Research article

Irrigation systems in smart cities coping with water scarcity: The case of Valdebebas, Madrid (Spain)

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ABSTRACT

This study is aimed at assessing the performance of irrigation systems in Valdebebas, an urban development located in Madrid (Spain), as an example of smart irrigation. Subsurface drip irrigation (SDI) is the major irrigation method, although surface drip irrigation (DI) is also applied in a small area. The irrigation scheduling is made by the park manager, using the plant water requirements based on the reference evapotranspiration retrieved from a nearby weather station, and a plant coefficient K_c . In this study, plant water requirements were estimated using the Water Use Classification of Landscape Species (WUCOLS) III method, in which plant water requirements are based on the composite of plant species and not on a single species, as in the case for classical crop coefficients. Water use efficiency is assessed by the relative water supply and the relative rainfall supply indicators. The results showed that the irrigation was better managed using the estimations of the park manager compared to the WUCOLS method although the irrigation scheduling is based only on the climatic information and does not consider other variables such as the soil water content.

1. Introduction

In arid and semiarid climates, conventional water resources (surface and subsurface water) have been traditionally used to irrigate parks, gardens, and sports facilities. They accounts for 60% of the total water consumption in urban areas (Brandt et al., 2017; Mini et al., 2014; Reyes-Paecke et al., 2019; Salvador et al., 2011).

Since urban water needs are high and conventional water resources are scarce, cities with a long dry season, such as Madrid, are seeking to maximize the sustainability of urban living by developing irrigation infrastructure that reuses treated wastewater from wastewater treatment facilities (Angelakis and Gikas, 2014; Ayuntamiento, 2018). However, the use of reclaimed wastewater does not ensure the optimum efficiency of the irrigation process. The criteria for operation in irrigation systems affect overall sustainability. Their lack of efficiency and the inappropriate irrigation scheduling can result either in over- or under-irrigation. For example, Salvador et al. (2011) observed that irrigation in Zaragoza's gardens (Spain) exceeded the water requirements by up to 225%. Martínez Gimeno (2014) reported that about 43% of water could be saved using an automated irrigation system at the Technical University of Valencia (Spain) by adjusting the irrigation time to the water needs of the most drought-sensitive species. Pérez-

Urrestarazu et al. (2018) reported that some gardens in the Real Alcazar historic parks in Seville (Spain) were overwatered by up to 700%, and others received only 32% of their total water requirements; these results could be caused by non-standardized irrigation and the use of different irrigation methods across the gardens. The same trends have been also reported in other Mediterranean climate areas, such as Chile (Reyes-Paecke et al., 2019), California (Mini et al., 2014), and Australia (Nouri et al., 2013).

The term 'smart irrigation' has been defined, as part of the global concept of smart cities, in the context of water scarcity and the need for water use efficiency. Smart irrigation includes a group of techniques and criteria aimed at optimal irrigation management, which requires an accurate determination of plant water requirements and optimal efficiency of irrigation systems in order to minimize water losses and to provide optimum use of the water supplies.

The accurate estimation of plant water requirements is a key factor. Plant water requirements can be measured using indirect methods, such as the use of reference evapotranspiration (ET_0) particularized to ornamental species (Costello, 1994), or direct methods, using either soil moisture sensors (SMS) (Patil and Desai, 2013), or satellite-based systems (Hof and Wolf, 2014; Mateos et al., 2013). Applying the selected methods can reduce water demand. For example, Haley et al. (2007)

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observed that water consumption was reduced by 30%, compared with traditional management, when the irrigation system was adjusted to the ET_0 of the previous year, and was reduced by 50% using SMS.

Optimum automation of irrigation systems and real-time monitoring are tools to achieve optimum efficiency, to minimize water losses, and to ensure maximum reuse. Recently, a number of studies have been carried out on the suitability and the benefits of monitoring and automation of irrigation systems (Todorovic et al., 2016). Some of these studies focus on techniques based on the Internet of Things for monitoring and controlling irrigation systems (Zhang, 2011). Smart controllers can achieve water use efficiency if they are coupled with smart design irrigation systems (Davis and Dukes, 2015).

