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de Alcalá

COMISIÓN DE ESTUDIOS OFICIALES  
DE POSGRADO Y DOCTORADO

## ACTA DE EVALUACIÓN DE LA TESIS DOCTORAL

Año académico 2019/20

DOCTORANDO: ZALACÁIN DOMENCH, DAVID

D.N.I./PASAPORTE: \*\*\*\*8093Y

PROGRAMA DE DOCTORADO: D411-CIENCIAS

DPTO. COORDINADOR DEL PROGRAMA: FÍSICA Y MATEMÁTICAS

TITULACIÓN DE DOCTOR EN: DOCTOR/A POR LA UNIVERSIDAD DE ALCALÁ

En el día de hoy 13/12/19, reunido el tribunal de evaluación nombrado por la Comisión de Estudios Oficiales de Posgrado y Doctorado de la Universidad y constituido por los miembros que suscriben la presente Acta, el aspirante defendió su Tesis Doctoral, elaborada bajo la dirección de **ANTONIO SASTRE MERLÍN // SILVIA MARTÍNEZ PÉREZ**.

Sobre el siguiente tema: *EFFECTS OF RECLAIMED WATER IRRIGATION IN THE SOIL-PLANT SYSTEM OF MADRID URBAN PARKS*

Finalizada la defensa y discusión de la tesis, el tribunal acordó otorgar la CALIFICACIÓN GLOBAL<sup>1</sup> de (no apto, aprobado, notable y sobresaliente): **SOBRESALIENTE**

Alcalá de Henares, 13 de DICIEMBRE de 2019

EL PRESIDENTE

Fdo.: JOSÉ MARTÍNEZ FERNÁNDEZ

EL SECRETARIO

Fdo.: EUGENIO MOLINA NAVARRO

EL VOCAL

Fdo.: MARÍA JOSÉ MARQUÉS PÉREZ

Con fecha 20 de enero de 2020 la Comisión Delegada de la Comisión de Estudios Oficiales de Posgrado, a la vista de los votos emitidos de manera anónima por el tribunal que ha juzgado la tesis, resuelve:

- ☒ Conceder la Mención de "Cum Laude"  
☐ No conceder la Mención de "Cum Laude"

FIRMA DEL ALUMNO,

Fdo.: ZALACÁIN DOMENCH, DAVID

La Secretaria de la Comisión Delegada

<sup>1</sup> La calificación podrá ser "no apto" "aprobado" "notable" y "sobresaliente". El tribunal podrá otorgar la mención de "cum laude" si la calificación global es de sobresaliente y se emite en tal sentido el voto secreto positivo por unanimidad.

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En aplicación del art. 14.7 del RD. 99/2011 y el art. 14 del Reglamento de Elaboración, Autorización y Defensa de la Tesis Doctoral, la Comisión Delegada de la Comisión de Estudios Oficiales de Posgrado y Doctorado, en sesión pública de fecha 20 de enero, procedió al escrutinio de los votos emitidos por los miembros del tribunal de la tesis defendida por **ZALACÁIN DOMENCH, DAVID**, el día 13 de diciembre de 2019, titulada, *EFFECTS OF RECLAIMED WATER IRRIGATION IN THE SOIL-PLANT SYSTEM OF MADRID URBAN PARKS* para determinar, si a la misma, se le concede la mención "cum laude", arrojando como resultado el voto favorable de todos los miembros del tribunal.

Por lo tanto, la Comisión de Estudios Oficiales de Posgrado y Doctorado **resuelve otorgar** a dicha tesis la

**MENCIÓN "CUM LAUDE"**

EL VICERRECTOR DE INVESTIGACIÓN Y TRANSFERENCIA

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## DILIGENCIA DE DEPÓSITO DE TESIS.

Comprobado que el expediente académico de D./D<sup>a</sup> \_\_\_\_\_  
reúne los requisitos exigidos para la presentación de la Tesis, de acuerdo a la normativa vigente, se  
procede, con fecha de hoy a registrar el depósito de la tesis en el Servicio de Estudios Oficiales de  
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Alcalá de Henares a \_\_\_\_\_ de \_\_\_\_\_ de 20\_\_\_\_



Pilar de la Vega Gallego  
Fdo. El Funcionario



**Doctoral Dissertation**

Tesis doctoral

**Effects of reclaimed water irrigation in the  
soil-plant system of Madrid urban parks**

Efectos del riego con agua regenerada en el sistema  
suelo-plantas de los parques urbanos de Madrid

**David Zalacáin Domench**

Universidad de Alcalá - 2019



Universidad de Alcalá

Programa de Doctorado en Ciencias (D411)

Effects of reclaimed water irrigation in the  
soil-plant system of Madrid urban parks

Tesis doctoral presentada por:

**DAVID ZALACÁIN DOMENCH**

Directores:

**ANTONIO SASTRE MERLÍN**

**SILVIA MARTÍNEZ PÉREZ**

Alcalá de Henares, septiembre de 2019



Antonio Sastre Merlín y Silvia Martínez Pérez, Profesores Titulares de “Geodinámica Externa” del Departamento de Geología, Geografía y Medio Ambiente de la Universidad de Alcalá y directores de esta Tesis Doctoral,

**HACEN CONSTAR**

Que el trabajo descrito en la presente memoria, titulado *“Effects of reclaimed water irrigation in the soil-plant system of Madrid urban parks”*, ha sido elaborado bajo su dirección por el doctorando David Zalacáin Domench en la Unidad Docente de Geología del referido departamento, dentro del Programa de Doctorado “Ciencias (D411)”. Ha sido realizada por compendio de artículos, reuniendo los requisitos exigidos a este tipo de tesis, así como los requisitos científicos de originalidad y rigor metodológicos adecuados para ser defendida ante el correspondiente tribunal.

Alcalá de Henares, a 1 de octubre de 2019



Antonio Sastre Merlín



Silvia Martínez Pérez

D/D<sup>a</sup> María José Ortiz Beviá, Coordinadora de la Comisión Académica del Programa de Doctorado en Ciencias

**HAGO CONSTAR** que la Tesis Doctoral titulada 'Effects of reclaimed water irrigation in the soil-plant system of Madrid urban parks' presentada por D **David Zalacaín Domenech** bajo la dirección de los Dr **Antonio Sastre Merlín y Silvia Martínez Pérez** ha sido realizada por compendio de artículos, reuniendo los requisitos exigidos a este tipo de tesis, así como los requisitos científicos de originalidad y rigor metodológicos para ser defendida ante un tribunal. Esta Comisión ha tenido también en cuenta la evaluación positiva anual del doctorando, habiendo obtenido las correspondientes competencias establecidas en el Programa.

Para que así conste a los efectos del depósito de la tesis, se firma en Alcalá de Henares a 15 de Octubre de 2019



Fdo.: María José Ortiz Beviá



**INFORME DEL DIRECTOR/A DE TESIS SOBRE "ANÁLISIS DE COINCIDENCIAS"  
DE LA TESIS DOCTORAL A TRAVÉS DEL PROGRAMA TURNITIN**

Antonio Sastre Merlín y Silvia Martínez Pérez, directores de la Tesis Doctoral realizada por el doctorando David Zalacáin Domench y que tiene por título *"Effects of reclaimed water irrigation in the soil-plant system of Madrid urban parks"*,

AUTORIZAN la defensa de la referida Tesis Doctoral.

El trabajo presentado ha sido analizado por la plataforma TURNITIN, arrojando un porcentaje de coincidencias del 72 %.

Justificación de la autorización (obligatorio en caso de que el porcentaje supere el 24%):

El elevado porcentaje de coincidencias se debe a que el documento de Tesis ha sido realizado por compendio de artículos científicos publicados en revistas de impacto de reconocido prestigio. Del porcentaje arriba citado, un 58 % corresponde a los tres artículos compendiados.

