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Title

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

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Measuring spatio-temporal trends in residential landscape irrigation extent and rate in Los Angeles, California using SPOT-5 satellite imagery --Manuscript Draft--

Manuscript Number:	WARM-D-14-01023R1	
Full Title:	Measuring spatio-temporal trends in residential landscape irrigation extent and rate in Los Angeles, California using SPOT-5 satellite imagery	
Article Type:	General paper	
Keywords:	urban irrigation, NDVI, single family residential, vegetation water demand, outdoor water use	
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Funding Information:	National Science Foundation (BCS-0948914)	Prof. Joseph P McFadden
Abstract:	<p>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.</p>	

Response letter

Dear Dr. Tsakiris and Reviewers,

Thank you very much for reviewing our manuscript. Your comments are very helpful for us to improve the manuscript. We have written a specific response to each of the review comments below, with reference to the page and line numbers in the revised manuscript.

In addition, in order to meet the journal's overall length requirement, we revised the text to make it more succinct and to remove any passages of text that were not essential to the main results of the paper. Our original manuscript also had several more figures, maps, and tables. We removed Figures 2, 4, 5, 6, 7, 9, 11 and Table 1, and revised the text accordingly so that the most important new results could be conveyed while shortening the overall length of the paper as requested by the journal. At the same time, the review comments requested that we add several new references (all of which have been added) as well as two new paragraphs requested by Reviewer #2 to elaborate on water management and conservation (also added to the revised version). If there are any further specific changes that you would like to meet the journal's requirements (adding back or removing additional material), we would be happy to make those changes as well.

We appreciate your time and effort in reviewing this revised version.

Sincerely,

Ying-Jung Chen, Joseph P. McFadden, Keith C. Clarke, and Dar A. Roberts

Responses to the Associate Editor's comments

** In the revised version of the paper the authors are asked to clearly state which is the novelty of the paper for which the paper deserves publication.*

The novelty of this paper is better summarized in the revised manuscript, as follows (p. 5, lines 3 – 8):

(1) relationships of relatively high resolution (10-m) satellite imagery to an extensive database of monthly water use records for all residential customers in Los Angeles

(2) estimation of SFR irrigation to both quantify water requirements of landscape vegetation, and to calculate a water conservation ratio (ratio of the estimated outdoor water use to the vegetation water demand) through WY 2005-2007, including wet, average, and dry extremes of annual rainfall.

** The authors are advised to follow strictly the Guide for Authors...*

We made significant changes throughout the text and we removed a total of 8 figures and tables to meet the journal's guidelines on overall length.

** Finally, it would be wise for the authors to link their paper to other papers published recently in the journals of EWRA such as WARM.*

We updated the references with recent publications appearing in WARM including Wentz and Gober (2007), Gage and Copper (2015).

Response to Reviewer # 1

Comment 1:

I suggest the title includes wording that describes what type of irrigation is meant; e.g.:

“...trends in residential landscape irrigation extent ...”.

Response:

We changed the title as “Measuring spatio-temporal trends in residential landscape irrigation extent and rate in Los Angeles, California using SPOT-5 satellite imagery”

Comment 2:

The Abstract needs to include some quantitative results.

Response:

We focused more of the abstract around quantitative results, while also reducing its length to meet the overall length requirements of the journal. The abstract now reads:

“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.”

Comment 3:

The authors use the direct speech with the first person; .i.e. we selected, we investigated, quite often. It is recommended to use indirect speech instead.

Response:

We fixed this throughout the manuscript.

Comment 4:

In the Introduction:

1- The reference McCarthy and Pataki is listed as of 2011, whereas in the reference list it is of 2010. This is in line 23 of p2 and 16 of p3.

Response:

We fixed the time of citation.

Comment 5:

In the Introduction:

2- On p3, line 4: the word climatess has extra s.

Response:

We fixed the typo.

Comment 6:

In the Introduction:

3- The authors need to do good literature review of the topic. There are several recent

relevant research work that is not quoted; for example:

Francesco Vuolo et al. (2015). Satellite-based irrigation advisory services: A common tool for different experiences from Europe to Australia. Agricultural Water Management

Angela Hof and Nils Wolf (2014). Estimating potential outdoor water consumption in private urban landscapes by coupling high-resolution image analysis, irrigation water needs and evaporation estimation in Spain. Landscape and Urban Planning

Response:

We are thankful for pointing to these recent published papers. We added reference to Hof and Wolf (2014) for the topic of detecting irrigated areas and irrigation rates by remote sensing techniques. The section now reads:

“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).”

Moreover, we also added the reference to Vuolo et al. (2015) for the topic of estimating vegetation water demand by modeling and remote sensing approaches. The section now reads:

“To examine irrigation rates via the latter approach, a common method is to use a vegetation water demand model that applies reference evapotranspiration (E_{T0}), irrigated area, a crop coefficient varying with plant types, the distribution uniformity of irrigation systems, and precipitation (Endter-Wada et al. 2008; Lowry Jr. et al. 2011; Sun et al. 2012). Lowry Jr. 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 Jr. et al. (2011) was selected.”

Comment 7:

In the Materials and Method:

1- *The reference Morris 2006 is relatively old; I suggest keeping only the WRCC 2014.*

Response:

We changed the text accordingly.

Comment 8:

In the Materials and Method:

2- *On p8, line 5, it says: “... (see below),..”, and nothing is stated regarding the image selection criteria within the same sub-section. It is stated, though, in sub-section 2-4; it is recommended to have the criteria moved upfront within 2.2.*

Response:

We changed the text accordingly. Please see P6. Line 9 – 12.

Comment 9:

In the Materials and Method:

3- *On p8, line 15, the average area coverage of postal carrier route polygons is stated; it is recommended to add the minimum and maximum area as well.*

Response:

We changed the text accordingly. The sentence now reads:

“The water billing data were aggregated into postal carrier route (CR) polygons (21.64, 0.55 and 5.918e-5 km² for maximum, mean and minimum areas, respectively) each covering subsections of a neighborhood.”

Comment 10:

In the Materials and Method:

4- On p12, sub-section 2.5, line 2: spell out DEM when first mentioned. Also, it is not stated why the authors selected the nearest neighbor method in particular. Reasons have to be mentioned for the selection, and it is better to try few others and assess their accuracy, then base your selection accordingly.

Response:

We spelled out DEM in the first reference. In addition, we clarified the reason for using nearest neighbor resampling at p 8 lines 17– 18.

Comment 11:

In the Materials and Method:

5- On p13, sub-section 2.5, line 3, it is stated that both approaches were tested and the first approach was selected. The reasons for the choice of the first approach are qualitative and not quantitative; choices should be based upon some criteria parameters using quantitative values.

Response:

We clarified this section to read:

“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.”