In addition to the requirements for optimum management of the irrigation infrastructure, proper hydraulic design and operation of the irrigation systems is important for ensuring the sustainability of the entire process. Many studies have identified trickle irrigation as the most efficient irrigation system, if it is properly designed and operated (Vidana Gamage et al., 2018). The drops of water are discharged by emitters near the plant, either on or beneath the soil surface. Among the advantages of trickle irrigation systems are reduced water stress, ease of automation and fertilization, reduced costs of design and operation (Subbaiah, 2013), improved irrigation efficiency (Yao et al., 2011), and a significant reduction in the wetted soil surface (Moncef and Khemaies, 2016).

The design of the Valdebebas urban development in Madrid (Spain) was guided by the smart cities development criteria (Rodríguez-Sinobas et al., 2018). The urban parks are mostly irrigated with subsurface drip irrigation (SDI) and limited areas are irrigated using surface drip irrigation (DI). The operation of these systems is centrally automated through a personal computer with software connected to a local weather station from which real-time data is collected. In general, there is a lack of studies addressing the optimum operation criteria for smart irrigation systems. For example, in Valdebebas, despite the modern design of the installed infrastructure, the actual hydraulic performance of the irrigation system is not controlled so there are doubts about the actual efficiency of the smart infrastructure.

Therefore, this study is aimed at assessing the performance of the smart irrigation system.

2. Case study: Valdebebas urbanization

The urban parks and gardens of Valdebebas are located in northeast Madrid (Fig. 1). The climate of the Madrid metropolitan area is considered transitional between the Cold Semiarid and Mediterranean climates. According to the Köppen classification, the city has the Csa climatic type; rainfall is concentrated in autumn and spring (Fig. 2), with an average aggregated annual rainfall of 435.8 mm, and a mean temperature of 14.59 °C, calculated from 1970 to 2000.

The urban parks have an upper layer of sandy loam soil which holds the plant's roots. Several soil samples at different depths were collected for analysis of their physical properties, which are presented in Table 1, as follows: θ_{cc} is the soil water content at field capacity (which equals a matric suction head of 1/3 atm), θ_{pwp} is the soil water content at permanent wilting point (corresponding to a suction matric head of 15 atm), CF is the coarse fragments, and K_s is the hydraulic saturated conductivity.

The urban development design has incorporated xeriscaping concepts, such as the selection of plant species with low water requirements and tolerance to water stress conditions; the areas covered with plants were optimized, and the lawn areas were minimized. Fig. 3 shows some pictures of the urban parks.

The urban development includes 1065 ha of parks that are irrigated using reclaimed wastewater fed from two 5000 m³ tanks and two pumping stations. The irrigation system covers 20 ha of vegetation, divided into 34 single irrigation zones (Fig. 1). Control and measurement elements (Woltzman flow meter, a pressure reducer, pressure

sustainer valve, pressure transducer, and an automated-cleaning disc filter) are placed at the upstream end of each irrigation zone.

For each irrigation zone, several sectors were defined depending on the plants' physiology. Each irrigation system in the sectors is operated with an electric valve commanded by a Site Control software provided by RainBird < SUP > R < /SUP > (USA). The specific characteristics of each irrigation system are presented in Table 2.

The irrigation season usually begins in May and ends in October. Irrigation events are scheduled by the irrigation manager as follows: lawn is irrigated daily, bushes and deciduous shrubs are irrigated every other day, and trees are irrigated once or twice per week. The irrigation depth is determined by the reference evapotranspiration ET_0 , measured at the weather station located at Valdebebas, and the crop coefficients which are assigned by the irrigation manager considering his expertise in plant development. The assigned values for lawn (LAW) were 0.9, between June and August, and 0.8 for the other months. The values for mixed shrubs and bushes (COL), trees (TREE) and shrubs and flower collections (SHR) were 0.8, between June and August, and 0.7 for the remainder months. The time for each irrigation event is determined by the Site Control Software taking into account the water requirements and the selected irrigation frequency but it does not consider the soil water availability.