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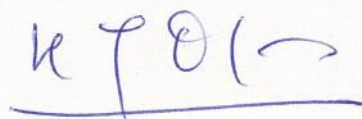
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*A Maritxu y Miguel*

*Caminante, son tus huellas  
el camino y nada más;  
Caminante, no hay camino,  
se hace camino al andar.*

*Al andar se hace el camino,  
y al volver la vista atrás  
se ve la senda que nunca  
se ha de volver a pisar.*

*Caminante, no hay camino,  
sino estelas en la mar.*

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# Abbreviations

<b>BD</b>	Bulk density
<b>CFU</b>	Colony Forming Units
<b>CND</b>	Counting Number Drops
<b>DW</b>	Drinking Water
<b>EC</b>	Electrical Conductivity
<b>ECe</b>	Plant specific threshold soil salinity
<b>ECw</b>	Electrical Conductivity of the applied irrigation water
<b>ET<sub>0</sub></b>	Evapotranspiration
<b>ESP</b>	Exchangeable Sodium Percentage
<b>ICP-MS</b>	Inductively Coupled Plasma Mass Spectrometry
<b>kPa</b>	Kilopascal
<b>LR</b>	Leaching requirement
<b>mPa</b>	Megapascal
<b>nd</b>	Not detected
<b>N<sub>TOT</sub></b>	Total Nitrogen
<b>NTU</b>	Nephelometric Turbidity Units
<b>PEMA</b>	Emperatriz María de Austria park
<b>PEMA_DW</b>	Plot of PEMA irrigated with drinking water
<b>PEMA_RW</b>	Plot of PEMA irrigated with reclaimed water
<b>PGW</b>	Garrigues Walker park
<b>PGW_DW</b>	Plot of PGW irrigated with drinking water
<b>PGW_RW</b>	Plot of PGW irrigated with reclaimed water
<b>RW</b>	Reclaimed water
<b>SAR</b>	Sodium adsorption ratio
<b>SOM</b>	Soil organic matter
<b>TDS</b>	Total dissolved solids
<b>TN</b>	Total Nitrogen
<b>TP</b>	Total porosity
<b>UV-Vis</b>	Ultraviolet-visible spectrophotometry
<b>WSA</b>	Water stable aggregates

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# Abstract

Water scarcity in many regions of the world is one of the greatest crises that mankind needs to address. The steady increase of water consumption and the decrease of available water resources are the main factors that determine it. This scenario leads to a paradigm shift: circular economy, where waste will become resources. Therefore, water reuse plays a fundamental role in circular economy.

Reclaimed water irrigation has become a long-standing practice over the world, especially among water deficit areas such as Spain. One of the first cities in Spain that started using reclaimed water to irrigate its urban parks was Madrid. Since the beginning of the 2000s, the City Council has developed a vast system of pipes and deposits to irrigate most of its parks with reclaimed water.

Despite its great advantages, water reuse could involve some risks. Reclaimed water irrigation, more mineralized than drinking water, may produce adverse effects in soils and plants, including the presence of pathogens and chemical contaminants as well as salinization, impacts on soil structure and effects on vegetation.

Therefore, the main objective of this Doctoral Dissertation was to assess the effects of reclaimed water irrigation in the soil-plant system of urban parks of Madrid (Spain).

To that end, this research was carried out along six successive years (2012–2017) in two public urban parks of Madrid: Emperatriz María de Austria Park and Garrigues Walker Park. Both were irrigated with reclaimed water since 2002 and 2012, respectively. Furthermore, two plots from each park were irrigated with reclaimed water (RW) and two other plots with drinking water (DW). Samples of irrigation water, soil solution, soil and leaves of four plant species –cedar, grass, hackberry and *Photinia*– were taken for further analysis.

Results achieved showed that reclaimed water of Madrid was adequate for irrigation according to international water quality standards. However, the use of reclaimed water to irrigate urban parks was potentially leading to a modification of some soil properties. The park which has been irrigated with reclaimed water for 15 years showed a slight soil salinization ( $EC > 2 \text{ dS m}^{-1}$ ). Furthermore, there was a steady increase of  $\text{Cl}^-$  (157%),  $\text{Na}^+$

(180%), SAR (127%) and EC (69%) in soils that were irrigated for 5 years with reclaimed water. Whereas in plots irrigated with drinking water significant lower values ( $p < 0.05$ ) for these parameters were observed. Likewise, it caused an increase of microaggregate stability in the topsoil, while macroaggregate stability decreased after RW irrigation in the top and the deepest layer. Soil penetration resistance was significantly higher ( $p < 0.05$ ) and infiltration rate was lower in the RW plot.

On the other hand, soil porosity results showed that there was no influence of the kind of irrigation water used. Furthermore, there was no soil sodification in RW plots and lower values of micronutrient concentration in soils were obtained when compared with other studies on reclaimed water irrigation in urban parks.

Regarding vegetation, Cl (%) leaf content was significantly higher ( $p < 0.05$ ) in those hackberries and *Photinias* irrigated with RW in comparison with those irrigated with DW. However, for Na (%) leaf content, there were only significant differences for cedars irrigated with RW versus DW in PGW. In most of the cases salt concentration in leaves were below the threshold when plants start to show injuries. Thus, no major salt stress symptoms were observed. Likewise, foliar micronutrient content of cedar leaves was nearly always within the optimum parameters. The statistical analysis carried out showed no correlation between micronutrient concentration in irrigation water and cedar leaves, thus cedar decline cannot be attributed to the input of these micronutrients by reclaimed water.

Moreover, irrigation with reclaimed water led to a grass biomass increase (on average of 66%), mainly due to the high proportion of nutrients received through the irrigation water, which acted as a fertilizer. Reclaimed water irrigation also contributed to a significant increase in nutrient removal by grass.

In conclusion, prolonged reclaimed water irrigation may be altering the features of the soil-plant system of urban parks. For that reason, and in order to avoid future problems, the use of reclaimed water in urban parks irrigation should be continuously monitored. One of the recommended measures proposed is to use an adequate leaching requirement (10%) in order to wash out the excessive salt accumulation in parks irrigated with reclaimed water. Eventually, the transfer of these research results to municipal managers may contribute to a better management of reclaimed water irrigation in urban parks, with the aim to prevent the likely appearance of adverse symptoms on sensitive plants.

# Resumen

Una de las grandes crisis que debe afrontar la humanidad hoy en día es la escasez de agua que tiene lugar en muchas partes del mundo. El incremento del consumo, unido al descenso en la disponibilidad del recurso son los principales factores que determinan la escasez hídrica. Este escenario conduce a un cambio de paradigma: la economía circular, donde los desechos se convierten en recursos. Así pues, la reutilización de agua juega un papel fundamental en la economía circular.

El riego con agua regenerada se ha convertido en una práctica habitual a lo largo del planeta, especialmente en aquellos países que sufren estrés hídrico, como es el caso de España. Así, una de las primeras ciudades en España en regar sus parques urbanos con agua regenerada fue Madrid. Desde principios de este siglo, el ayuntamiento ha construido una notable infraestructura de conducciones y depósitos reguladores con ese objetivo.

Sin embargo, y a pesar de sus grandes ventajas, la reutilización de aguas puede conllevar ciertos riesgos. El riego con agua regenerada, más mineralizada que el agua potable, puede producir efectos adversos en suelos y plantas, entre los que destacan la presencia de patógenos y contaminantes químicos, la salinización de los suelos y los impactos en su estructura y la afección a la vegetación.

Por lo tanto, el objetivo de esta Tesis ha sido realizar una evaluación de los efectos que produce el riego con agua regenerada sobre las características del suelo y la vegetación en los parques urbanos de la ciudad de Madrid.