Comment 12:

In the Materials and Method:

6- In sub-section 2.8, line 14, again the authors selected the water demand model of Lowry et al. (2011) for no good reason mentioned. Nouri et al. (2013) compared three different approaches and their work is more recent. It is recommended to either use their more recent approaches, or at least compare between Lowry's and the best Nouri et al. reached.

Response:

We clarified this section to read:

“After reviewing three different approaches from Nouri et al. (2013), we selected the approach of Lowry Jr. 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.”

Comment 13:

In the Results Section:

1- On p17, the authors mention about Method 1 and Method 3; they reasoned why they chose Method 3, but nothing is stated about Method 2.

Response:

We clarified this section to read:

“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 (Figure 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.”

Comment 14:

The Conclusions Section is just too long; it is recommended to have them concise and precise, may be in point form or few paragraphs.

Response:

We made changes throughout the Conclusions section to shorten it significantly and make it more focused on the specific new findings in this paper. (p. 21, line 10 to p. 22, line 16).

Response to Reviewer # 2

Comment 15:

I recommend for the authors to add two sections or paragraphs. The first will be to discuss water management practices (how do SFR decide on the amount and time of landscape irrigation), water pricing and tariffs in the area. The second section will be in the end of the manuscript regarding how could we utilize the study in improving water conservation.

Response:

We added two paragraphs discussing water management practices, water pricing and tariffs at the end of sub-section 4.4. (p. 20 lines 6–21, p. 21, lines 1–7).

We also added another paragraph in the Conclusion section regarding the utilization of the study in improving water conservation. (p. 22, lines 4–16).

Comment 16:

The last comment is the need to use SI units in all figures (figure 3, 9 and 11 have US customary units).

Response:

We redrew the original Figure 3 using SI units. However, the original Figures 9 and 11 already showed SI units. We eliminated Figures 9 and 11 in order to meet the overall length limitations of the journal. The original Figure 3 is now Figure 2 in the revised manuscript.

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1 **Measuring spatio-temporal trends in residential landscape irrigation extent and rate**
2 **in Los Angeles, California using SPOT-5 satellite imagery**

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9 *Submitted to: Water Resources Management*

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18 **Acknowledgments:**

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

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5 1 **Title: Measuring spatio-temporal trends in residential landscape irrigation extent**
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8 2 **and rate in Los Angeles, California using SPOT-5 satellite imagery**
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12 4 **Abstract:**

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15 5 Irrigation is a large component of urban water budgets in semi-arid regions and is critical
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18 6 for the management of landscape vegetation and water resources. This is particularly true
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21 7 for Mediterranean climate cities such as Los Angeles, where water availability is limited
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24 8 during dry summers. These interactions were examined by using 10-m resolution satellite
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27 9 imagery and a database of monthly water use records for all residential water customers
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29 10 in Los Angeles in order to map vegetation greenness, the extent and distribution of
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32 11 irrigated areas, and irrigation rates. A water conservation ratio between rates of irrigation
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35 12 and vegetation water demand was calculated to assess over-irrigation. The analyses were
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38 13 conducted for the water years (WY) 2005–2007, which included wet, average, and dry
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41 14 extremes of annual rainfall. Although outdoor water usage was highest in the dry year,
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44 15 vegetation greenness could not be maintained as well as in wetter years, suggesting that
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47 16 lower greenness was due to water stress. However, annual rainfall from WY 2005 to
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62 21 largely because the climatic demand for water by vegetation decreased in wet years, but
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1 irrigation rates changed little from year-to-year. This overwatering can be addressed by
2 water conservation, planning and public education, especially in the current California
3 drought. The approach demonstrated here should be transferable to other cities in
4 semi-arid climates.

5
6 Key words: urban irrigation, NDVI, single family residential, vegetation water demand,
7 outdoor water use

8 9 **1. Introduction**

10 In the southwestern United States, the consequences of climate change include urban
11 heat island effects, severe droughts, and decreasing spring snowpack. As a result, water
12 supplies are shrinking and water shortages will continue (Garfin 2013). At the same
13 time, water demand in urban areas will increase with population growth. Approximately
14 70% of urban water use occurs in residential areas (LADWP 2008) and 40–70% of
15 residential water use is for irrigation and other outdoor purposes (St. Hilaire et al. 2008).
16 Understanding the water needs of urban vegetation and managing water budgets are
17 crucial for water conservation in cities with semi-arid or Mediterranean climates, such
18 as in Southern California, where summer rainfall is limited (Lowry Jr. et al. 2011; Sun
19 et al. 2012; Nouri et al. 2013). However, relatively few studies have investigated the
20 impact of urban vegetation on water use budgets in Los Angeles (McCarthy and Pataki
21 2010; Bijoor et al. 2012).

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

12 Few studies have analyzed monthly single family residential (SFR) water use records
13 at sufficiently fine spatial scales to estimate outdoor water use (OWU) and correlate it
14 with urban irrigated areas detected by satellite imagery (Lowry Jr. et al. 2011; Hof and
15 Wolf 2014). For example, Lowry Jr. et al. (2011) acquired residential water use data at
16 the county level to validate results from an irrigation demand model that was based on
17 imagery, climate, and geographic information system (GIS) data. Gage and Cooper
18 (2015) analyzed the relationship among SFR OWU, land cover, vertical structure, and
19 socioeconomic and demographic factors at the parcel scale. In this study, monthly water
20 use for residential customers was obtained from the Los Angeles Department of Water
21 and Power (LADWP) at the scale of 9-digit postal delivery areas (ZIP codes).

1 Spatio-temporal patterns of urban irrigation rates and areas are more accurate when using
2 monthly SFR water billing records at this fine scale (Friedman et al. 2013) as compared
3 to more aggregated analyses.

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

17 Our objectives were to: (1) map the extent of irrigated area within SFR lands using
18 NDVI thresholding; (2) estimate irrigation rates within SFR lands and their relationship
19 to vegetation greenness; (3) evaluate how SFR irrigation rates were influenced by
20 climate variation (i.e., precipitation); (4) assess vegetation water demand from a

1 landscape irrigation demand model; and (5) examine the magnitude and interannual
2 variability between OWU and vegetation water demand.

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

9 10 **2. Materials and Methods**

11 **2.1 Study area**

12 **< Insert Figure 1. >**

13 The City of Los Angeles (34°06'36"N, 118°24'40"W) covers 1215 km² and is
14 located within the Los Angeles basin in Southern California, U.S.A. (Figure 1). The city
15 population of 3.8 million ranks second in the U.S. (U.S. Census 2010). The climate is
16 Mediterranean, with most precipitation occurring in winter, an annual precipitation of
17 375 mm (downtown), and an annual average temperature of 18.2°C (WRCC 2014). The
18 major types of native vegetation in the city are coastal sage scrub and chaparral, but
19 conifer forests, riparian corridors, and oak woodlands are found at higher elevations
20 (Rundel and Gustafson 2005). Urban vegetation types have changed from native
21 grasslands and woodlands to non-native species and impervious surfaces such as asphalt

1 due to urbanization and human planting activities (Gillespie et al. 2012). Urban
2 vegetation in the City of Los Angeles depends on irrigation and is highly water
3 consumptive, especially during the dry summer season (Clarke et al. 2013).