3. Methodology

In order to test the performance of the irrigation system and the suitability of the management of the irrigation network, the irrigation zones: 107, 108, 202, 203, 204, 301 and 302 (see Fig. 1), representative of the entire district, were selected and their water requirements were estimated with the WUCOLS III methodology (Costello and Jones, 2014).

The climatic data were recorded daily in 2017 from the weather station located at Valdebebas district.

3.1. Landscape water requirements

The WUCOLS III methodology estimates a landscape coefficient (K_L) using the water requirements of different plant species in a park. It is composed of three coefficients: K_d , the plant density coefficient, K_{mc} , the microclimate coefficient, and K_s , the plant species coefficient (see eq. (1)). The park water requirements, ET_L , are then determined by multiplying the reference evapotranspiration (ET_0) and K_L (eq. (2)).

$$K_L = K_s K_{mc} K_d \quad (1)$$

$$ET_L = ET_0 K_L \quad (2)$$

Plants with similar water requirements were grouped at the park design stage to optimize the irrigation efficiency. Hence, in order to estimate K_s for each park, the same value was considered for each group. Table 3 shows the groups, the species, the K_s for each specie (retrieved from Costello (1994); Costello and Jones (2014)), and the adopted K_s for each group. The K_s value (K_s -group, plant type) was calculated as the average of the K_s value of each specie within the group (K_s -specie). For the deciduous species, the K_s value was minored 20% outside the maximum demand period (April, May, October, and November).

The microclimate coefficient (K_{mc}) is based on the area occupied by surrounding open areas, dark pavements, walls reflecting solar radiation, shadows or open water bodies. K_d corresponds to the plant density coefficient which determines the leaf area exposed to transpiration. Table 4 presents the selected K_s and K_d values for each selected zone.

3.2. Irrigation performance

The performance of the irrigation management was assessed with two indicators: the relative water supply (RWS) (eq. (3)) and the

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Fig. 1. Location of Valdebebas urban development and their irrigation zones.

Fig. 2. Average climatic data collected from the weather station Madrid-Retiro

Table 1
Physical properties from planting soil in the urban parks.

Depth	θ_{CC}	θ_{PWP}	Density	(1-CF) (%)	K_s (mm min ⁻¹)
(cm)	(cm ³ cm ⁻³)	(cm ³ cm ⁻³)	(g cm ⁻³)		
0–15	0.13	0.09	0.98	64	3.67
16–35	0.11	0.07	1.25	70	2.01
35	0.18	0.12	1.55	75	0.75

relative rainfall supply (RRS) (eq. (4)).

$$RWS = \frac{H_b + P_e}{ET} = \frac{H_b + 0.75(P_5)}{ET} \quad (3)$$

$$RRS = \frac{P_e}{ET} \quad (4)$$

Where: ET is the water requirement, H_b the applied irrigation depth and P_e the effective precipitation, which was estimated as a percentage of the total precipitation greater than 5 mm, P_5 .

The index RWS is classified into three groups: stressed ($RWS < 0.7$), optimum ($0.7 < RWS < 1.5$) and overwatered ($RWS > 1.5$) (Levine, 1982). Thus, values close to 1 indicate optimal irrigation management.

The indicators were calculated from May to October 2017.

3.3. Water balance

The water balance, as it is defined in Eq. (5), was used to estimate the variation in soil water content $\Delta\theta$ during the irrigation season which would correspond to soil water availability for plants. The water balance was computed using daily data from the Valdebebas weather station.

$$I + P_e = ET + D + \Delta\theta \quad (5)$$

where: I is the irrigation, P_e the effective precipitation, ET the

Table 2
Plant types and irrigation systems.

