Title
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Journal
Water Resources Management, 30(2)

ISSN
0920-4741

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Publication Date
2016

DOI
10.1007/s11269-015-1157-x

Peer reviewed

Water Resour Manage
DOI 10.1007/s11269-015-1144-2

Measuring Spatio-temporal Trends in Residential Landscape Irrigation Extent and Rate in Los Angeles, California Using SPOT-5 Satellite Imagery

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Received: 8 November 2014 / Accepted: 15 September 2015

Abstract Irrigation is a large component of urban water budgets in semi-arid regions and is critical for the management of landscape vegetation and water resources. This is particularly true for Mediterranean climate cities such as Los Angeles, where water availability is limited during dry summers. These interactions were examined by using 10-m resolution satellite imagery and a database of monthly water use records for all residential water customers in Los Angeles in order to map vegetation greenness, the extent and distribution of irrigated areas, and irrigation rates. A water conservation ratio between rates of irrigation and vegetation water demand was calculated to assess over-irrigation. The analyses were conducted for the water years (WY) 2005–2007, which included wet, average, and dry extremes of annual rainfall. Although outdoor water usage was highest in the dry year, vegetation greenness could not be maintained as well as in wetter years, suggesting that lower greenness was due to water stress. However, annual rainfall from WY 2005 to 2007 did not significantly influence the variability in the magnitude and spatial pattern of irrigation, with mean irrigated rates ranging only from 81 to 86 mm. The water conservation ratio showed that 7 % of the postal carrier routes across the city were over-irrigated in the dry year, but 43 % were over-irrigated in the wet year. This was largely because the climatic demand for water by vegetation decreased in wet years, but irrigation rates changed little from year-to-year. This overwatering can be addressed by water conservation, planning and public education, especially in the current California drought. The approach demonstrated here should be transferable to other cities in semi-arid climates.

Keywords Urban irrigation · NDVI · Single - family residential · Vegetation water demand · Outdoor water use

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Published online: 19 September 2015

1 Introduction

In the southwestern United States, the consequences of climate change include urban heat island effects, severe droughts, and decreasing spring snowpack. As a result, water supplies are shrinking and water shortages will continue (Garfin 2013). At the same time, water demand in urban areas will increase with population growth. Approximately 70 % of urban water use occurs in residential areas (LADWP 2008) and 40–70 % of residential water use is for irrigation and other outdoor purposes (St. Hilaire et al. 2008). Understanding the water needs of urban vegetation and managing water budgets are crucial for water conservation in cities with semi-arid or Mediterranean climates, such as in Southern California, where summer rainfall is limited (Lowry et al. 2011; Sun et al. 2012; Nouri et al. 2013). However, relatively few studies have investigated the impact of urban vegetation on water use budgets in Los Angeles (McCarthy and Pataki 2010; Bijoor et al. 2012).

Spatio-temporal trends in vegetation growth within residential irrigated areas can be detected by remote sensing techniques (Velpuri et al. 2009). The normalized difference vegetation index (NDVI), defined as the difference between reflectance in the near infrared and red bands divided by the sum of these bands, is a spectral index for detecting vegetation greenness. Irrigated areas and irrigation rates have been estimated in urban areas and croplands using remote sensing techniques, including unsupervised classification (Velpuri et al. 2009; Gumma et al. 2011), spectral mixture analysis (Johnson and Belitz 2012; Hof and Wolf 2014), irrigation fraction (Velpuri et al. 2009; Johnson and Belitz 2012), object-oriented segmentation and classification (Hof and Wolf 2014), NDVI thresholding (Stow et al. 2003; Pervez and Brown 2010), and decision tree algorithms (Ozdogan and Gutman 2008).

Few studies have analyzed monthly single - family residential (SFR) water use records at sufficiently fine spatial scales to estimate outdoor water use (OWU) and correlate it with urban irrigated areas detected by satellite imagery (Lowry et al. 2011; Hof and Wolf 2014). For example, Lowry et al. (2011) acquired residential water use data at the county level to validate results from an irrigation demand model that was based on imagery, climate, and geographic information system (GIS) data. Gage and Cooper (2015) analyzed the relationship among SFR OWU, land cover, vertical structure, and socioeconomic and demographic factors at the parcel scale. In this study, monthly water use for residential customers was obtained from the Los Angeles Department of Water and Power (LADWP) at the scale of 9-digit postal delivery areas (ZIP codes). Spatio-temporal patterns of urban irrigation rates and areas are more accurate when using monthly SFR water billing records at this fine scale (Friedman et al. 2013) as compared to more aggregated analyses.