4 **2.2 Data**

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

16 A parcel-level land use map was acquired from the Southern California Association
17 of Governments (SCAG). Monthly water billing records for SFR customers within the
18 City of Los Angeles were acquired from the LADWP. The water billing data were
19 aggregated into postal carrier route (CR) polygons (21.64, 0.55 and $5.918e-5$ km² for
20 maximum, mean and minimum areas, respectively) each covering subsections of a
21 neighborhood.

1 Monthly precipitation and ETo values were acquired from the National Climate
2 Data Center (NCDC) and California Irrigation Management Information Systems
3 (CIMIS) stations in Glendale, Santa Monica, and Long Beach. The CIMIS ETo data were
4 from reference surfaces, such as well-watered, actively growing short grass that covered
5 most of the soil, and ETo was calculated using a modified Penman–Monteith model
6 (Temesgen et al. 2005). Precipitation data were acquired from the long-term NCDC
7 stations at Los Angeles International airport, Long Beach, Van Nuys airport, and
8 Downtown Los Angeles.

9 10 **2.3 Water use data analysis**

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

19 The IWU was subtracted from the total water use billing records to estimate OWU
20 within SFR areas. Three methods were evaluated from the literature for estimating IWU.
21 First, the lowest monthly water use has been used to represent IWU (Friedman et al.

1 2013). Second, Johnson and Belitz (2012) found that there was 20 mm (rainfall
2 equivalent) of IWU in SFR areas in the San Fernando Valley, California. Third, DeOreo
3 et al. (2011) collected IWU data from SFR areas in California in 2005 and found a mean
4 daily IWU of 662.5 liters per household.

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

12 13 **2.5 Image preprocessing**

14 Atmospheric correction and orthorectification of the images were done in ENVI
15 5.0 by applying rational polynomial coefficients with a 10-meter Digital Elevation
16 Model from the U.S. Geological Survey using nearest neighbor resampling, yielding a
17 spatial accuracy of ± 3 to 5 pixels. Nearest neighbor resampling was selected because it
18 did not alter pixel level reflectance values required for NDVI calculations. Geometric
19 correction was conducted by registering the images using a third-order polynomial
20 based on an average of 40 reference ground control points, resulting in mean RMS
21 errors of ± 1 pixel.

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

14 **2.6 Image analysis for irrigated areas**

15 **2.6.1 Simple NDVI threshold**

16 The mosaicked imagery was masked by a SFR parcel GIS layer to map irrigated
17 areas within SFR sectors. The pixel values within SFR parcels for each CR were
18 extracted. This procedure generated 14% systematic errors due to boundary effects in
19 the imagery. The number of pixels classified as irrigated was summed, each pixel
20 representing an area of 100 m^2 within each CR.
21

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

7 There were 2033 CRs that included residential water billing records. For the year
8 2005, the available number of CR polygons was reduced to 1809 because the imagery
9 available in the SPOT-5 archive did not cover a section of the northwest study area. For
10 all three years, approximately 10 CRs (0.5 % of all CR sectors for the study area) lacked
11 water billing records from LADWP and were excluded from subsequent analyses. The
12 data did not follow a normal distribution; therefore, a logarithmic transformation was
13 applied to estimated OWU and the irrigated pixel areas before regression analyses. After
14 acquiring the optimal NDVI threshold value, maps of irrigated areas were generated at
15 the pixel level.

17 **2.7 Irrigation rate estimation and climate variable comparison**

18 To estimate irrigation rates from water billing records, the amount of OWU was
19 normalized by the total area occupied by SFR parcels within each CR. The ETo,
20 irrigation rates, precipitation, and total water supply (sum of precipitation and irrigation
21 rates) were plotted from WY 2005–2007 in order to compare interannual variations. The

1 relationships among vegetation greenness, precipitation, ETo, and irrigation rates were
2 explored with regression models. The precipitation and ETo station data were overlain
3 with the CR map to identify the nearest CR polygon and mapped by CRs regionally.

4 5 **2.8 Vegetation water demand assessment**

6 To examine differences in irrigation rates among water years, the estimated irrigation
7 was compared to modeled vegetation water demand. Vegetation water demand can be
8 estimated from a model based on climatic and vegetation variables (Endter-Wada et al.
9 2008; Lowry Jr. et al. 2011; Nouri et al. 2013). After reviewing three different
10 approaches from Nouri et al. (2013), we selected the approach of Lowry Jr. et al. (2011)
11 as the most appropriate for the scale of our study, recognizing that the importance of
12 irrigation systems and irrigated areas may have slightly underestimated our summer
13 season irrigation requirements.

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

$$16 \quad I_m = ((ET_{om} \cdot PF) - R_m) \cdot (A/DU) \quad (1)$$

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

20 The ETo and R data were from CIMIS and NCDC, and irrigated areas were
21 extracted as described above. The plant factors from Lowry Jr. et al. (2011) of 0.5 for

1 tree or shrub canopies, 0.8 for exposed turf grass, and 0.4 for grass under canopy were
2 applied. DU is a factor for the uniformity of water application. Because irrigation
3 systems usually are non-uniform, the value of DU was 0.75, which assumes that
4 landscape irrigation systems are 75% efficient in residential areas (Lowry Jr. et al.
5 2011). Using this information, the ratio between OWU and vegetation water demand
6 was calculated to evaluate the degree of over-irrigation in each CR polygon.

8 **3. Results**

9 **3.1 SFR outdoor water use analysis**

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

15 **<Insert Figure 2.>**

16 Three different methods for estimating SFR OWU from total residential water use
17 were examined. After aggregating the data by CR ($N=2030$), the methods were evaluated
18 with a series of linear regressions between OWU estimated by each method and the
19 amount of irrigated area estimated by applying a range of NDVI thresholds. Method 1, a
20 minimum-month approach to estimate IWU had the highest correlation coefficient with
21 irrigated areas across all NDVI threshold values. However, it was not selected because

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

11

12 **3.2 Irrigated area detection**

13 The SFR irrigated area was mapped using the NDVI threshold that produced the
14 highest correlation between estimated OWU and irrigated area in each year of the study.
15 Within a given method of estimating OWU, the peak R^2 and the corresponding NDVI
16 threshold values were relatively similar across the three water years (Table 1). However,
17 the optimal NDVI thresholds for detecting irrigated land were lower for all methods in
18 the dry year of 2007. This suggests that a similar amount of water was used during the
19 dry season in all three years (Figure 2), but it could only maintain a lower level of
20 vegetation greenness in the dry year of 2007 as compared to the years having average or
21 high rainfall. The most extensive areas of irrigated land were in the San Fernando Valley,

1 the Santa Monica Mountains, Pacific Palisades, and part of East Los Angeles.
2 Conversely, non-irrigated areas were concentrated in downtown and southern Los
3 Angeles.