Plant typology	Irrigation system	Emitter nominal flow rate	Emitter spacing	Irrigation depth
		(L h ⁻¹)	(m)	(mm h ⁻¹)
Lawn	SDI	0.8	0.15 × 0.15	20.7
Bushes	SDI	0.7	0.3 × 0.3	9.2
Trees-parks	SDI	2.3	0.3 × 0.3	20.7
Trees-avenue	DI - SDI	2.3	0.5 × 0.5	9.0
Shrubs -Deciduous	DI	2.3	0.5 × 0.5	9.0
Mixed shrubs-Roundabouts	DI	1.0	0.3 × 0.3	9.2

evapotranspiration, D the seepage and $\Delta\theta$ the soil water content variation between two intervals.

4. Results

The following results refer to the data collected daily from the weather station at Valdebebas from May to October 2017.

4.1. Comparison between estimated requirements and volumes applied

The K_C and K_L coefficients are depicted for each plant type in Fig. 4 for the evaluated sectors.

The K_L coefficients are smaller than K_C except in the LAW category and its K_s value assigned by the WUCOLS III procedure is about 0.8. If the irrigation depth were determined with the coefficients presented in Fig. 4, the WUCOLS III procedure would give smaller irrigation requirements than those calculated using K_C . Therefore, if the water requirements for TREE, COL, SHR were estimated using K_L , they would be reduced by 36%, 43%, and 39%, respectively, and water requirements

Fig. 3. Examples of landscaping characteristics in Valdebebas.

Table 3
Adopted K_s coefficient for each species' group.

Plantation type	Genus	sp.	Variety	K_s specie	K_s Group-Plant type
COL	<i>Viburnum</i>	<i>tinus</i>		0.5	0.5
	<i>Viburnum</i>	<i>tinus</i>	'Eve Price'	0.5	
	<i>Viburnum</i>	<i>tinus</i>	'Purpureum'	0.5	
	<i>Escallonia</i>	ssp.	'Iveyi'	0.5	0.45
	<i>Lonicera</i>	<i>nitida</i>	'Elegant'	0.4	
	<i>Pittosporum</i>	<i>tobira</i>	'Nana'	0.45	0.45
	<i>Festuca</i>	<i>glauca</i>		0.4	0.4
	<i>Tulbaghia</i>	<i>violacea</i>		0.4	
	<i>Tulbaghia</i>	<i>violacea</i>	'White'	0.4	
	<i>Lavandula</i>	<i>angustifolia</i>	'Hitcote Pink'	0.3	
	<i>Gaura</i>	<i>lindheimeri</i>		0.5	
	<i>Gaura</i>	<i>lindheimeri</i>	'Siskiyou Pink'	0.5	
	<i>Cistus</i>	<i>X skanbergi</i>		0.3	
	<i>Cistus</i>	<i>florentinus</i>		0.3	
	<i>Liriope</i>	<i>muscaris</i>		0.5	0.4
	<i>Iris</i>	<i>germanica</i>		0.3	
	<i>Pennisetum</i>	<i>alopecuroides</i>		0.2	
	<i>Tulbaghia</i>	<i>violacea</i>		0.4	
	<i>Tulbaghia</i>	<i>violacea</i>	'White'	0.4	
	<i>Hedera</i>	<i>hibernica</i>	'Sagittifolia'	0.5	
SHR	<i>Chrysanthemum</i>	<i>leucanthemum</i>		0.5	
	<i>Iris</i>	ssp.	Multiples	0.6	
	<i>Hemerocallis</i>	ssp.	Multiples	0.5	
	<i>Trachelospermum</i>	<i>jasminoides</i>	'Tricolor'	0.5	
	<i>Rosa</i>	ssp.		0.5	
LAW TREE	<i>Cynodon</i>	<i>dactylon</i>		0.8	
	<i>Acacia</i>	<i>dealbata</i>		0.2	
	<i>Acer</i>	<i>platanoides</i>		0.6	
	<i>Cercis</i>	<i>siliquastrum</i>	'Multistem'	0.2	
	<i>Lagerstroemia</i>	<i>indica</i>	'Rosea'	0.4	
	<i>Morus</i>	<i>alba</i>	'Fruitless'	0.4	
	<i>Sophora</i>	<i>japonica</i>		0.4	
	<i>Sorbus</i>	<i>aria</i>		0.5	
	<i>X Chitalpa</i>	<i>tashkentensis</i>	'Summer bells'	0.4	

Table 4
Density and microclimate factors calculated for the study sectors.