Residential irrigation rates have been quantified using two approaches: (1) estimating OWU from household monthly water bills, or (2) analyzing the water requirements of different vegetation types (Salvador et al. 2011; Nouri et al. 2013). To examine irrigation rates via the latter approach, a common method is to use a vegetation water demand model that applies reference evapotranspiration (ETo), irrigated area, a crop coefficient varying with plant types, the distribution uniformity of irrigation systems, and precipitation (Endter-Wada et al. 2008; Lowry et al. 2011; Sun et al. 2012). Lowry et al. (2011) found that residential irrigation rates using a vegetation water demand model were influenced by the area of irrigation. Similarly, Vuolo et al. (2015) demonstrated a novel approach by using imagery derived from a leaf area index and crop evapotranspiration to calculate crop water requirements and irrigation depths in the agriculture system. Because identifying irrigated areas was one of the main objectives of this study, the vegetation water demand model proposed in Lowry et al. (2011) was selected.

Our objectives were to: (1) map the extent of irrigated area within SFR lands using NDVI thresholding; (2) estimate irrigation rates within SFR lands and their relationship to vegetation greenness; (3) evaluate how SFR irrigation rates were influenced by climate variation (i.e., precipitation); (4) assess vegetation water demand from a landscape irrigation demand model; and (5) examine the magnitude and interannual variability between OWU and vegetation water demand.

New results were reported including: (1) relationships of 10-m resolution satellite imagery to an extensive database of monthly water use records for all residential customers in Los Angeles, and; (2) estimation of SFR irrigation both to quantify water requirements of landscape vegetation, and to calculate a water conservation ratio (ratio of estimated OWU to the vegetation water demand) through WY 2005-2007, including wet, average, and dry extremes of annual rainfall.

2 Materials and Methods

2.1 Study Area

The City of Los Angeles (34°06′36″N, 118°24′40″W) covers 1215 km^2 and is located within the Los Angeles basin in Southern California, U.S.A. (Fig. 1). The city population of 3.8 million ranks second in the U.S. (U.S. Census 2010). The climate is Mediterranean, with most precipitation occurring in winter, an annual precipitation of 375 mm (downtown), and an annual average temperature of 18.2 °C (WRCC 2014). The major types of native vegetation in the city are coastal sage scrub and chaparral, but conifer forests, riparian corridors, and oak woodlands are found at higher elevations (Rundel and Gustafson 2005). Urban vegetation types have changed from native grasslands and woodlands to non-native species and impervious surfaces such as asphalt due to urbanization and human planting activities (Gillespie et al. 2012). Urban vegetation in the City of Los Angeles depends on irrigation and is highly water consumptive, especially during the dry summer season (Clarke et al. 2013).

2.2 Data

SPOT-5 (Satellite Pour l'Observation de la Terre) imagery was used to quantify vegetation greenness and map the extent of irrigation. Its fine resolution, ranging from 5 to 10 m for the panchromatic and multi-spectral bands, can isolate pixels that fell within SFR parcels, which provided a closer correspondence between our vegetation data and the household water billing records. The selection of imagery for this study was based on three criteria: (1) ≤10 % cloud cover, (2) dry season conditions (after February in each year and before the first rainfall of the winter season), and (3) viewing geometry <23° from vertical. Based on linear regressions between estimated OWU and imagery in different seasons, the highest coefficients of determination (R^2) were for dry season NDVI and OWU; therefore, only dry season imagery was used for further analysis.

A parcel-level land use map was acquired from the Southern California Association of Governments (SCAG). Monthly water billing records for SFR customers within the City of Los Angeles were acquired from the LADWP. The water billing data were aggregated into postal carrier route (CR) polygons (21.64, 0.55 and 5.918e-5 km^2 for maximum, mean and minimum areas, respectively) each covering subsections of a neighborhood.