4 <Insert Table 1.>

6 **3.3 Irrigation rate estimation**

7 The irrigation rate within SFR land was determined by dividing the estimated OWU
8 by the total irrigated area within each CR. There was high spatial heterogeneity in SFR
9 irrigation rates. Annual rainfall from WY 2005 to 2007 did not significantly influence the
10 variability in the magnitude and spatial pattern of irrigation, resulting in irrigation rates
11 ranging from 81 to 86 mm (Figure 3 (a)). Consistent with this, similar relationships
12 among years between SFR mean NDVI and irrigation rates were found. In all three years
13 of the study, as the SFR mean NDVI of CRs increased, their irrigation rates remained
14 constant.

15 <Insert Figure 3.>

17 **3.4 Vegetation water demand and water conservation assessment**

18 To understand how climate variables influence vegetation greenness within SFR
19 irrigated areas, the mean cumulative precipitation, ETo, and irrigation across all CRs are
20 shown in Figure 4. The total water supply from precipitation plus irrigation was greater
21 than ETo in the wet year (2005), approximately equal to ETo in the average water year

1 (2006), and lower than ETo in the dry year (2007). SFR irrigation was lower than
2 precipitation in the wet year (2005), but at least twice as large as precipitation in average
3 and dry years (2006 and 2007). The values of ETo and SFR irrigation were similar during
4 the first four months of all three water years, which fall during the relatively wet season
5 in Los Angeles. There was an inflection point in April/May when the SFR irrigation
6 increased as the dry season began. At the same time, vegetation was in a high-growth
7 period due to increasing solar radiation and received irrigation.

8 **<Insert Figure 4.>**

9 The slope of the cumulative SFR irrigation curve during the dry periods (April to
10 September, see Figure 4) showed an increasing trend from wet to dry years (slopes of
11 67.6, 68.9, 71.7 mm month⁻¹ for years 2005, 2006, and 2007, respectively). The
12 vegetation water demand during the three years was significantly correlated with the SFR
13 mean NDVI ($R^2=0.51, 0.43, 0.40$, for 2005 to 2007 respectively; $p<0.001$). This suggests
14 that there was no significant reduction in the amount of SFR landscape vegetation from
15 year to year and that landscape vegetation water demand changed little across the three
16 water years.

17 The spatial distribution of the water conservation ratio is mapped for the SFR area of
18 each CR (Figure 3 (b)). Over-irrigation was detected by using the threshold of mean
19 water conservation ratio in the average rainfall year, which was >2 within each CR. The
20 water conservation ratio in the wet year (2005) was dominated by high precipitation and
21 reduced ETo, such that 43% of CRs in the city were over-irrigated. In the average and dry

1 years of 2006 and 2007 the spatial variability in the water conservation ratio was more
2 pronounced, with over-irrigated areas located in southern Los Angeles and parts of the
3 San Fernando Valley (Figure 3(b)). The water conservation ratio showed that 7% of CRs
4 across the city were over-irrigated in the dry year, but 43% were over-irrigated in the wet
5 year. This was largely because the climatic demand for water by vegetation decreased in
6 wet years, but irrigation rates changed little from year-to-year.

7

8 **4. Discussion**

9 **4.1 SFR outdoor water use analysis**

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

20 The interannual variations of OWU in this study are consistent with previous work
21 showing that water consumption within urban areas is lower in wet years than in average

1 or dry years, primarily due to reduced irrigation (Eisenstein and Kondolf 2008).
2 Nonetheless, as shown by Friedman et al. (2013), there is potential for error in the
3 assumption that OWU is attributable to irrigation without accounting for the small portion
4 of specialized OWU such as swimming pools and car washing.

6 **4.2 Irrigated area detection**

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

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

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8 **4.3 Irrigation rate estimation**
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10 3 Irrigation rates were spatially heterogeneous, but regions of relatively high and low
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12 4 irrigation rates were still distinguishable. The irrigation rate in SFR areas was consistent
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15 5 with the distribution of the irrigated areas and the mean NDVI. The spatial patterns
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18 6 revealed that high irrigation rates were clustered in the San Fernando Valley and West
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21 7 Hollywood, whereas lower irrigation rates were clustered in downtown Los Angeles,
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24 8 South Los Angeles, and Long Beach (Figure 3 (a)). Mini et al. (2014a) showed that such
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26 9 spatial patterns in irrigation rates are consistent with variations in neighborhood income
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29 10 level and land use in Los Angeles.
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31 11 The variations in mean NDVI were not related to differences in SFR irrigation
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34 12 because irrigation rates were relatively constant among CRs even though they varied in
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37 13 NDVI. This suggests that landscape irrigation systems were widely used but that the
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40 14 amount of irrigation water applied in low NDVI areas was in excess of vegetation demand
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42 15 (Endter-Wada et al. 2008). An additional contributing factor could be OWU applied for
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45 16 other purposes, which would affect smaller (lower NDVI) parcels more than larger parcels
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48 17 (Nouri et al. 2013; Friedman et al. 2013).
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53 **4.4 Vegetation water demand and water conservation assessment**
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55 20 Our comparison of climate variables and irrigation rates showed that OWU as
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58 21 estimated from water billing records can capture the interannual variability of irrigation
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1 rates (Figure 4). Similarly, in subtropical cities where precipitation is higher than in our
2 study area, irrigation rates derived from monthly water billing records in wet years were
3 correspondingly lower (Romero and Dukes 2013a, 2013b). In contrast to subtropical
4 cities, ETo was approximately equal to the total water supply (precipitation plus
5 irrigation) in an average rainfall year, but higher than the total water supply in a dry year.
6 This reflects the degree to which vegetation water demand depends on climate variability
7 in both precipitation and ETo.

8 Our results demonstrated that vegetation greenness (NDVI) was strongly correlated
9 with vegetation water demand, but it was not a good predictor of irrigation rate. These
10 patterns were similar across three years that differed widely in rainfall, despite the small
11 overall reduction of vegetation greenness in 2007 (Table 1). This suggests that
12 imagery-derived vegetation greenness can be a useful indicator of vegetation water
13 demand, but it is difficult to use greenness to predict irrigation rates because of
14 widespread over-irrigation in urbanized areas (Hurd et al. 2006; Romero and Dukes
15 2011).

16 There was a trend of decreasing over-irrigation in the average and dry years, largely
17 because the climatic demand for water by vegetation increased but irrigation rates
18 changed little (especially during the dry summer months). There were consistent spatial
19 patterns of the water conservation ratio from WY 2005 to 2007 (Figure 3(b)). Smaller
20 values of the water conservation ratio (indicating that irrigation was \leq vegetation water
21 demand) were found in downtown Los Angeles and the Santa Monica Mountains, and

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1 likely resulted from smaller residential parcel sizes, which have less vegetation cover for
2 irrigation. In contrast, larger water conservation ratios (indicating over-irrigation) were
3 found in areas with large residential parcels such as the San Fernando Valley. The
4 implementation of water restriction laws and improved water conservation is
5 recommended in these areas (Survis and Root 2012; Ozan and Alsharif 2013).