Sector	K_d	K_{mc}
107	0.8	0.8
108	0.8	0.8
202	0.8	1.0
203	0.8	0.9
204	0.8	0.9
301	1.1	1.0
302	1.1	1.0

would increase by 17% for LAW.

4.2. Irrigation performance

As was expected for a Mediterranean climate, the mean RRS value is small (0.23), and a constant deficit during the study season was observed (see Fig. 6). Only 74 mm of ET_0 (923 mm) was supplied by rainfall during the study season.

Fig. 5 shows that RRS was small and no difference was observed either among plant categories or zones. July showed the largest value coinciding with the occurrence of two heavy storm events. Thus, it is highlighted that plants need irrigation for their development.

The RWS values presented in Table 5 were determined considering the actual irrigation depth H_b and two hypotheses for ET estimation: (1) using the K_C assigned by the garden's manager ($ET = ET_{K_C}$), and (2) using the K_L values assigned by WUCOLS III ($ET = ET_{K_L}$).

Table 5 shows that estimations of both K_C and K_L lead to over-irrigation in July and August although their estimations for the other months are more accurate. The K_C values for TREE and to a lesser extent for LAW, yielded optimum values compared to other plant types. Given

that H_b is the same for both RWS_{K_C} and RWS_{K_L} , the higher RWS_{K_L} values point out that much higher over irrigation would result if K_L were used to calculate the irrigation requirements.

Fig. 6 presents the percentage of water not wasted when ET_{K_C} is used to estimate the irrigation requirements instead of ET_{K_L} .

Water savings of 200% are observed in TREE in August. K_L results in lower water consumption for LAW in October.

4.3. Soil water balance

Fig. 7 presents the variation in the soil water content during the irrigation season.

The amount of water that reaches the soil ($I + Pe - ET - D$) maintains soil water content between the field capacity (FC) level and the lower limit of the easily available water range (EA). As shown in Fig. 7, the soil water content decreased below the threshold of the plant available water during the late spring, in all plant categories except in LAW, which was the category in which the least differences were observed between RWS_{K_L} and RWS_{K_C} (see Fig. 5). The irrigation events increase the soil water content above the saturated level which increases the risk of surface runoff and root damage.

5. Discussion

In this paper we have study the suitability in the operation of a smart irrigation system. For this purpose, we have compared the current practices of the garden's manager using a set of K_C coefficients with the K_L coefficients estimated through the WUCOLS III methodology. We have analyzed the volume and the schedule of the applied irrigation and assessed the soil water availability.

In general, the plants water requirements determined by either K_C or K_L , resulted in over-irrigation. The water demand estimated by K_C

Fig. 4. K_c and K_l coefficients for each plant category and sectors: 107 (a), 108 (b), 202 (c), 203 (d), 204 (e), 301 (f), and 302 (g).

Fig. 5. Variation in RRS during the season for the evaluated sectors and plant categories: COL (a), LAW (b), SHR (c) and TREE (d).

Fig. 6. Differences between RWS_{KL} and RWS_{Kc} in COL (a), LAW (b), SHR (c) and TREE (d).

Table 5

RWS for programmed crop coefficient K_c and proposed landscape coefficient K_L .