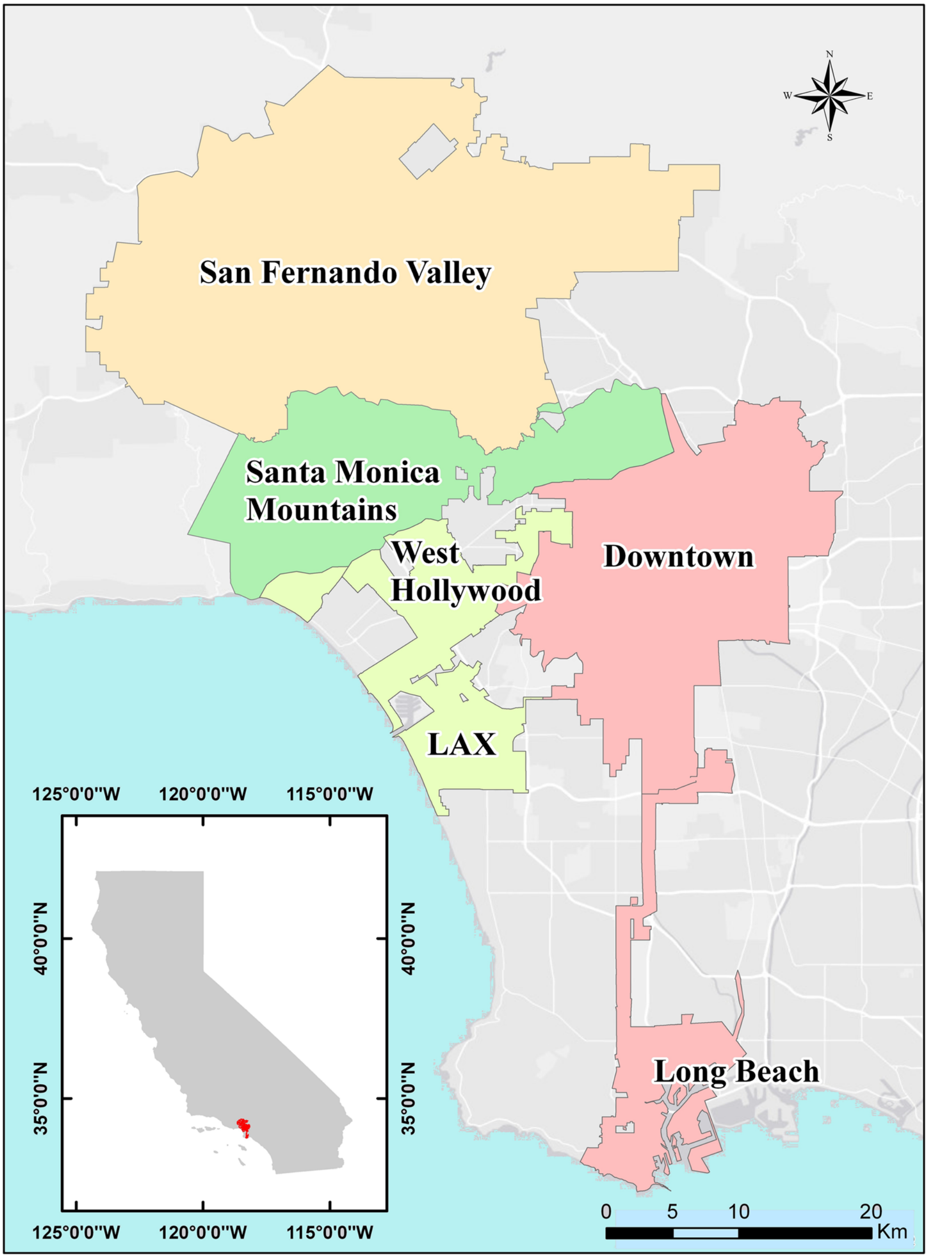

Fig. 1 City of Los Angeles showing the major geographic areas referenced in the text

Monthly precipitation and ETo values were acquired from the National Climate Data Center (NCDC) and California Irrigation Management Information Systems (CIMIS) stations in Glendale, Santa Monica, and Long Beach. The CIMIS ETo data were from reference surfaces, such as well-watered, actively growing short grass that covered most of the soil, and ETo was calculated using a modified Penman–Monteith model (Temesgen et al. 2005).

Precipitation data were acquired from the long-term NCDC stations at Los Angeles International airport, Long Beach, Van Nuys airport, and Downtown Los Angeles.

2.3 Water Use Data Analysis

The 9-digit ZIP code data consist of lists of street addresses from the United States Postal Service rather than the polygonal areas defined in a GIS layer. For this reason, GIS polygons of CR were acquired, the next higher level of spatial aggregation, from Maponics LLC (White River Junction, Vermont, USA) as they provided continuous coverage of polygons for further analysis. In addition, monthly means of the water billing records by CR were calculated from WY 2005 to 2007 to identify the month of the lowest water use in each year, which served as a baseline for indoor water use (IWU).

The IWU was subtracted from the total water use billing records to estimate OWU within SFR areas. Three methods were evaluated from the literature for estimating IWU. First, the lowest monthly water use has been used to represent IWU (Friedman et al. 2013). Second, Johnson and Belitz (2012) found that there was 20 mm (rainfall equivalent) of IWU in SFR areas in the San Fernando Valley, California. Third, DeOreo et al. (2011) collected IWU data from SFR areas in California in 2005 and found a mean daily IWU of 662.5 l per household.

The highest monthly water use occurs during the dry season, which reflects that the bulk of water consumption is OWU. One previous study indicated that most of OWU in urban areas was for irrigation (Friedman et al. 2013). To correlate OWU with satellite imagery, imagery from the month of highest water usage was selected and each of the three different IWU assessments was subtracted from the highest monthly water use. Linear regressions between estimated OWU and imagery-derived mean NDVI values for each CR were performed to select the optimal OWU method for our analyses.

2.4 Image Preprocessing

Atmospheric correction and orthorectification of the images were done in ENVI 5.0 (Exelis LLC, Rochester, NY, U.S.A.) by applying rational polynomial coefficients with a 10-m Digital Elevation Model from the U.S. Geological Survey using nearest neighbor resampling, yielding a spatial accuracy of ±3 to 5 pixels. Nearest neighbor resampling was selected because it did not alter pixel level reflectance values required for NDVI calculations. Geometric correction was conducted by registering the images using a third-order polynomial based on an average of 40 reference ground control points, resulting in mean RMS errors of ±1 pixel.