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

14 SFR water usage can be significantly affected by the following factors: household
15 income, landscape greenness, water price and tariffs, household volume allocation, and
16 precipitation (Mini et al. 2014b). Lee and Tanverakul (2015) indicated that residential
17 water use under a uniform and tiered rate structure can be affected by water price, and
18 household characteristics can influence water price elasticity in East Los Angeles,
19 suggesting pricing systems that strongly react to larger parcel sizes. In this study, the
20 amount of landscape irrigation was highly variable since owners of larger residential
21 parcels may use automatic irrigation systems, resulting in greater amounts of water

1 consumption than smaller parcels watered by hand. In addition, some SFR homeowners
2 irrigated more than the demands of landscape vegetation, but others irrigated far less
3 (Gage and Cooper 2015). Thus, parcel sizes and vegetation water demand could be the
4 major components to determining SFR water consumption and price (Wentz and Gober
5 2007; Gage and Cooper 2015). It is critical to provide climate zone-specific water
6 conservation information for water agencies and urban planners in order to distribute
7 water resources among different landscape types and parcel sizes efficiently.

8 9 **5. Conclusions**

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

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1 show that spatial variations in NDVI were strongly correlated with vegetation water
2 demand, but NDVI was not a good predictor of irrigation rates due to widespread
3 over-irrigation.

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

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3
4
5 **1 References:**
6

7
8 2 Bijoor, N. S., McCarthy, H. R., Zhang, D., & Pataki, D. E. (2012) Water sources
9
10 3 of urban trees in the Los Angeles metropolitan area. *Urban Ecosystems*, 15(1):195-214
11
12

13 4
14
15 5 Clarke, L. W., G. D. Jenerette, & A. Davila. (2013) The luxury of vegetation and the legacy
16
17 6 of tree biodiversity in Los Angeles, CA. *Landscape and Urban Planning*, 116: 48-59
18
19

20 7
21
22
23 8 DeOreo, W.B., P.W. Mayer, L. Martien, M. Hayden, A. Funk, M. Kramer-Duffield, R.
24
25 9 Davis, J. Henderson, B. Raucher, P. Gleick, M. Hebeberger, F. Sanchez, & A. McNulty.
26
27 10 (2011) *California Single-Family Water Use Efficiency Study*. Prepared by AcquaCraft
28
29 11 Inc. for the California Department of Water Resources and Irvine Ranch Water District.
30
31
32

33 12
34
35
36 13 Eisenstein, W., & Kondolf, G. M. (2008) Planning Water Use in California. *ACCESS*,
37
38 14 33(Fall): 8-17
39
40

41 15
42
43
44 16 Endter-Wada, J., Kurtzman, J., Keenan, S. P., Kjelgren, R. K., & Neale, C. M. (2008)
45
46 17 Situational Waste in Landscape Watering: Residential and Business Water Use in an
47
48 18 Urban Utah Community¹. *JAWRA Journal of the American Water Resources*
49
50 19 *Association*, 44(4):902-920
51
52
53
54
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46
47
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49
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61
62
63
64
65

1 Friedman, K., Heaney, J. P., Morales, M., & Palenchar, J. E. (2013) Predicting and
2 managing residential potable irrigation using parcel-level databases. *Journal-American*
3 *Water Works Association*, 105(7):E372-E386

5 Gage, E., & Cooper, D. J. (2015) The Influence of Land Cover, Vertical Structure, and
6 Socioeconomic Factors on Outdoor Water Use in a Western US City. *Water Resources*
7 *Management*, 1-14

9 Garfin, G. (2013) *Assessment of Climate Change in the Southwest United States: A Report*
10 *Prepared for the National Climate Assessment*. Island Press.

12 Gillespie, T. W., Pincetl, S., Brossard, S., Smith, J., Saatchi, S., Pataki, D., & Saphores, J.
13 D. (2012) A time series of urban forestry in Los Angeles. *Urban Ecosystems*, 15(1):
14 233-246

16 Gumma, M. K., Thenkabail, P. S., Hideto, F., Nelson, A., Dheeravath, V., Busia, D., &
17 Rala, A. (2011) Mapping irrigated areas of Ghana using fusion of 30 m and 250 m
18 resolution remote-sensing data. *Remote Sensing*, 3(4): 816-835

20 Hurd, B. H., St. Hilaire, R., & White, J. M. (2006) Residential landscapes, homeowner
21 attitudes, and water-wise choices in New Mexico. *HortTechnology*, 16(2):241-246

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60
61
62
63
64
65

1 Hogue, T. S., & Pincetl, S. (2015) Are you watering your lawn? *Science*, 348(6241):
2 1319-1320
3
4 Hof, A., & Wolf, N. (2014) Estimating potential outdoor water consumption in private
5 urban landscapes by coupling high-resolution image analysis, irrigation water needs and
6 evaporation estimation in Spain. *Landscape and Urban Planning*, 123: 61-72
7
8 Johnson, T. D., & Belitz, K. (2012) A remote sensing approach for estimating the location
9 and rate of urban irrigation in semi-arid climates. *Journal of Hydrology*, 414: 86-98
10
11 Lee, J., & Tanverakul, S. A. (2015) Price elasticity of residential water demand in
12 California. *Journal of Water Supply: Research and Technology—AQUA*, 64(2):211-218
13
14 Los Angeles Department of Water and Power (LADWP) (2008) *Securing L.A. water*
15 *supply action plan*, City of Los Angeles, Los Angeles, CA, 32p.
16
17 Lowry Jr, J. H., Ramsey, R. D., & Kjergren, R. K. (2011) Predicting urban forest growth
18 and its impact on residential landscape water demand in a semiarid urban environment.
19 *Urban Forestry & Urban Greening*, 10(3):193-204
20
21 McCarthy, H. R., & Pataki, D. E. (2010) Drivers of variability in water use of native and
non-native urban trees in the greater Los Angeles area. *Urban ecosystems*, 13(4): 393-414

1
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9
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58
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60
61
62
63
64
65

Mini, C., Hogue, T. S., & Pincetl, S. (2014a) Estimation of residential outdoor water use in Los Angeles, California. *Landscape and Urban Planning*, 127:124-135

Mini, C., Hogue, T. S., & Pincetl, S. (2014b) Patterns and controlling factors of residential water use in Los Angeles, California. *Water Policy*, 16(6):1054-1069

Mini, C., Hogue, T. S., & Pincetl, S. (2015) The effectiveness of water conservation measures on summer residential water use in Los Angeles, California. *Resources, Conservation and Recycling*, 94:136-145