Sector		RWS ET_c						RWS ET_L					
Typology		May	Jun	Jul	Aug	Sep	Oct	May	Jun	Jul	Aug	Sep	Oct
107	COL	1.33	1.95	1.56	1.94	1.76	1.63	1.61	2.92	2.38	2.67	2.84	2.04
	LAW	0.97	1.54	1.26	1.41	1.71	1.27	0.92	1.65	1.72	1.51	1.90	0.81
	SHR	1.21	1.82	1.46	1.77	1.86	1.51	1.61	2.92	2.38	2.67	2.84	2.04
	TREE	0.89	1.42	1.30	1.3	1.69	1.01	2.39	4.05	3.19	4.31	3.05	2.76
108	COL	1.33	1.95	1.56	1.94	1.93	1.63	1.45	2.63	2.14	2.41	2.55	1.84
	LAW	0.89	1.42	1.30	1.3	1.69	1.01	0.82	1.48	1.55	1.36	1.71	0.73
	SHR	0.97	1.65	1.35	1.51	1.71	1.27	1.45	2.63	2.14	2.41	2.55	1.44
	TREE	1.25	1.71	1.51	1.73	1.91	1.37	2.15	3.64	2.87	3.88	2.75	2.48
204	COL	1.25	1.71	1.51	1.73	1.91	1.37	1.43	2.6	2.11	2.38	2.52	1.81
	LAW	0.97	1.65	1.35	1.51	1.71	1.27	1.09	1.95	2.04	1.79	2.25	0.97
	SHR	1.21	1.82	1.46	1.77	1.86	1.51	1.43	2.60	2.11	2.38	2.52	1.81
	TREE	0.89	1.42	1.30	1.30	1.69	1.01	2.02	3.42	2.69	3.64	2.58	2.33
203	COL	1.25	1.71	1.51	1.73	1.91	1.37	1.43	2.6	2.11	2.38	2.52	1.81
	LAW	0.97	1.65	1.35	1.51	1.71	1.27	1.36	2.44	2.55	2.24	2.82	1.21
	SHR	0.97	1.65	1.35	1.51	1.71	1.27	1.40	2.52	2.33	2.31	2.67	1.51
	TREE	0.89	1.42	1.30	1.30	1.69	1.01	1.78	3.10	2.47	3.10	2.62	2.13
202	COL	1.11	1.68	1.43	1.62	1.81	1.32	1.34	2.42	1.97	2.21	2.35	1.69
	LAW	1.15	1.75	1.41	1.68	1.82	1.45	1.26	2.27	2.38	2.09	2.62	1.12
	SHR	0.91	1.49	1.33	1.36	1.70	1.06	1.43	2.60	2.11	2.38	2.52	1.81
	TREE	0.92	1.53	1.35	1.40	1.70	1.10	1.93	3.27	2.57	3.48	2.47	2.23
301	COL	1.33	1.84	1.47	1.84	1.93	1.63	1.04	1.89	1.54	1.73	1.83	1.32
	LAW	0.97	1.54	1.26	1.41	1.71	1.27	1.09	1.95	2.04	1.79	2.25	0.97
	SHR	1.15	1.8	1.45	1.73	1.82	1.45	1.04	1.89	1.54	1.73	1.83	1.32
	TREE	0.89	1.42	1.30	1.30	1.69	1.01	1.39	2.36	1.85	2.51	1.78	1.61
302	COL	1.25	1.71	1.51	1.73	1.91	1.37	1.15	2.08	1.69	1.90	2.02	1.45
	LAW	0.97	1.54	1.26	1.41	1.71	1.27	1.09	1.95	2.04	1.79	2.25	0.97
	SHR	1.11	1.68	1.43	1.62	1.81	1.32	1.13	2.05	1.78	1.87	2.08	1.33
	TREE	0.97	1.65	1.35	1.51	1.71	1.27	1.70	2.88	2.27	3.07	2.17	1.96

Fig. 7. Soil water balance for each plant type for (a) COL; (b) TREE; (c) SHR and (d) LAW.

and K_L would have been 78646 m³ and 50918 m³, respectively. Thus, a 35.2% (27728 m³) of the consumed water would have been saved using the first coefficient. The highest savings would correspond to SHR and COL with 15703 y 12092 m³, respectively.