Dry season images were mosaicked within a given year to quantify the irrigated areas and rates. After mosaicking, the overlapping areas between the image tiles were used to perform a normalization to remove any systematic additive differences in NDVI values between images. Image normalization techniques were based on two approaches: (1) addition or subtraction using the mean NDVI difference in the overlapping region of images and (2) pseudo-invariant feature identification, targeting 10 features distributed between high and low NDVI values within the overlapping region of images. The first approach suggested that the mean NDVI difference values within the overlaid areas differed by only 0.001 to 0.03. On the other hand, the regression analysis showed that NDVI differences within the overlaid areas were not significantly correlated to NDVI values in the reference image ($R^2 = -0.05$ to 0.05; p-value = 0.2 to 0.7). The first approach was selected because it was simple and insensitive to small differences caused by minor geometric offsets within the overlapping regions of images.

2.5 Image Analysis for Irrigated Areas

2.5.1 Simple NDVI Threshold

The mosaicked imagery was masked by a SFR parcel GIS layer to map irrigated areas within SFR sectors. The pixel values within SFR parcels for each CR were extracted. This procedure generated 14 % systematic errors due to boundary effects in the imagery. The number of pixels classified as irrigated was summed, each pixel representing an area of 100 m^2 within each CR.

NDVI thresholding was used to classify the irrigated pixels by testing a series of NDVI values ranging from 0 to 0.7. To retrieve the optimal threshold value with the highest correlation between irrigated pixel areas and estimated OWU, a series of linear regressions between OWU (from billing data after applying each of the three IWU estimation approaches) and the number of pixels exceeding the NDVI threshold in each CR was performed.

There were 2033 CRs that included residential water billing records. For the year 2005, the available number of CR polygons was reduced to 1809 because the imagery available in the SPOT-5 archive did not cover a section of the northwest study area. For all three years, approximately 10 CRs (0.5 % of all CR sectors for the study area) lacked water billing records from LADWP and were excluded from subsequent analyses. The data did not follow a normal distribution; therefore, a logarithmic transformation was applied to estimated OWU and the irrigated pixel areas before regression analyses. After acquiring the optimal NDVI threshold value, maps of irrigated areas were generated at the pixel level.

2.6 Irrigation Rate Estimation and Climate Variable Comparison

To estimate irrigation rates from water billing records, the amount of OWU was normalized by the total area occupied by SFR parcels within each CR. The ETo, irrigation rates, precipitation, and total water supply (sum of precipitation and irrigation rates) were plotted from WY 2005–2007 in order to compare interannual variations. The relationships among vegetation greenness, precipitation, ETo, and irrigation rates were explored with regression models. The precipitation and ETo station data were overlain with the CR map to identify the nearest CR polygon and mapped by CRs regionally.

2.7 Vegetation Water Demand Assessment

To examine differences in irrigation rates among water years, the estimated irrigation was compared to modeled vegetation water demand. Vegetation water demand can be estimated from a model based on climatic and vegetation variables (Endter-Wada et al. 2008; Lowry et al. 2011; Nouri et al. 2013). After reviewing three different approaches from Nouri et al. (2013), we selected the approach of Lowry et al. (2011) as the most appropriate for the scale of our study, recognizing that the importance of irrigation systems and irrigated areas may have slightly underestimated our summer season irrigation requirements.

Lowry et al. (2011) established an equation (Eq. 1) to model the water demand from vegetated landscapes:

$$I_m = ((ET_{om} \cdot PF) - R_m) \cdot (A/DU) \quad (1)$$

Where I_m is total irrigation rate for the month; PF is plant factor; ET_{om} is total reference evapotranspiration for the month; R_m is total precipitation for the month; DU is the distribution uniformity of the irrigation system, and A is the irrigated area.

The ETo and R data were from CIMIS and NCDC, and irrigated areas were extracted as described above. The plant factors from Lowry et al. (2011) of 0.5 for tree or shrub canopies, 0.8 for exposed turf grass, and 0.4 for grass under canopy were applied. DU is a factor for the uniformity of water application. Because irrigation systems usually are non-uniform, the value of DU was 0.75, which assumes that landscape irrigation systems are 75 % efficient in residential areas (Lowry et al. 2011). Using this information, the ratio between OWU and vegetation water demand was calculated to evaluate the degree of over-irrigation in each CR polygon.

3 Results

3.1 SFR Outdoor Water Use Analysis

Residential water billing records revealed seasonal and interannual differences in monthly CR mean total SFR water usage (Fig. 2). The volumes of highest water consumption during the summer months were similar across WY2005-2007, while the volume of lowest consumption (in February) was more variable. The lowest water consumption was in the wet year of 2005 and the highest was in the dry year of 2007.

