated to the percent households with one or more people 60 years and over (r of 0.45, $p < 0.05$). Owner-occupied housing units also irrigate more than renter-occupied housing; with correlation between landscaping irrigation and the percent of owner-occupied housing units equal to 0.57 ($p < 0.05$).

Table 5
Summary of irrigation rate estimates by period.

Irrigation rate	FY2001–FY2007 (mm/year)	FY2008–FY2009 (% change from FY2001–FY2007)	FY2010 (% change from FY2001–FY2007)
Average	439	−6%	−35%
Range	142–1182	−74%–+109%	−92%–+38%
Standard deviation	132	11%	10.5%

Table 6
Expected irrigation change during restriction periods by income group. Below 25th quartile includes tracts with a median household income below the 25th quartile of the tract income, medium level included tracts with a median household income between the 25th and 75th quartile, and above 75th quartile includes tracts with a median household income above the 75th quartile.

	FY2008–FY2009 Percent expected change from FY2001–FY2007			FY2010 Percent expected change from FY2001–FY2007		
Income group	Below 25th quartile	Medium level	Above 75th quartile	Below 25th quartile	Medium level	Above 75th quartile
Average expected change in irrigation (%)	−12%	−6%	−4%	−36%	−35%	−35%
Range	−74%–+17%	−41%–+108%	−32%–+14%	−77%–+21%	−92%–+38%	−77%–−21%
Standard deviation	14%	11%	6%	14%	10.5%	6%

During the FY2008–FY2009 restriction period, the expected percent change in irrigation relative to the FY2001–FY2007 period ranged from −74% to +109% with an average of −6% (and standard deviation equal to 11%) (Table 5). During the increased mandatory restrictions period in FY2010, the expected percent change in landscaping irrigation varied from −92% to +38% with an average of 35% decrease relative to the FY2001–FY2007 period (and standard deviation equal to 10.5%) (Table 5). These results indicate a large spatial variation in landscaping irrigation change per tract over the city. Overall, a higher decrease in irrigation is expected during the FY2010 period. A higher decrease in irrigation is observed in the warmer and northern parts of the city and a lower decrease is observed in the denser downtown areas. We hypothesize that the increase in irrigation observed in some tracts for these two water restrictions periods may be due to uncertainties in the model or restrictions not being efficient in these areas.

Further analysis of the change in landscaping irrigation was undertaken by income group at the census tract level. The irrigation results were disaggregated in three income groups: the first group includes the tracts with a median household income below the 25th quartile, the second group includes tracts with a median household income between the 25th quartile and 75th quartile, and the last group includes tracts with a median household income above the 75th quartile. In FY2008–FY2009, the average expected percent change in landscaping irrigation was higher for the lower income group than for the higher income group, from −12% to −4% respectively (Table 5). Voluntary conservation and mandatory waste water provisions were less effective for the higher income group. In FY2010, stringent mandatory restrictions including water rates increase and two-day irrigation per week had the same effect on the three income groups, around 35% expected decrease in landscaping irrigation (Table 5). The combination of pricing and non-pricing measures may induce water conservation for all income groups.

Table 6

6. Conclusion

The current study evaluates outdoor use and landscaping irrigation methods in Los Angeles using water billing data and remote-sensing products. Two methods described by the Pacific Institute in California and a developed remote-sensing NDVI model are applied at the census tract level using aggregated water use data and high-resolution vegetation, land cover and land use products.

The minimum use month and average minimum use methods result in outdoor use estimates that are below outdoor use values found in other studies including the analysis of data logging measurements in California (DeOreo et al., 2011; Mayer and DeOreo, 1999). We note that the two methods underestimate outdoor use due to the existence of landscaping irrigation during the lowest water consumption months in Los Angeles. Landscaping irrigation results from the NDVI model compare reasonably well with irrigation requirement estimates from other studies (Johnson & Belitz, 2012; Salvador et al., 2011). However, when compared with ET estimates from turf grass and irrigated turf grass parks, our model produces lower landscaping irrigation estimates. This is likely due to the fact that residential landscape in Los Angeles is often composed of trees, turf grass and tree-covered turf grass which are likely to produce variable surface evapotranspiration (Pincetl et al., 2012).

Based on the NDVI model, landscaping irrigation use represents, on average, 54% of total single-family water use. This use would decrease by 6% and 35% on average across the city during voluntary and mandatory water waste provisions (FY2008 and FY2009) and increased mandatory (FY2010) restrictions periods, respectively, assuming all water reductions would occur in landscaping irrigation. Model results show large variability in landscaping irrigation estimates (large standard deviation found in our results) across the city: the standard deviation is equal to one-third of the average estimate during FY2001–FY2007 and it remains consistent over the three periods (FY2001–FY2007, FY2008–FY2009, FY2010). This might be explained by differences in climate zones and in the proportion of trees and turf grass cover in residential landscaping between the tracts. In addition, our results show that income is strongly correlated with landscaping irrigation patterns in the city.

The current work is one of the first to show where and how residential outdoor water is used across a large, semi-arid metropolis. Key results include that outdoor use varies significantly across Los Angeles, with larger values in the northern and warmer parts of the city and lower values in the Downtown areas. We also note that stringent mandatory restrictions are more efficient at reducing residential irrigation than the voluntary program.

We advocate that introducing a new threshold in water pricing and/or water allotments specifically targeting customers with higher landscaping irrigation may be effective. In addition, partitioning indoor and outdoor use is important to more accurately assess landscaping irrigation needs for specific vegetated cover and the potential savings (for both money and water) from reducing over-watering. We advocate that the use of dual-metering data can address this need and is critical to further improve landscape water budgets and models. It would require additional expense to implement dual-metering systems across the LADWP service area and further investigations of the costs and benefits are needed.

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