Con ese fin se ha llevado a cabo este estudio durante seis años consecutivos (2012-2017), seleccionándose a tal efecto dos parques urbanos de Madrid: el Parque Emperatriz María de Austria y el Parque Garrigues Walker. Estos parques comenzaron a regarse con agua regenerada en el año 2002 y 2012, respectivamente. Se seleccionaron dos parcelas experimentales en cada parque, una regada con agua regenerada y otra, a modo de control, en la que se mantuvo el riego con agua potable. En cada una de las parcelas de estudio se tomaron periódicamente muestras del agua de riego, del agua del suelo, del suelo y de cuatro especies representativas de vegetación – almez, cedro, césped y *Photinia*–.

Los resultados obtenidos han mostrado que el agua regenerada de Madrid es adecuada para el riego conforme a los parámetros internacionales de calidad del agua de riego. Sin embargo, el uso de agua regenerada para el riego de parques urbanos puede conducir potencialmente a una modificación de las propiedades fisicoquímicas del suelo. Así, se ha observado una ligera salinización del suelo (conductividad eléctrica  $> 2 \text{ dS m}^{-1}$ ) tras quince años de riego con agua regenerada en uno de los parques. También se ha producido un aumento constante del  $\text{Cl}^-$  (157%),  $\text{Na}^+$  (180%), SAR (127%) y de la conductividad eléctrica (69%) de los suelos regados con agua regenerada durante cinco años, mientras que, en las parcelas regadas con agua potable, se han obtenido unos valores significativamente inferiores ( $p < 0.05$ ) para estos mismos parámetros. Asimismo, se ha producido un incremento en la estabilidad de los microagregados en superficie, a la vez que la estabilidad de los macroagregados disminuyó después del riego con agua regenerada en la capa más superficial y en la más profunda. La resistencia a la penetración del suelo ha resultado significativamente mayor ( $p < 0.05$ ) y la tasa de infiltración menor en la parcela regada con agua regenerada.

Por otra parte, los resultados relativos a la porosidad del suelo no han mostrado ninguna influencia del tipo de agua de riego utilizada. No se ha observado sodificación del suelo en las parcelas regadas con agua regenerada y la concentración de micronutrientes ha sido inferior que la descrita en otros estudios con este tipo de riego en parques urbanos.

En cuanto a la vegetación, se han obtenido valores significativamente superiores ( $p < 0.05$ ) de  $\text{Cl}$  (%) en las hojas de los almeces y *Photinias* regados con agua regenerada en comparación con aquellos regados con agua potable. Sin embargo, para el contenido foliar de  $\text{Na}$  (%), sólo ha habido diferencias significativas entre los cedros regados con agua regenerada y agua potable en el PGW. En general, la concentración de sales ha estado, en la mayoría de casos, por debajo del umbral en el que las plantas empiezan a mostrar daños. Por lo tanto, no se ha observado ningún síntoma significativo de estrés salino. De la misma manera, la concentración de micronutrientes en las hojas de los cedros se ha situado casi siempre dentro de los valores óptimos. El análisis estadístico realizado no ha mostrado correlación entre su concentración en el agua de riego y en las hojas de los cedros, por lo que el decaimiento que viene observándose en algunos ejemplares de esta especie no ha podido ser atribuido a la aportación de estos micronutrientes en el agua de riego.

Por otro lado, el riego con agua regenerada ha producido un incremento de la biomasa herbácea (de un 66% de media), fundamentalmente debido a la mayor proporción de nutrientes aportada por el agua de riego regenerada, que ha actuado como fertilizante. Por esta razón el riego con este tipo de agua también ha contribuido al significativo aumento en la eliminación de nutrientes por parte de la cubierta herbácea.

Para concluir, el riego prolongado con agua regenerada podría estar alterando las características del sistema suelo-planta de los parques urbanos. Por ello, a fin de evitar futuros problemas, el uso de este tipo de agua en el riego de parques urbanos debería ser controlado constantemente. Una de las medidas recomendadas que se propone es utilizar una fracción de lavado del suelo en torno al 10%, al objeto de lixiviar el exceso de acumulación de sales en los parques regados con este tipo de agua. Finalmente, la transferencia de los resultados de la investigación a los gestores municipales puede contribuir a un mejor manejo del riego con agua regenerada de los parques urbanos; y ello con el fin de dar prioridad a prevenir la posible aparición de síntomas adversos en aquellas especies de plantas más sensibles.





# CHAPTER 1

## General Introduction

## Water reuse

Water scarcity in many regions of the world is one of the greatest crises that mankind needs to address (Gu et al., 2019; Rijsberman, 2006). The steady increase of water consumption and the decrease of available water resources are the main factors that determine this crisis (Ricart and Rico, 2019). Climate change is increasing even more the existing stress, jeopardizing water security (Lavrnić et al., 2017; Tram VO et al., 2014).

This scenario leads to a paradigm shift: circular economy, where waste will become resources. Nowadays, circular economy has attracted attention worldwide as a way to overcome the current production and consumption model (Ghisellini et al., 2016). Geissdoerfer et al. (2017) defined circular economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. Therefore, water reuse is one of the main exponents of circular economy.

The first evidence of water reuse was documented in the island of Crete, during the Minoan Civilization times (3000– 1000 BC), where wastewater was used for agricultural irrigation (Angelakis et al., 2005). During the 14th and 15th centuries that practice was steadily extended in Europe, such as in Valencia (Spain) and in other northern countries as France, Germany and United Kingdom (Angelakis and Durham, 2008). In the nineteenth century, the introduction of large-scale wastewater carriage systems for discharge into surface waters led to indirect use of wastewater for inadvertent potable water supplies. This unplanned reuse, together with a lack of an adequate water and wastewater treatment, caused disastrous epidemics of waterborne diseases (Asano and Levine, 1996). However, it was not until the 20th century that water reuse became regulated, being the State of California a frontrunner in this issue in 1918 (Asano and Levine, 1996). Later on in the 1960s, technological advances in physical, chemical and biological processing of wastewater, led up to the beginning of the contemporary era of water reclamation and reuse (Asano et al., 2007). Therefore, in the last sixty years there has taken place a great increase in water reuse. Plenty of examples can be found all over the world (Miller, 2006).

Nowadays, many countries in arid and semi-arid areas have explored the use of reclaimed water to face water scarcity (Garcia and Pargament, 2015; Smith et al., 2018). Numerous developed countries have settled water policies based on maximizing the use of reclaimed water (Wang et al., 2017).

Singapore is a fine example of the great development of this practice. This southeast Asian city-state established in 2002 the *NEWater* strategy in order to reuse water for potable and non-potable uses (Tortajada and Nambiar, 2019). Other country that is taking a major stake in water reuse is China. The most populous country in the world has allocated substantial political and economic resources to encourage water reuse nationwide (Wang et al., 2017).

Regarding the European Union, Cyprus and Malta are the two member states leading in that field, where 89% and about 60% of their treated wastewater, respectively, were reused in 2006 (Lavrnić et al., 2017). However, Europe presents a clearly differentiated north-south reality. Southern European countries are promoting water reuse to cope with its structural water stress, whereas Northern European countries could mainly rely on its conventional water resources and introduce water reuse mostly for industrial purposes (TYPESA, 2013). Within these Southern countries, Spain highlights as the one with more water reuse projects, with a 45% of the schemes practicing reuse in the whole European Union (Water Reuse Europe, 2018). Furthermore, Hochstrat et al. (2006) according to their simulation, found that Spain presented the highest projected reuse potential within Europe.

In terms of legislation, Spain is one of the European leaders in water reuse (Kirhensteine et al., 2016). The first law that promoted water reuse in Spain was the Water Law 29/1985 (BOE, 1985) which stipulates in article 101 that: “The Government will set the basic conditions for direct water reuse, according to wastewater treatments, treated water quality and the intended uses”. Later on, the Royal Decree 1/2001 approved a new Water Law (BOE, 2001), which did not include any significant development.