As it was stated in the introduction section, some studies reported that automated system and/or adequate operational criteria resulted in significant water savings (Pérez-Urrestarazu et al., 2018; Salvador et al., 2011; Martínez Gimeno, 2014). The Valdebebas' results agree with them and, since its irrigation system is fully controlled and automated, they also highlight the need for a proper determination of irrigation depth. Although nowadays municipalities, sport fields and private urbanizations are provided with technological devices for precision irrigation, over irrigation results a common practice when a proper water control is lacked, and also the irrigation scheduling is based on either the technicians' experience or the appearance of ornamental plants. However, when water is scarce, they get worried and make investments to optimize urban water use.

The WUCOLS III method may have the advantage to provide a more accurate estimation of the water demands compared to the common K_C methods, since it considers three coefficients in the determination of the reference evapotranspiration. Nonetheless, the WUCOLS III method can also generate an over-estimation of the water use requirements if K_s , K_d or K_{mc} are not properly determined. Since the K_s values are determined using the average value for the existing plants, K_d and K_{mc} could be adapted for specific plant types.

Otherwise, the lack of standards for K_s , K_d and K_{mc} estimation is a disadvantage to determinate K_L with accuracy. The K_s coefficient, either assigned by the maintenance personnel (once the garden set up is finished) or by the landscaper (at the design stage), regards to generic plant species and, its extrapolation to the specific plant varieties found in gardens would have limitations. The K_d coefficient is associated to

the leaf area index surface, which is difficult to measure in ornamental gardens due to their heterogeneity. Finally, the K_{mc} coefficient is associated to the temperature and wind variation across the park, which results in technical difficulties for its calculation since gardens and parks are heterogeneous not only by their multiple plant species but also by their structure.

The information available from the weather station and the tools for controlling the irrigation network (both the software and the operating elements) undoubtedly provided enough flexibility to manage the irrigation in a more precise and accurate way. Since many plant types are over-irrigated during certain months, further studies could be conducted to analyze divergence between K_L and K_C . Provided that the method for K_s estimation in this work is reasonable and that the K_d value, or plant density is considered constant, the comparison between K_L and K_C could be used to deduce the optimum K_{mc} values for each sector that could provide valuable information about the local differences among sectors.

The accuracy and reliability in the estimation of water requirements on parks and gardens by WUCOLS III could be improved considering some tools such as satellite thermal images or the Normalized Difference Vegetation Index (NDVI). The first can help to monitor temperature variation within a microclimate (Alchanatis et al., 2010; Jones et al., 2009). The NDVI can be used to estimate the plants' leaf density and their evapotranspiration (Li et al., 2019; Segovia-Cardozo et al., 2019). Although these tools are used for horticultural crops they are seldom developed for ornamental species. Likewise, green areas could adopt precision irrigation by monitoring "in situ" soil water content, with soil water probes. Thus, the soil water content data will be transferred to the irrigation central station, and lately used for the determination of the doses and the frequency of irrigation.

6. Conclusions

In this paper, the performance of a smart irrigation system was assessed. The irrigation infrastructure, which is located at the Valdebebas urban development in Madrid (Spain), is made up of trickle irrigation emitters (DI) and SDI units. The irrigation system is fed by a reclaimed wastewater network and is automated for control of the irrigation efficiency. The irrigation scheduling and operation is managed by the maintenance staff who calculate the crop coefficients and the frequency of the irrigation events based on the climatic variables measured at a local weather station. The human decisions are supported by control software that operates the whole irrigation system.

Despite the number of control devices and the automation of the system, the on-the-ground decisions relating to the assignment of crop coefficients have a significant effect on the efficiency of irrigation. The estimations carried out in the present work showed that the use of the landscape coefficient leads to over-irrigation in most of the study areas and a subsequent reduction in water use efficiency. The operating decisions are based solely on climatic variables, and not on the soil water availability. This can lead to inefficient management of the irrigation because the saturation level is often reached, which leads to surface runoff or, alternatively, under-irrigation leading to the soil water content dropping below the easily available water threshold.

Therefore, smart irrigation systems and, specifically, the study irrigation system in Valdebebas, allow for automation and control of the irrigation system which helps to optimize the irrigation operating conditions. However, the on-the-ground decisions, such as the determination of the crop coefficient used to determine the irrigation depth, do influence the efficiency of the water use.

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