Nouri, H., Beecham, S., Hassanli, A. M., & Kazemi, F. (2013) Water requirements of urban landscape plants: A comparison of three factor-based approaches. *Ecological Engineering*, 57:276-284

Ozan, L. A., & Alsharif, K. A. (2013) The effectiveness of water irrigation policies for residential turfgrass. *Land Use Policy*, 31:378-384

Ozdogan, M., & Gutman, G. (2008) A new methodology to map irrigated areas using multi-temporal MODIS and ancillary data: An application example in the continental US. *Remote Sensing of Environment*, 112(9):3520-3537

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1 Pervez, M. S., & Brown, J. F. (2010) Mapping irrigated lands at 250-m scale by merging
2 MODIS data and national agricultural statistics. *Remote Sensing*, 2(10):2388-2412
3
4 Romero, C. C., & Dukes, M. D. (2011) Are landscapes over-irrigated in Southwest
5 Florida? A spatial–temporal analysis of observed data. *Irrigation Science*, 29(5):
6 391-401
7
8 Romero, C. C., & Dukes, M. D. (2013a) Net irrigation requirements for Florida
9 turfgrasses. *Irrigation Science*, 31(5):1213-1224
10
11 Romero, C. C., & Dukes, M. D. (2013 b) Estimation and Analysis of Irrigation in
12 Single-Family Homes in Central Florida. *Journal of Irrigation and Drainage*
13 *Engineering*, 140(2)
14
15 Rundel, P. W., & Gustafson, R. (2005) *Introduction to the plant life of southern*
16 *California: Coast to Foothills*. London: University of California Press.
17
18 Salvador, R., Bautista-Capetillo, C., & Playán, E. (2011) Irrigation performance in private
19 urban landscapes: A study case in Zaragoza (Spain). *Landscape and urban planning*,
20 100(3):302-311
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1 St. Hilaire, R., Arnold, M. A., Wilkerson, D. C., Devitt, D. A., Hurd, B. H., Lesikar, B. J.,
2 Lohr, V. I., Martin, C. A., McDonald, G. V., Morris, R. L., Pittenger, D. R., Shaw, D. A., &
3 Zoldoske, D. F. (2008) Efficient water use in residential urban landscapes. *HortScience*,
4 43(7): 2081-2092
5
6 Stow, D., Coulter, L., Kaiser, J., Hope, A., Schutte, K., & Walters, A. (2003) Irrigated
7 vegetation assessment for urban environments. *Photogrammetric Engineering and Remote*
8 *Sensing*, 69(4):381-390
9
10 Sun, H., Kopp, K., & Kjølgren, R. (2012) Water-efficient urban landscapes: Integrating
11 different water use categorizations and plant types. *HortScience*, 47(2):254-263
12
13 Survis, F. D., & Root, T. L. (2012) Evaluating the effectiveness of water restrictions: A
14 case study from Southeast Florida. *Journal of environmental management*, 112: 377-383
15
16 Temesgen, B., Eching, S., Davidoff, B., & Frame, K. (2005) Comparison of some
17 reference evapotranspiration equations for California. *Journal of irrigation and*
18 *drainage engineering*, 131(1): 73-84
19
20 United States Census Bureau (2010) *2010 United States Census Gazetteer for Places*:
21 January 1, 2010. (Accessed August 17th, 2015).

1
2
3
4
5
6
7
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9
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Velpuri, N. M., Thenkabail, P. S., Gumma, M. K., Biradar, C., Dheeravath, V.,
Noojipady, P., & Yuanjie, L. (2009) Influence of resolution in irrigated area mapping and
area estimation. *Photogrammetric Engineering & Remote Sensing*, 75(12): 1383-1395

Vuolo, F., D’Urso, G., De Michele, C., Bianchi, B., & Cutting, M. (2015) Satellite-based
irrigation advisory services: A common tool for different experiences from Europe to
Australia. *Agricultural Water Management*, 147: 82-95

West Regional Climate Center (WRCC)
<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca5115>. (Accessed August 17th, 2015).

Wentz, E. A., & Gober, P. (2007) Determinants of small-area water consumption for the
city of Phoenix, Arizona. *Water Resources Management*, 21(11):1849-1863

Zhang, X., Goldberg, M., Tarpley, D., Friedl, M. A., Morisette, J., Kogan, F., & Yu, Y.
(2010) Drought-induced vegetation stress in southwestern North
America. *Environmental Research Letters*, 5(2):024008

figure 1

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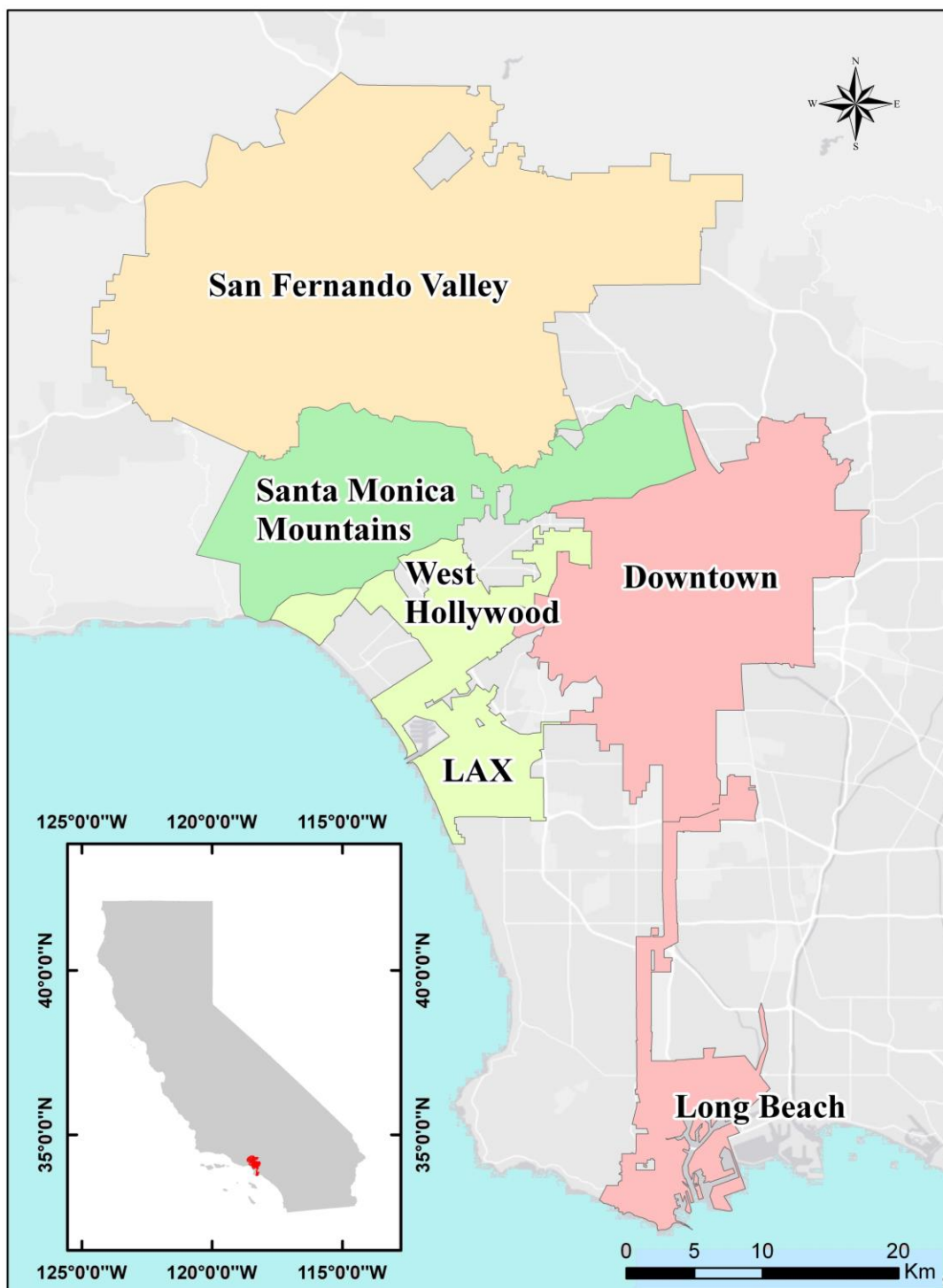