It was not until 2007, when a specific regulation was approved: the Royal Decree 1620/2007, which establishes the regulation applicable to water reuse (BOE, 2007). This Royal Decree 1620/2007 provided a major boost in water reuse in Spain, as it develops many key issues. It starts with a set of key definitions and classifies the allowed uses in five categories: urban, agricultural, industrial, recreational and environmental. The use of reclaimed water is expressly forbidden for the following uses: human consumption (except for a disaster situation), specific uses of the food industry, hospital facilities, filter-feeding mollusks aquaculture, bathing waters, cooling towers and evaporation condensers, fountains and ornamental waters and for any other use that public health or environmental authorities may consider as a risk. The Decree also sets up water quality criteria for each intended use, including urban uses (Table 1.1). Furthermore, it explains the legal framework and the

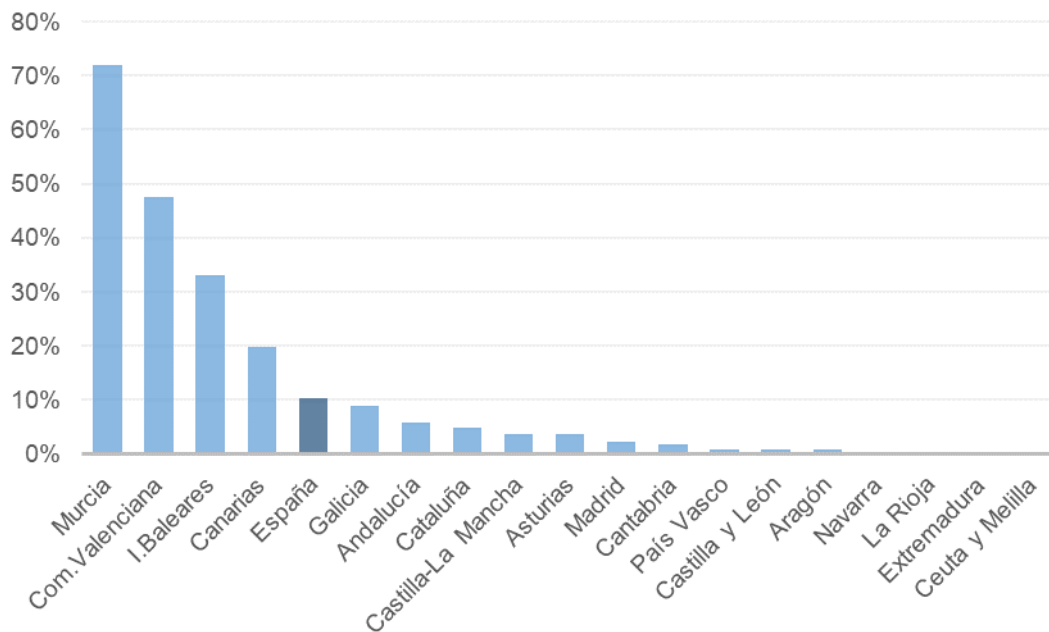
different roles of Public Administrations and the end users, specifying the procedure to get an authorization or a concession for water reuse.

**Table 1.1.** Water quality criteria for water reuse according to an urban use (Annex I.A. Royal Decree 1620/2007). CFU: Colony Forming Units; NTU: Nephelometric Turbidity Units.

Urban use	Maximum permissible value				Other criteria
	Intestinal nematodes (eggs/10L)	<i>Escherichia Coli</i> (CFU/100ml)	Suspended Solids (mg/L)	Turbidity (NTU)	
<b>1.1. Residential:</b> a) Private garden irrigation b) Discharge of toilet water	1	0	10	2	<i>Legionella spp.</i> 100 CFU/L (if there is a risk of aerosolization)
<b>1.2. Urban services:</b> a) Urban green areas irrigation b) Street cleaning c) Firefighting systems d) Car-wash facilities	1	200	20	10	

Spain produced 493,000,000 m<sup>3</sup> of reclaimed water in 2016, representing a 10.4% of the total volume of treated wastewater in the country (INE, 2019). This volume has remained relatively stable since 2006. INE (2019) has reported (2011-2016) that around 62% of reclaimed water were reused in agriculture, 19% in green and leisure areas, 7% in industry, 1% in street cleaning and the remaining 11% in other uses.

It should be noted that there are plenty of differences of water reuse volume between the Spanish regions (Fig. 1.1). As Fig. 1.1 shows, the Mediterranean regions are the leaders in water reuse. Although water reuse represents a small proportion of the total water demand on the whole country, it plays an essential role in some regions such as Canary Islands, Balearic Islands, Valencian Community or Region of Murcia (Paranychianakis et al., 2015).



**Fig. 1.1.** Percentage (%) of water reuse in different regions of Spain in 2016 (INE, 2019)

The structural water deficit in both Júcar and Segura river basins, together with an increasing demand due to the excessive urban growth in some coastal zones of southeastern Spain and the major presence of intensive agriculture, has made it necessary to include water reuse in its water management (Iglesias and Ortega, 2008). The Segura river basin (Murcia) is the only Spanish basin whose natural water resources cannot cover its water demands (Pedrero et al., 2010). Therefore, Region of Murcia is the Spanish leader in water reuse (Fig. 1.1). Its current 93 wastewater treatment plants, most of them with advanced tertiary treatments, are an example of their decided commitment in water reuse (Navarro, 2018). Consequently, that affects directly the economic improvement of the region (Gil-Meseguer et al., 2019).

The Valencian Community despite being the second region in percentage of water reuse is the Spanish leader in terms of reclaimed water total volume (200,000,000 m<sup>3</sup>). There are several examples of this water reuse along this region, such as the urban use in the city of Alicante (Melgarejo et al., 2016) and the traditional irrigation system of ‘*L’Horta*’ of Valencia (Ortega-Reig et al., 2014).

In Canary Islands, non-conventional resources are combined. Water reuse (19.8%) is combined with seawater desalination to confront water scarcity, as is the case of Lanzarote (Díaz et al., 2013).

Regarding Catalonia, there are several examples of water reuse. The ‘Consorti de la Costa Brava’ (Girona) was a pioneer institution on the promotion of reclaimed water, starting in 1989 with golf course irrigation (Asano et al., 2007). Later on, the water reuse project of El Prat de Llobregat (Barcelona) was a definitive commitment to an integrated water resources management in the Barcelona metropolitan area (Mujeriego et al., 2008). One of the main uses for this reclaimed water is aquifer recharge to perform a barrier against seawater intrusion (Cazurra, 2008; Pérez et al., 2011).

The case of Madrid region is paradigmatic. The Water reuse program of the Community of Madrid (Madrid Dpura, 2005-2010) was a milestone. It involved a final investment of €600 million (del Villar-García, 2017) including the construction and extension of wastewater treatment plants, the installation of tertiary treatment systems and the development of a distribution network for reclaimed water. Nowadays, there are 24 municipalities using reclaimed water, mainly for park irrigation, supplied by Madrid's water utility (Canal de Isabel II) through a reclaimed water network of 493 km (Community of Madrid, 2016).

## Background and relevance

The use of reclaimed water has become one of the main alternative resources in water-deficit countries to cope with water scarcity. Water reuse has been the subject of study in the light of its biological quality and, mainly, of its health safety (Becerra-Castro et al., 2015; O'Connor et al., 2008; Salgot, 2008). This is especially important when this reclaimed water is used in public green areas. However, it is essential to define its working conditions from physico-chemical quality requirements.

Reclaimed water irrigation provides a host of benefits: a constant and reliable water supply (Toze, 2006), an increase of water security (Rahman et al., 2016), a decrease of the pressure on sensitive water bodies (Miller, 2006), a reduction in pollutant discharges, better downstream water quality and savings in fertilizer applications (Anderson, 2003).