Three different methods for estimating SFR OWU from total residential water use were examined. After aggregating the data by CR ($N = 2030$), the methods were evaluated with a series of linear regressions between OWU estimated by each method and the amount of

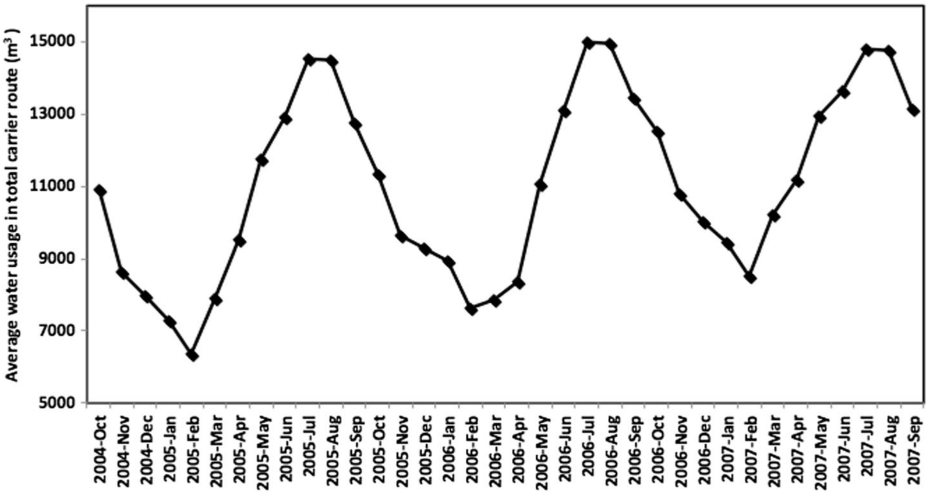

Fig. 2 Monthly CR mean total SFR water usage for water year 2005–2007 ($N = 2033$ carrier routes)

irrigated area estimated by applying a range of NDVI thresholds. Method 1, a minimum-month approach to estimate IWU had the highest correlation coefficient with irrigated areas across all NDVI threshold values. However, it was not selected because the minimum-month approach can overestimate indoor (and thus underestimate outdoor) water consumption (Mini et al. 2014a). This was evident from the pattern of increasing February SFR water use from wet to dry years (Fig. 2). Method 2 had the lowest correlation coefficients and was not used. Method 3 had the second highest correlation coefficients across the lower range of NDVI thresholds where the peak correlations were observed. It used a fixed, per-household estimate of IWU based on household surveys in California in 2005. The correlation coefficients were higher and the curve was more sharply peaked in drier years, whereas correlations were lower in the wet year when vegetation greenness was less dependent on irrigation. Therefore, method 3 produced maps less likely to underestimate the extent of irrigated land across the urban region.

3.2 Irrigated Area Detection

The SFR irrigated area was mapped using the NDVI threshold that produced the highest correlation between estimated OWU and irrigated area in each year of the study. Within a given method of estimating OWU, the peak R^2 and the corresponding NDVI threshold values were relatively similar across the three water years (Table 1). However, the optimal NDVI thresholds for detecting irrigated land were lower for all methods in the dry year of 2007. This suggests that a similar amount of water was used during the dry season in all three years (Fig. 2), but it could only maintain a lower level of vegetation greenness in the dry year of 2007 as compared to the years having average or high rainfall. The most extensive areas of irrigated land were in the San Fernando Valley, the Santa Monica Mountains, Pacific Palisades, and part of East Los Angeles. Conversely, non-irrigated areas were concentrated in downtown and southern Los Angeles.

3.3 Irrigation Rate Estimation

The irrigation rate within SFR land was determined by dividing the estimated OWU by the total irrigated area within each CR. There was high spatial heterogeneity in SFR irrigation rates. Annual rainfall from WY 2005 to 2007 did not significantly influence the variability in the magnitude and spatial pattern of irrigation, resulting in irrigation rates ranging from 81 to 86 mm (Fig. 3a). Consistent with this, similar relationships among years between SFR mean

Table 1 Maximum R^2 and NDVI thresholds for regressions between estimated OWU and irrigated area

Year	Methods	2005	2006	2007
Carrier routes (N)		1801	2030	2030
R^2	1	0.46	0.50	0.48
	2	0.34	0.34	0.39
	3	0.40	0.40	0.40
NDVI threshold value	1	0.29	0.29	0.26
	2	0.29	0.29	0.26
	3	0.25	0.24	0.23