Figure 1. City of Los Angeles showing the major geographic areas referenced in the text.

figure 2

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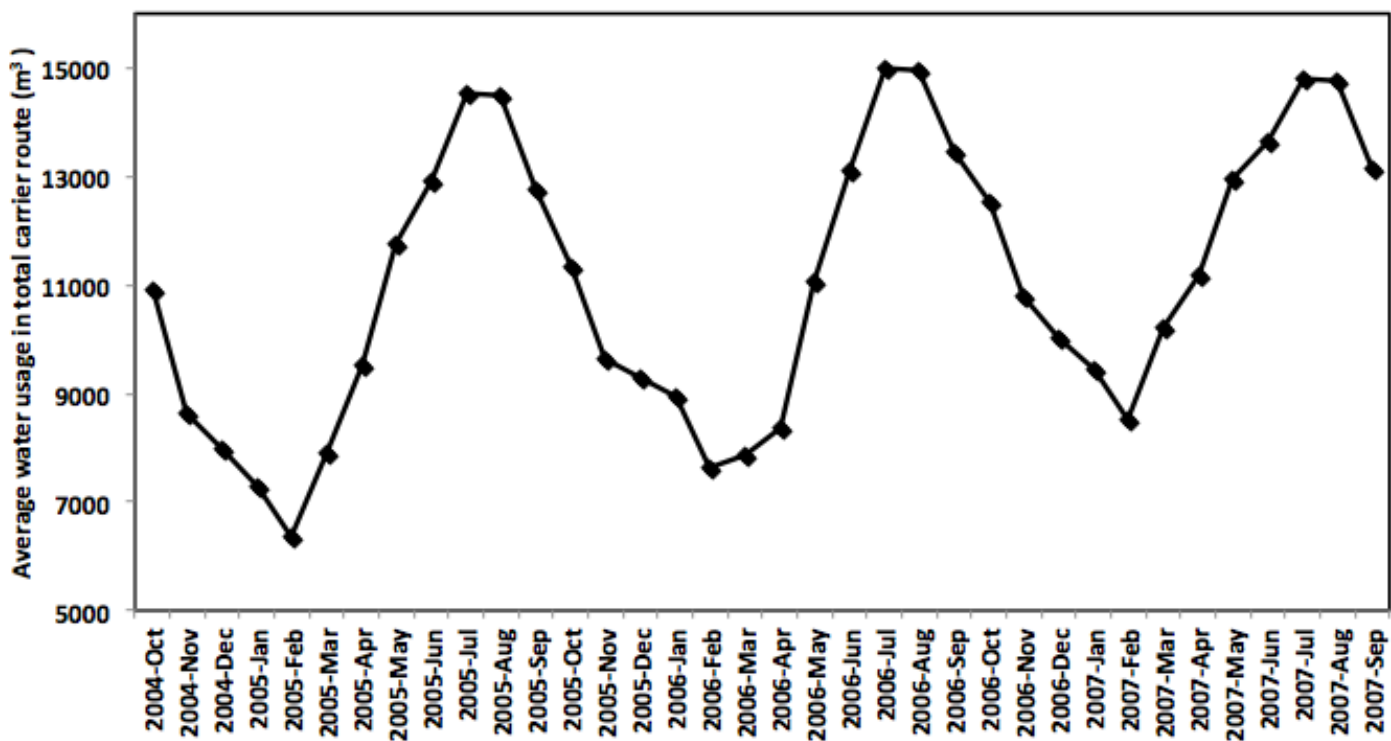
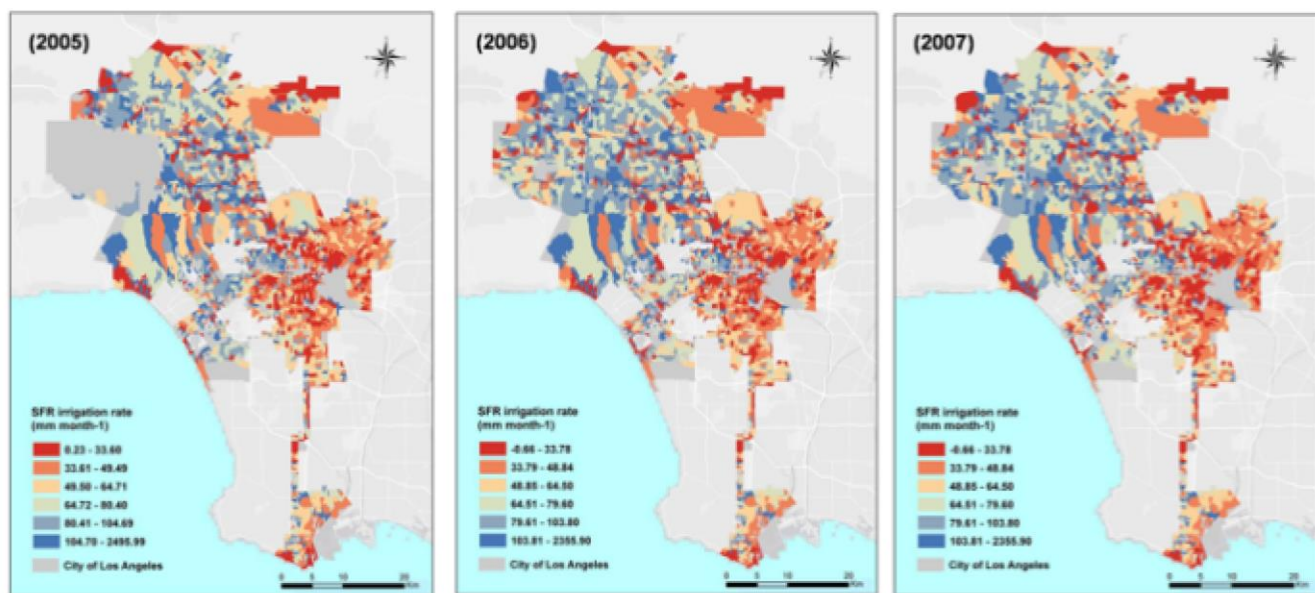


Figure 2. Monthly CR mean total SFR water usage for water year 2005–2007 (N = 2033 carrier routes).