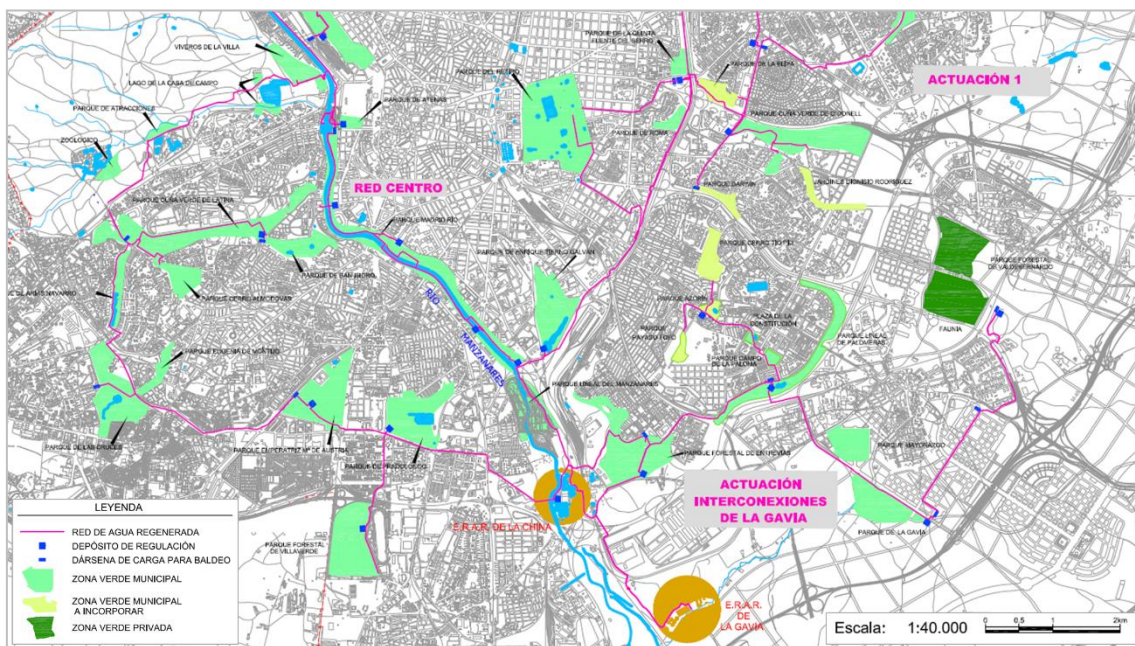
However, water reuse, if not properly managed, could involve some environmental and health risks (Rahman et al., 2016). Reclaimed water irrigation may produce adverse effects in soils and plants, including the presence of pathogens and chemical contaminants as well as salinization and impacts on soil structure (Toze, 2006).



Most of the studies about reclaimed water irrigation are focus on agriculture. However, landscape and vegetation development could be modified by reclaimed water irrigation. Despite there are few studies on urban parks, there is a lack of papers studying in depth this issue. That is why this Doctoral Dissertation would bring some light on this topic, clarifying the effects of reclaimed water irrigation in the soil-plant system of urban parks.

Madrid City Council started thinking of reclaimed water irrigation of its urban parks during the drought that took place in the middle of the 1990s (Iglesias and Ortega, 2008). Nowadays, the City Council has developed a vast system of more than 150 km of pipes and 65 deposits to irrigate most of its urban parks (1400 ha) with reclaimed water. In 2015, 6,600,000 m<sup>3</sup> of wastewater were reclaimed, 78% was intended for green area irrigation (Fig. 1.2) and the 22% remaining for street and sewage cleaning (Madrid City Council 2019).

In 2009, due to the decline of several cedars, Madrid City Council wanted to undertake an in-depth study in some parks irrigated with reclaimed water and signed a partnership agreement with a research team from the University of Alcalá. Therefore, this work is framed within the collaboration agreements signed between the University of Alcalá and the operating companies of the irrigation and landscape service for Madrid City Council: IMESAPI SA (2009-2013) and FCC (UTEs 5 y 6) (2014-2017).



**Fig. 1.2.** Reclaimed water network in Madrid (Madrid city council, 2019)

## Main objectives

The main objective of this Dissertation was to assess the effects of reclaimed water irrigation in the soil-plant system of urban parks of Madrid (Spain).

## Specific objectives

1. To estimate the long-term salinization risk in soils and the resulting salt accumulation in plants.
2. To assess the influence of reclaimed water irrigation on soil physical properties of urban parks.
3. To assess the effects of reclaimed water irrigation in urban parks by studying changes in grass nutrient balance and its biomass production.
4. To evaluate the effects of five major micronutrients, Boron (B), Copper (Cu), Iron (Fe), Manganese (Mn) and Zinc (Zn), in soils and cedars of Madrid urban parks.
5. To obtain reliable and useful information to help municipal managers in their decision-making process for maintaining urban parks in a good environmental status.

## Dissertation structure

This Dissertation is structured in six chapters. The first one is devoted to the introduction. Then, there are four chapters containing the four scientific papers on which this Doctoral Dissertation is based. They reproduce the content of research papers that have been published in peer-reviewed journals. The original structure has been maintained, and thus it may result in some inevitable redundancy describing the study area and the ‘material and methods’ section. Each chapter contains a references section. The main conclusions are outlined in Chapter 6.

A brief description of the chapters (2 to 5) is presented below:

- **Chapter 2**

Salt accumulation in soils and plants under reclaimed water irrigation in urban parks of Madrid (Spain). Published in 2019 in *Agricultural Water Management* (Appendix 1).

**Citation:** Zalacáin, D.; Martínez-Pérez, S.; Bienes, R.; García-Díaz, A.; Sastre-Merlín, A., 2019. Salt accumulation in soils and plants under reclaimed water irrigation in urban parks of Madrid (Spain). *Agric. Water Manag.* 213, 468–476.  
<https://doi.org/10.1016/j.agwat.2018.10.031>

#### AGRICULTURAL WATER MANAGEMENT

2018 *Journal Impact Factor*: 3.542

*Categories*: Agronomy (Q1) & Water Resources (Q1)

- **Chapter 3**

Influence of reclaimed water irrigation in soil physical properties of urban parks: A case study in Madrid (Spain). Published in 2019 in *Catena* (Appendix 2).

**Citation:** Zalacáin, D.; Bienes, R.; Sastre-Merlín, A.; Martínez-Pérez, S.; García-Díaz, A., 2019. Influence of reclaimed water irrigation in soil physical properties of urban parks: A case study in Madrid (Spain). *Catena* 180, 333-340.  
<https://doi.org/10.1016/j.catena.2019.05.012>

#### CATENA

2018 *Journal Impact Factor*: 3.851

*Categories*: Geosciences, multidisciplinary (Q1); Soil Science (Q1) & Water Resources (Q1)

- **Chapter 4**

Turfgrass biomass production and nutrient balance of an urban park irrigated with reclaimed water. Published in 2019 in *Chemosphere* (Appendix 3).

**Citation:** Zalacáin, D.; Martínez-Pérez, S.; Bienes, R.; García-Díaz, A.; Sastre-Merlín, A., 2019. Turfgrass biomass production and nutrient balance of an urban park irrigated with reclaimed water. *Chemosphere* 237, 124481.  
<https://doi.org/10.1016/j.chemosphere.2019.124481>

## CHEMOSPHERE

2018 Journal Impact Factor: 5.108

Categories: Environmental Sciences (Q1)

- **Chapter 5**

Effects of reclaimed water irrigation on micronutrient concentration in soils and cedars of urban Parks. Manuscript ID: WS-EM19289. Submitted to *Water Supply* on 24/06/2019 and currently under review.

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## CHAPTER 2

Salt accumulation in soils and plants  
under reclaimed water irrigation  
in urban parks of Madrid (Spain)

## Abstract

Reclaimed water irrigation in urban parks is expanding all over the world and could cause salt accumulation in soil and plants. Since the beginning of the 2000s, the city of Madrid (Spain) has been using reclaimed water to irrigate its parks. The main aim of this study was to estimate salt accumulation in soils and plants due to reclaimed water irrigation in two urban parks of Madrid. It was conducted over five consecutive years and the chemical properties in soil solution, soil and plant leaves of four species were analyzed. Two plots from each park were selected, one irrigated with reclaimed water (RW) and another one irrigated with drinking water (DW).