Regression models were statistically significant at p-value < 0.001

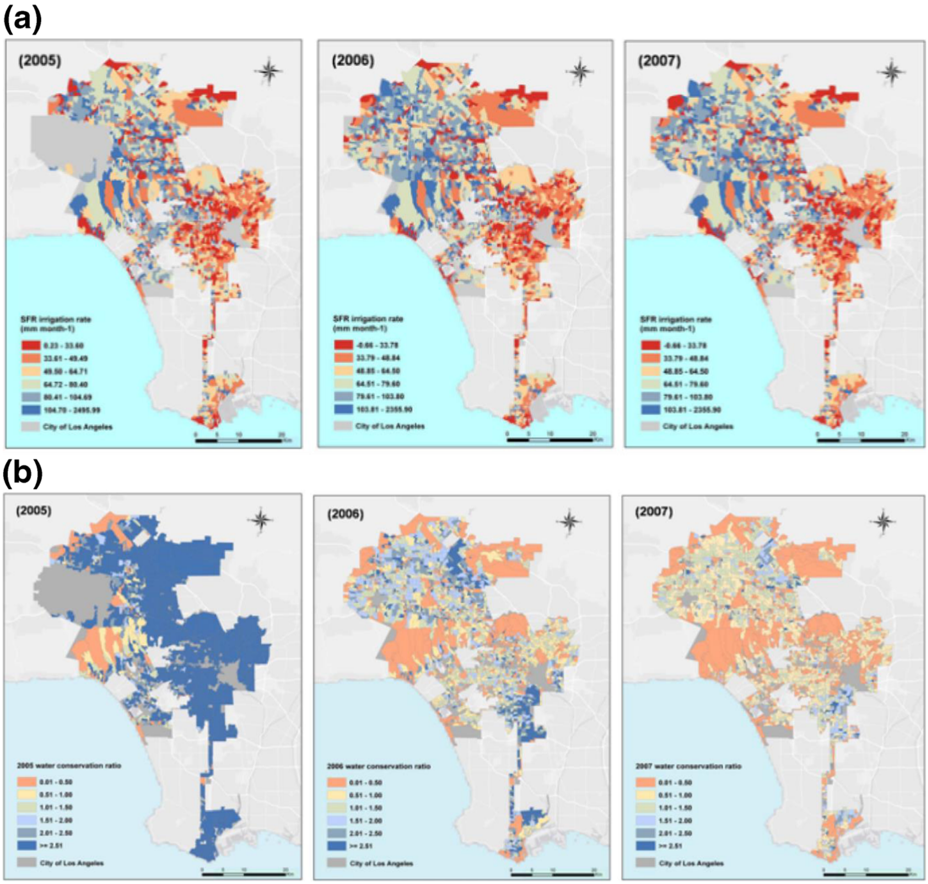

Fig. 3 **a** Irrigation rate of SFR parcels within each CR **b** water conservation ratio of estimated OWU to modeled vegetation water demand for all SFR parcels within each CR across the City of Los Angeles

NDVI and irrigation rates were found. In all three years of the study, as the SFR mean NDVI of CRs increased, their irrigation rates remained constant.

3.4 Vegetation Water Demand and Water Conservation Assessment

To understand how climate variables influence vegetation greenness within SFR irrigated areas, the mean cumulative precipitation, ETo, and irrigation across all CRs are shown in Fig. 4. The total water supply from precipitation plus irrigation was greater than ETo in the wet year (2005), approximately equal to ETo in the average water year (2006), and lower than ETo in the dry year (2007). SFR irrigation was lower than precipitation in the wet year (2005), but at least twice as large as precipitation in average and dry years (2006 and 2007). The values of ETo and SFR irrigation were similar during the first four months of all three water years, which fall during the relatively wet season in Los Angeles. There was an inflection point in April/May when the SFR irrigation increased as the dry season began. At the same time, vegetation was in a high-growth period due to increasing solar radiation and received irrigation.

The slope of the cumulative SFR irrigation curve during the dry periods (April to September, see Fig. 4) showed an increasing trend from wet to dry years (slopes of 67.6,

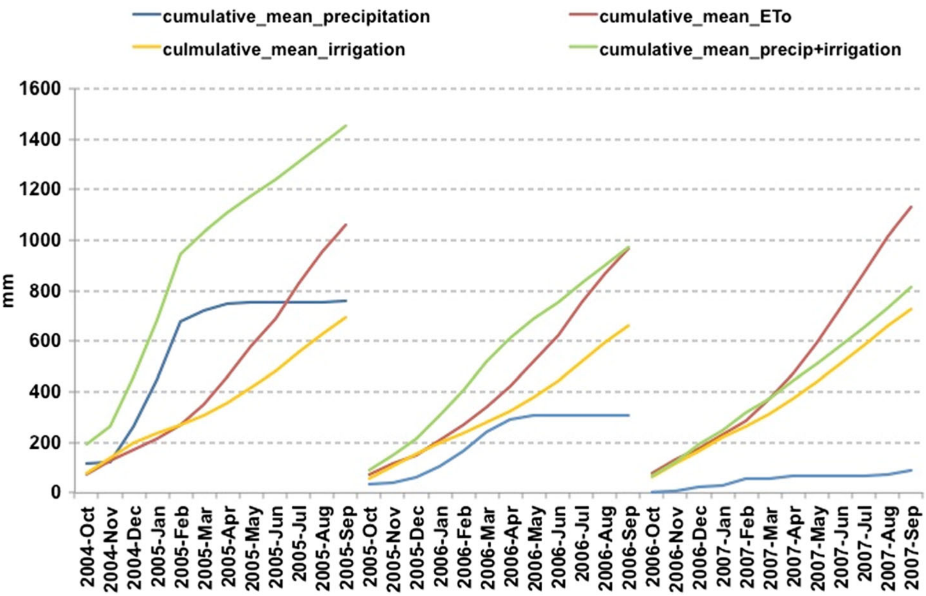

Fig. 4 Mean cumulative precipitation, ETo, and SFR irrigation across all postal carrier routes in the City of Los Angeles

68.9, 71.7 mm month^{-1} for years 2005, 2006, and 2007, respectively). The vegetation water demand during the three years was significantly correlated with the SFR mean NDVI (R^2 = 0.51, 0.43, 0.40, for 2005 to 2007 respectively; $p < 0.001$). This suggests that there was no significant reduction in the amount of SFR landscape vegetation from year to year and that landscape vegetation water demand changed little across the three water years.