(a)



(b)

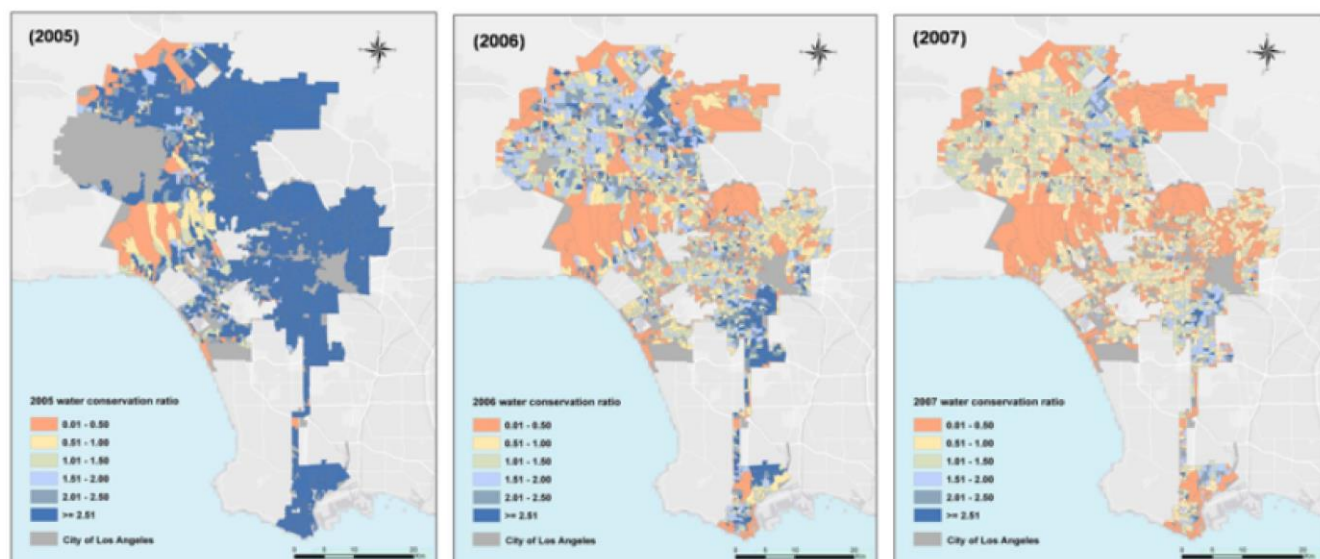


Figure 3. (a) Irrigation rate of SFR parcels within each CR (b) water conservation ratio of estimated OWU to modeled vegetation water demand for all SFR parcels within each CR across the City of Los Angeles.

figure 4

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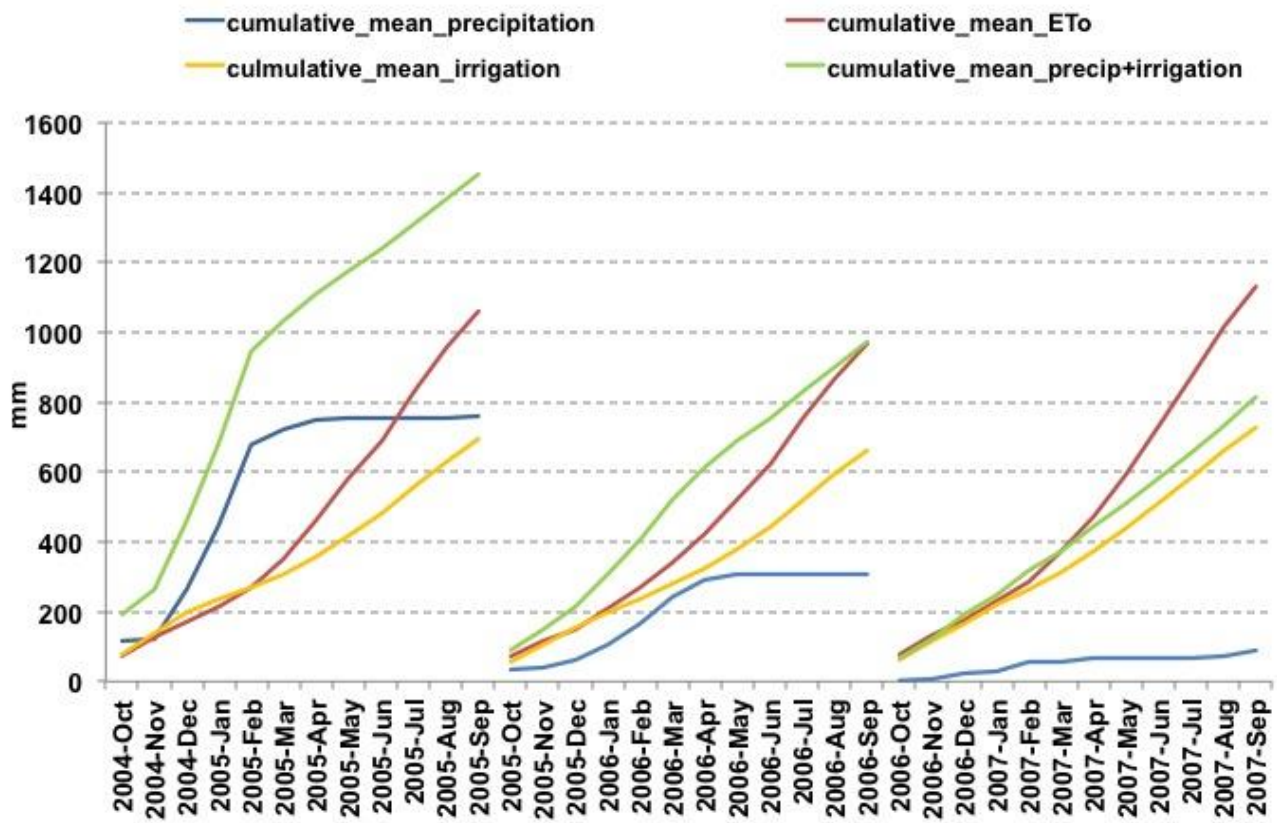


Figure 4. Mean cumulative precipitation, ETo, and SFR irrigation across all postal carrier routes in the City of Los Angeles.

Table 1. Maximum R² 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

Note: regression models were statistically significant at p -value<0.001.