There was a steady increase of  $\text{Cl}^-$ ,  $\text{Na}^+$ , SAR and electrical conductivity (EC) in soils that were RW irrigated for 5 years, while in DW plots lower values for these parameters were observed. Likewise, there was no soil sodification in RW plots. On the contrary, the park which has been RW irrigated for 15 years showed a slight soil salinization ( $\text{EC} > 2 \text{ dS m}^{-1}$ ).

There were significant differences for the Cl and Na (%) leaf content between species irrigated with RW versus DW. Overall, salt concentration in leaves was similar to the values found in the literature, being in most of the cases below the threshold when plants start to show injuries. However, an adequate leaching requirement (9 %) is advisable in order to wash out the excessive salt accumulation in parks irrigated with reclaimed water.

## 2.1. Introduction

Soil salinization associated with irrigation is a global problem (Dehaan and Taylor, 2002; Rengasamy, 2006; Szabolcs, 1989; Yu et al., 2010). Almost 20% of irrigated land is threatened by salinization, and this percentage is still on the rise (Li et al., 2014). One of the processes that promotes soil salinization is reclaimed water irrigation (Chen et al., 2013a; Klay et al., 2010; Sou-Dakouré et al., 2013; Urbano et al., 2017). Due to water deficit, reclaimed water and wastewater irrigation is expanding all over the world (Bixio et al., 2006; Chu et al., 2004; Hamilton et al., 2007). Reclaimed water is defined as treated wastewater after an additional or complementary treatment that adjusts its quality for its intended use (BOE, 2007). Salinity levels in reclaimed water are usually high due to common tertiary treatment processes do not remove most mineral salts, unless it is combined with expensive desalination processes, such as reverse osmosis (Haruvy, 2006; Rebhun, 2004). Sodium and other forms of salinity are the most persistent in reclaimed water and are among the most difficult to remove from water, which usually requires the use of expensive cation exchange resins or reverse osmosis membranes (Toze, 2006). After municipal use, water increases its salinity, mainly due to sodium salts and chlorides (Rebhun, 2004). These can originate from many sources such as detergents, soaps and washing material, as well as some chemicals used during the water treatment process (water chlorination) and other sources (Elgallal et al., 2016; Qadir and Scott, 2010).

Reclaimed water irrigation in urban parks is an increasing trend all over the world (Chen et al., 2013b; Furumai, 2008; Qian and Mecham, 2005; Yi et al., 2011). This increase is due to two critical factors: technological advances made in wastewater treatments and a rise of water deficit in many parts of the world (Lyu et al., 2016). This kind of irrigation implies a series of benefits such as its reliability as a water source along the time and mainly during drought episodes (Hanjra et al., 2012; Wilcox et al., 2016). The reduction of fertilizers use due to its high nutrient content (Montemurro et al., 2017) and the possibility of keeping fresh water resources for high-quality uses (Sastre-Merlín et al., 2016a) are other advantages associated with their use.

Salinization derived of a low-quality irrigation water had been widely studied for agricultural areas (Cassaniti et al., 2009; Letey et al., 2011), but there are few studies for urban green areas (Chen et al., 2015; Nouri et al., 2013). In one of those studies, Chen et al. (2013b) found that there was soil salinity accumulation in urban parks of Beijing irrigated with

reclaimed water, about 20% higher in the top 0.20 m than those irrigated with drinking water. However, soil salinization did not appear yet in seven parks of study, except for one, which presented a mild soil salinization. The same author (Chen et al., 2015) concluded that there was an increase in soil salinity and a slight soil alkalization, but no soil salinization was observed after 3-9 years of reclaimed water irrigation, which could be attributed to the over irrigation practices in Beijing parks.

On the other hand, there is an extensive literature that has researched on the effects caused by RW irrigation on plants and a majority of it has been developed for agricultural species, with an economic interest (Cirelli et al., 2012; Papadopoulos et al., 2009). There are several studies for the effects on citrus trees (Pedrero et al., 2015, 2012) and on olive trees (Ayoub et al., 2016; Petousi et al., 2015) among other species. Moreover, there is also a broad literature on crop salt tolerance (Öztürk et al., 2006; Parida and Das, 2005), as well as studies on ornamental and landscape species (Fornes et al., 2007; Niu and Cabrera, 2010; Rhoades et al., 1992). Despite these species have not an economic performance, they are judged by their aesthetic value (Wu and Dodge, 2005). Salinity is of rising importance in landscaping due to the increase of reclaimed water irrigation in green urban areas (Cassaniti et al., 2012). Sodium and chloride, two of the main constituents of reclaimed water, are suspected of the decline of redwood trees in California, where RW is used for public park irrigation (Barnes et al., 2007). Adverse symptoms were noticed on some redwoods under RW irrigation, such as leaf necrosis and even branch and tree death, in extreme cases. Likewise, Nackley et al. (2015) found that growth and appearance of this kind of conifer (*Sequoia sempervirens*) is negatively affected when it is irrigated with high EC reclaimed water. Other species affected was *Photinia*, which had a significant decrease in plant growth under sprinkle irrigation with reclaimed water (Gori et al., 2008). In other study, Bañón et al. (2011) concluded that RW irrigation of *Lantana camara* led to an excessive uptake of chloride and sodium in leaves, which entailed defoliation, growth decline and loss of aesthetic value.

Soil salinity stresses plants in two ways: high concentrations of salts in soils complicate water extraction for roots and high concentrations of salts within the plant can be toxic (Munns and Tester, 2008). Long-term saline water irrigation cause an accumulation of toxic ions, particularly  $\text{Na}^+$  and  $\text{Cl}^-$  in the rhizosphere, which initially causes osmotic stress, due to a decrease in the water potential of the root system (Acosta-Motos et al., 2014; Ashraf et al., 2017). Moreover, the gradual accumulation of these phytotoxic ions in plants could lead to a

nutritional imbalance (Parida and Das, 2005; Rengasamy, 2006; Stevens et al., 2008), together with a decrease in growth (Bañón et al., 2011) and damages in leaves and roots (Azza Maher et al., 2007; Cassaniti et al., 2012).

Madrid City Council started thinking of reclaimed water irrigation of its urban parks during the drought that took place in the middle of the 1990s (Iglesias and Ortega, 2008). Nowadays, the City Council has developed a vast system of more than 150 km of pipes and 65 deposits to irrigate most of its urban parks (1400ha) with reclaimed water (Madrid City Council, 2018). In 2009 Madrid City Council wanted to undertake an in-depth study of the decline of several cedars in some parks irrigated with reclaimed water and signed a partnership agreement with our research team. Therefore, the main objective of this research was to estimate the long-term salinization risk in soils and the resulting salt accumulation in plants of two urban parks of Madrid (Spain) on account of reclaimed water irrigation. A secondary goal was to obtain reliable and useful information to help municipal managers in their decision-making process for maintaining urban parks in good environmental condition.

## 2.2. Materials and methods

### 2.2.1. Study area

The research was carried out in the city of Madrid (Spain), where reclaimed water is used to irrigate most of its parks since the beginning of the 2000s. This water comes from several water reclamation plants after a tertiary treatment of the wastewater produced by the city of 3.2 million inhabitants. Average annual precipitation (1981-2010) is 421 mm, the annual mean temperature is 15 °C (AEMET, 2018) and average annual evapotranspiration ET (Penman) is 930 mm. According to these data, Madrid's climate is classified as arid by Lang aridity index and as Mediterranean semi-arid by Martonne (Quan et al., 2013). It is characterized by dry and warm summers and cold winters. Nearly all the precipitation is concentrated in spring and autumn.