The spatial distribution of the water conservation ratio is mapped for the SFR area of each CR (Fig. 3b). Over-irrigation was detected by using the threshold of mean water conservation ratio in the average rainfall year, which was >2 within each CR. The water conservation ratio in the wet year (2005) was dominated by high precipitation and reduced ETo, such that 43 % of CRs in the city were over-irrigated. In the average and dry years of 2006 and 2007 the spatial variability in the water conservation ratio was more pronounced, with over-irrigated areas located in southern Los Angeles and parts of the San Fernando Valley (Fig. 3b). The water conservation ratio showed that 7 % of CRs across the city were over-irrigated in the dry year, but 43 % were over-irrigated in the wet year. This was largely because the climatic demand for water by vegetation decreased in wet years, but irrigation rates changed little from year-to-year.

4 Discussion

4.1 SFR Outdoor Water Use Analysis

The lowest February water use occurred in 2005 as irrigation water was conserved because precipitation was abundant that year. Interannual variation in February water use suggests that irrigation is a significant component of total SFR water use even during the “minimum-month” of the year, especially if winter conditions are dry. The estimates of OWU were made by subtracting estimated IWU from the total water use, rather than using a minimum-month approach (Romero and Dukes 2011; Friedman et al. 2013). This idea is based on previous studies observing that IWU is nearly homogeneous through different water years if there are no changes in water conservation regulations (e.g., low-flow devices) that could produce trends in IWU (Romero and Dukes 2011; Friedman et al. 2013; Mini et al. 2014a).

The interannual variations of OWU in this study are consistent with previous work showing that water consumption within urban areas is lower in wet years than in average or dry years, primarily due to reduced irrigation (Eisenstein and Kondolf 2008). Nonetheless, as shown by Friedman et al. (2013), there is potential for error in the assumption that OWU is attributable to irrigation without accounting for the small portion of specialized OWU such as swimming pools and car washing.

4.2 Irrigated Area Detection

Our NDVI threshold differed from the way Stow et al. (2003) determined theirs due to logistic constraints, including the large spatial extent of our study area and the prohibitive cost of a field survey. While IWU surveys would be desirable, our regression analyses suggest that the literature-based estimate of IWU was sufficient to determine NDVI thresholds for mapping irrigated areas at the citywide scale (Table 1). The differences in NDVI thresholds between different water years showed that vegetation greenness could reflect varying responses of vegetation growth among dry, average, and wet years. This is consistent with Zhang et al. (2010) who found that vegetation growth diminished relatively quickly when transitioning from an average to a dry year due to water stress.

The spatial patterns of SFR irrigated and non-irrigated areas were consistent with variations in the amount of land owned by SFR households in different areas of the city. The highest concentration of irrigated areas was found within the San Fernando Valley, which is mostly associated with larger SFR parcel sizes with irrigated landscape vegetation.

4.3 Irrigation Rate Estimation

Irrigation rates were spatially heterogeneous, but regions of relatively high and low irrigation rates were still distinguishable. The irrigation rate in SFR areas was consistent with the distribution of the irrigated areas and the mean NDVI. The spatial patterns revealed that high irrigation rates were clustered in the San Fernando Valley and West Hollywood, whereas lower irrigation rates were clustered in downtown Los Angeles, South Los Angeles, and Long Beach (Fig. 3a). Mini et al. (2014a) showed that such spatial patterns in irrigation rates are consistent with variations in neighborhood income level and land use in Los Angeles.

The variations in mean NDVI were not related to differences in SFR irrigation because irrigation rates were relatively constant among CRs even though they varied in NDVI. This suggests that landscape irrigation systems were widely used but that the amount of irrigation water applied in low NDVI areas was in excess of vegetation demand (Endter-Wada et al. 2008). An additional contributing factor could be OWU applied for other purposes, which would affect smaller (lower NDVI) parcels more than larger parcels (Nouri et al. 2013; Friedman et al. 2013).

4.4 Vegetation Water Demand and Water Conservation Assessment

Our comparison of climate variables and irrigation rates showed that OWU as estimated from water billing records can capture the interannual variability of irrigation rates (Fig. 4). Similarly, in subtropical cities where precipitation is higher than in our study area, irrigation rates derived from monthly water billing records in wet years were correspondingly lower (Romero and Dukes 2013a, b). In contrast to subtropical cities, ETo was approximately equal to the total water supply (precipitation plus irrigation) in an average rainfall year, but higher than the total water supply in a dry year. This reflects the degree to which vegetation water demand depends on climate variability in both precipitation and ETo.

Our results demonstrated that vegetation greenness (NDVI) was strongly correlated with vegetation water demand, but it was not a good predictor of irrigation rate. These patterns were similar across three years that differed widely in rainfall, despite the small overall reduction of vegetation greenness in 2007 (Table 1). This suggests that imagery-derived vegetation greenness can be a useful indicator of vegetation water demand, but it is difficult to use greenness to predict irrigation rates because of widespread over-irrigation in urbanized areas (Hurd et al. 2006; Romero and Dukes 2011).

There was a trend of decreasing over-irrigation in the average and dry years, largely because the climatic demand for water by vegetation increased but irrigation rates changed little (especially during the dry summer months). There were consistent spatial patterns of the water conservation ratio from WY 2005 to 2007 (Fig. 3b). Smaller values of the water conservation ratio (indicating that irrigation was ≤ vegetation water demand) were found in downtown Los Angeles and the Santa Monica Mountains, and likely resulted from smaller residential parcel sizes, which have less vegetation cover for irrigation. In contrast, larger water conservation ratios (indicating over-irrigation) were found in areas with large residential parcels such as the San Fernando Valley. The implementation of water restriction laws and improved water conservation is recommended in these areas (Survis and Root 2012; Ozan and Alsharif 2013).

Our results showed consistent over-irrigation in SFR areas during three years when there were no major changes in water use regulation. Mini et al. (2015) examined the impact of water restrictions between 2008 and 2010 and the impact of a price increase on SFR water use in the city of Los Angeles. Their study reported that increasing water prices along with restricting OWU to two days per week reduced average single-family city water use 23 % more than did restricting the time and frequency of daily irrigation during the summer of fiscal year 2010. Thus, the time and frequency of landscape irrigation in SFR areas depends on the implementation of water restriction periods.

SFR water usage can be significantly affected by the following factors: household income, landscape greenness, water price and tariffs, household volume allocation, and precipitation (Mini et al. 2014b). Lee and Tanverakul (2015) indicated that residential water use under a uniform and tiered rate structure can be affected by water price, and household characteristics can influence water price elasticity in East Los Angeles, suggesting pricing systems that strongly react to larger parcel sizes. In this study, the amount of landscape irrigation was highly variable since owners of larger residential parcels may use automatic irrigation systems, resulting in greater amounts of water consumption than smaller parcels watered by hand. In addition, some SFR homeowners irrigated more than the demands of landscape vegetation, but others irrigated far less (Gage and Cooper 2015). Thus, parcel sizes and vegetation water demand could be the major components to determining SFR water consumption and price

(Wentz and Gober 2007; Gage and Cooper 2015). It is critical to provide climate zone-specific water conservation information for water agencies and urban planners in order to distribute water resources among different landscape types and parcel sizes efficiently.

5 Conclusions

This study applied an NDVI threshold approach to retrieve trends of SFR irrigated rates and areas from satellite imagery and water billing records for three consecutive water years (wet, average, and dry). Although estimated OWU was highest in the dry year, vegetation greenness was not maintained as well as in wetter years, suggesting that vegetation faced water stress conditions. The most extensive areas of irrigated land and the highest irrigation rates were located in the San Fernando Valley, the Santa Monica Mountains, Pacific Palisades, and parts of East Los Angeles. The spatial pattern of irrigation was not affected by variations in annual rainfall. The spatial variability in the water conservation ratio was more pronounced in the average and dry years, with over-irrigated areas located in southern Los Angeles and parts of the San Fernando Valley. The decrease in over-irrigation from wet to drier years was attributed to increased climatic demand for water with no significant change in irrigation rates. Our results also show that spatial variations in NDVI were strongly correlated with vegetation water demand, but NDVI was not a good predictor of irrigation rates due to widespread over-irrigation.

The current California drought has raised the importance of the analysis and reporting of residential OWU because water agencies are rarely able to distinguish the amounts of IWU and OWU (Hogue and Pincetl 2015). The implications of this study include not only improved estimation of the spatial and temporal variability of irrigation areas and vegetation greenness, but also enhanced understanding of the patterns and dynamics of irrigation rates and vegetation water demand in urban landscapes. Our study provides detailed information on the spatial distribution of water conservation conditions in residential areas of Los Angeles. The fine scale maps generated in this study could be used by water agencies and urban planners to distribute water more efficiently and to implement conservation practices such as differing price structures or watering restrictions for different geographic areas. The NDVI thresholding approach in combination with water use data is expected to be transferable to other cities in semi-arid climates.

Acknowledgments We thank the Resource Center for SPOT Imagery at UCSB for providing SPOT-5 images and the Los Angeles Department of Water and Power for providing the residential water billing records. This research was funded by an Urban Long-Term Research Areas Exploratory (ULTRA-Ex) grant from the National Science Foundation (BCS–0948914).

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