This study was conducted along 5 consecutive years (2012-2016) in two public urban parks of Madrid: Emperatriz María de Austria Park (hereafter PEMA, 40° 22' 53" N, 3° 43' 16" W) and Garrigues Walker Park (hereafter PGW, 40° 22' 11" N, 3° 39' 41" W). Both parks were irrigated with reclaimed water since 2002 and 2012, respectively. Two plots from each park

were irrigated with reclaimed water (PGW\_RW and PEMA\_RW) and two more irrigated with drinking water (PGW\_DW and PEMA\_DW). Study plots in both parks were adjacent and its size was about 1000 m<sup>2</sup> for PEMA and around 400 m<sup>2</sup> for PGW. Several adult shrubs (*Photinia* sp), ten adult hackberries (*Celtis australis*) and nine adult cedars (*Cedrus atlantica* and *Cedrus deodara*) were selected for the study.

Soil texture (0-0.6 m) was classified as sandy clay loam according to USDA soil classification for both plots in PGW (PGW\_DW and PGW\_RW) and PEMA\_RW and sandy loam for PEMA\_DW (Table 2.1). Soils were classified as Hortic Terric Anthrosols in PGW and as Terric Anthrosols in PEMA (IUSS Working Group WRB, 2015).

### 2.2.2. Irrigation water sampling and analysis

The average irrigation volume was about 940 mm per year for each plot. The irrigation season was usually extended through 8 months and the plots were irrigated on a daily basis, except on weekends. Once a year, in July, reclaimed water and drinking water were sampled directly from the park's sprinklers. Each plot had low-pressure sprinklers (Hunter PGP ultra, Hunter Industries) at a spacing of 6-8 m and operating within manufacturer's specifications. Samples were collected in 125 ml plastic bottles, refrigerated and transferred to the laboratory for further analysis. The parameters evaluated were: Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH and concentrations of HCO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, PO<sub>4</sub><sup>3-</sup>, SO<sub>4</sub><sup>2-</sup>, NH<sub>4</sub><sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup>. Ion concentration was determined by ion chromatography, except for bicarbonates and pH that were potentiometrically determined. Each water sample was analyzed following the procedures described by APHA (2012).

### 2.2.3. Soil solution sampling and analysis

Soil solution sampling was carried out in three different times of the year throughout the irrigation season: at the beginning (March), in the middle (July) and at the end (October). It was sampled by suction porous ceramic cup lysimeters (Soilmoisture Equipment Corp.) of 4.8 cm outside diameter, installed in every plot at 0.15, 0.35 and 0.60 m depth, with three replicates each. Before placing them in the field, the lysimeters were washed with deionized water. Likewise, in order to ensure a continuous contact of the porous ceramic cup with the soil matrix, a slurry (1:2 soil:deionized water) was introduced at the bottom of the drilled hole before lysimeter installation. A vacuum of 70 kPa was applied to the suction cups to obtain the soil solution and for each depth, a sample composed of three soil solution sub-

samples was taken. Analyses methods and determined parameters were the same as for the irrigation water samples.

**Table 2.1.** Particle size distribution, pH, Soil Organic Matter (SOM) and total nitrogen in the four study plots over the five years of study (2012-2016).

Study plot	Depth	pH	% SOM	N <sub>TOT</sub>	% Clay	% Sand	% Silt	Soil texture
PGW_DW	0-0.05 m	7.8	5.5	2802	17	60	23	Sandy loam
	0.10-0.20 m	7.9	1.6	952	23	52	25	Sandy clay loam
	0.30-0.40 m	7.9	0.4	297	23	54	23	Sandy clay loam
	0.55-0.65 m	7.9	0.3	231	20	58	22	Sandy clay loam
PGW_RW	0-0.05 m	7.9	6.9	3332	21	60	19	Sandy clay loam
	0.10-0.20 m	8.0	2.6	1543	28	48	24	Sandy clay loam
	0.30-0.40 m	7.9	0.9	550	26	54	20	Sandy clay loam
	0.55-0.65 m	7.8	0.4	281	24	55	21	Sandy clay loam
PEMA_DW	0-0.05 m	7.4	5.8	2701	17	65	18	Sandy loam
	0.10-0.20 m	7.8	0.7	517	18	67	15	Sandy loam
	0.30-0.40 m	7.8	0.3	250	16	68	16	Sandy loam
	0.55-0.65 m	7.6	0.3	233	14	76	10	Sandy loam
PEMA_RW	0-0.05 m	7.8	6.1	3130	15	66	29	Sandy loam
	0.10-0.20 m	8.1	1.2	776	20	64	16	Sandy clay loam
	0.30-0.40 m	7.8	0.4	347	22	57	21	Sandy clay loam
	0.55-0.65 m	7.5	0.5	384	20	60	20	Sandy clay loam

#### 2.2.4. Soil sampling and analysis

Soil sampling was carried out twice a year, once in March (before the irrigation season) and once in October (right after the irrigation season). Soil samples were collected at four depths: 0-0.05 m, 0.10-0.20 m, 0.30-0.40 m, 0.55-0.65 m using a 6-cm Edelman-type auger. Each soil sample contained approximately 1 kg of soil and was composed of three soil sub-samples randomly collected from each depth. These samples were air-dried, then passed through a 2mm sieve and ground before analysis by ion chromatography and potentiometry determination of the saturated paste extract. Electrical conductivity (EC) and pH were determined at 25 °C using a conductivity meter (Metrohm 856, Switzerland) and a pH-meter



(Metrohm 826, Switzerland), respectively. Soil organic matter (SOM) was determined by wet oxidation (Walkley and Black, 1934). N content was determined by Kjeldahl method (Bremner and Mulvaney, 1982) and soil texture by hydrometer method (Gee and Bauder, 1986). Soluble salt content ( $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$  and  $\text{Na}^+$ ) was determined in the saturated paste extract as described by Rhoades (1982).

#### 2.2.5. Plant leaves sampling and analysis

Composite samples of one kind of shrub (*Photinia sp*) and two species of trees (hackberry [*Celtis australis*] and cedar [*Cedrus atlantica* and *Cedrus deodara*]) were collected once a year, in July, at irrigation season highpoint. Samples of hackberry were collected only in PEMA, while *Photinia sp* and cedar samples were collected in PGW (*Cedrus atlantica*) and in PEMA (*Cedrus deodara*). Each leaf sample contained approximately 500 g of fully developed green leaves, composed of several sub-samples collected from different specimens present in each plot. In the case of hackberries and cedars, samples were collected around the canopy of each tree at a height nearly 2 m above the ground. Then, were placed in paper bags and transferred to the laboratory, where they were rinsed with distilled water, oven dried at 60 °C and crushed after that. Following acid digestion with nitric acid in a microwave system (Kalra, 1998), Cl and Na concentration were determined by potentiometry and by inductively coupled plasma mass spectrometry (ICP-MS), respectively.

#### 2.2.6. Statistical analysis

All data were analyzed using IBM SPSS Statistics for Windows, version 22.0 (Armonk, NY: IBM Corp.). Normality was assessed by Kolmogorov-Smirnov test and data did not follow a normal distribution even after several data transformations. As data did not follow a normal distribution, non-parametric Mann-Whitney U tests were applied at a 0.05 significance level to assess significant differences between means of each parameter.

### 2.3. Results and discussion

#### 2.3.1. Irrigation water quality

Concentrations of dissolved ions, viz.  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$  and  $\text{Na}^+$ , were significantly higher in reclaimed water (RW) in comparison with drinking water (DW) (Table

2.2). Sodium adsorption ratio (SAR) and electrical conductivity (EC) were also greater in reclaimed water. In PGW all the parameters were significantly higher for reclaimed water, except for  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\text{NH}_4^+$  and pH, while in PEMA only pH did not differ. Generally both irrigation waters were adequate for irrigation according to FAO water quality standards (Ayers and Westcot, 1985). However, regarding these standards, reclaimed water could have a slight to moderate degree of restriction on use for some parameters (EC, TDS,  $\text{HCO}_3^-$ ,  $\text{Na}^+$  and  $\text{Cl}^-$ ). Thus, focus should be placed on the high  $\text{Na}^+$  and  $\text{Cl}^-$  content in RW, which could imply a risk of soil salinization (Tarchouna et al., 2010). The total mass of  $\text{Cl}^-$  and  $\text{Na}^+$  entering the parks through reclaimed water were of 93 kg  $\text{Cl}^- \text{ ha}^{-1}$ , 62 kg  $\text{Na}^+ \text{ ha}^{-1}$  (PEMA) and 114 kg  $\text{Cl}^- \text{ ha}^{-1}$ , 77 kg  $\text{Na}^+ \text{ ha}^{-1}$  (PGW).

**Table 2.2.** Physico-chemical characteristics of drinking and reclaimed water used during the experiment. Mean and standard deviation (SD) values were calculated from the five years of study (2012-2016). TDS-Total Dissolved Solids; EC-Electrical Conductivity; nd-not detected.

Parameter	PGW_DW	PGW_RW	PEMA_DW	PEMA_RW	n
$\text{HCO}_3^-$ (mg $\text{L}^{-1}$ )	29.8 ± 20.7 a	167 ± 98.5 b	54.6 ± 34.8 a	190 ± 27.7 b	5
$\text{Cl}^-$ (mg $\text{L}^{-1}$ )	16.8 ± 2.9 a	114 ± 23.6 b	15.7 ± 3.0 a	93.2 ± 8.9 b	5
$\text{NO}_3^-$ (mg $\text{L}^{-1}$ )	1.7 ± 1.2 a	15.5 ± 15.1 a	1.6 ± 1.3 a	10.5 ± 5.6 b	5
$\text{NO}_2^-$ (mg $\text{L}^{-1}$ )	0.2 ± 0.1 a	5.9 ± 8.4 a	0.02 ± 0.0 a	10.2 ± 12.2 b	5
$\text{PO}_4^{3-}$ (mg $\text{L}^{-1}$ )	nd	0.3 ± 0.6	nd	0.5 ± 0.6	5
$\text{SO}_4^{2-}$ (mg $\text{L}^{-1}$ )	14.1 ± 1.8 a	97.6 ± 28 b	14.8 ± 12 a	74.5 ± 14 b	5
$\text{NH}_4^+$ (mg $\text{L}^{-1}$ )	0.3 ± 0.5 a	18.7 ± 17.2 a	0.6 ± 0.9 a	29.2 ± 6.8 b	5
$\text{Ca}^{2+}$ (mg $\text{L}^{-1}$ )	13.1 ± 3.4 a	44.2 ± 9.5 b	12.9 ± 11.6 a	35.9 ± 3.6 b	5
$\text{Mg}^{2+}$ (mg $\text{L}^{-1}$ )	2.3 ± 0.6 a	11.1 ± 2.8 b	2.7 ± 1.9 a	8.6 ± 1.2 b	5
$\text{K}^+$ (mg $\text{L}^{-1}$ )	1.1 ± 0.1 a	19.7 ± 3.2 b	0.7 ± 0.7 a	17.3 ± 2.8 b	5
$\text{Na}^+$ (mg $\text{L}^{-1}$ )	8.2 ± 1.1 a	77 ± 13.9 b	11.1 ± 3.3 a	62.3 ± 10.5 b	5
SAR	0.3 ± 0.1 a	2.8 ± 0.6 b	0.5 ± 0.2 a	2.6 ± 0.4 b	5
TDS (g $\text{L}^{-1}$ )	0.1 ± 0.0 a	0.6 ± 0.1 b	0.1 ± 0.0 a	0.5 ± 0.1 b	5
pH	7.6 ± 0.2 a	7.5 ± 0.3 a	7.6 ± 0.2 a	7.7 ± 0.2 a	5
EC (dS $\text{m}^{-1}$ )	0.1 ± 0.02 a	0.9 ± 0.07 b	0.2 ± 0.08 a	0.8 ± 0.1 b	5

Different lowercase letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test, between treatments for the same park.

Obtained reclaimed water agronomic parameters were compared with those reported in relevant literature (e.g. Kalavrouziotis et al., 2008; Lubello et al. 2004; Pereira et al. 2011). They were within average of tertiary treated wastewaters. Electrical conductivity (EC) values of reclaimed water used for irrigation usually have a high variability, depending on its origins, season and treatment. They range from  $0.8 \text{ dS m}^{-1}$  (Lubello et al., 2004; Qian and Mecham, 2005) to more than  $3.5 \text{ dS m}^{-1}$  (Nicolás et al., 2016). In this study, EC values for reclaimed water were around  $0.85 \text{ dS m}^{-1}$ , which are in the lowest range of those obtained in the bibliography. However, both EC values could imply a slight to moderate degree of restriction on use due to a salinity potential problem (Ayers and Westcot, 1985). When comparing DW from the two parks there were not significant differences. Likewise, the same outcomes were observed when comparing RW from the two parks. Such absence of significant differences is due to the RW pipeline network in Madrid that mixes reclaimed water from several treatment plants.

### 2.3.2. Salt accumulation in soil solution

Table 2.3. shows chemical characteristics of soil solution obtained by lysimeters in the four plots. The main differences between treatments (DW vs RW) were for  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ , SAR and EC, which had significant higher values for RW than DW irrigation. Almost all these nutrients match with those nutrients with higher values in reclaimed irrigation water. During the irrigation season, irrigation water was infiltrated and mixed with the previous soil solution. In case of high evapotranspiration rates, soil solution in the first soil layers mostly consists on the infiltrated irrigation water (Gloaguen et al., 2007). When  $\text{Na}^+$  concentration in irrigation water is high, as in this case (Table 2.2.), the introduced  $\text{Na}^+$  may replace other exchangeable cations on the exchange complex. This exchange of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  by  $\text{Na}^+$ , gave SAR values significantly higher for the RW irrigated plots, which could lead to large Exchangeable Sodium Percentage (ESP) and consequently results in clay swelling and dispersion (Netzer et al., 2014; Sou-Dakouré et al., 2013).

**Table 2.3.** Chemical characteristics of soil solution for both treatments in each park (2012-2016). Average, standard deviation (SD) and number of cases (n). EC-Electrical Conductivity.

Parameter	PGW_DW	PGW_RW	PEMA_DW	PEMA_RW	n
HCO <sub>3</sub> <sup>-</sup> (mg L <sup>-1</sup> )	370 ± 147 a	393 ± 166 a	402 ± 161 a	526 ± 212 b	40
Cl <sup>-</sup> (mg L <sup>-1</sup> )	50.3 ± 35.0 a	241 ± 166 b	27.3 ± 9.9 a	573 ± 379 b	40
NO <sub>3</sub> <sup>-</sup> (mg L <sup>-1</sup> )	18.9 ± 35.4 a	87.4 ± 93.8 b	22.9 ± 23.5 a	38.8 ± 72.6 a	40
NO <sub>2</sub> <sup>-</sup> (mg L <sup>-1</sup> )	0.1 ± 0.2 a	0.2 ± 0.3 a	0.2 ± 0.9 a	0.4 ± 1.8 a	40
PO <sub>4</sub> <sup>3-</sup> (mg L <sup>-1</sup> )	2.7 ± 2.3 a	2.4 ± 2.0 a	4.2 ± 10.1 b	1.8 ± 6.0 a	40
SO <sub>4</sub> <sup>2-</sup> (mg L <sup>-1</sup> )	80.4 ± 60.5 a	223 ± 117 b	53.4 ± 42.5 a	640 ± 485 b	40
NH <sub>4</sub> <sup>+</sup> (mg L <sup>-1</sup> )	0.4 ± 0.8 a	0.4 ± 0.9 a	0.2 ± 0.5 a	0.1 ± 0.3 a	40
Ca <sup>2+</sup> (mg L <sup>-1</sup> )	94.4 ± 39.1 a	157 ± 69.2 b	103 ± 44.5 a	322 ± 222 b	40
Mg <sup>2+</sup> (mg L <sup>-1</sup> )	43.2 ± 20.3 a	64.4 ± 39.2 b	33.2 ± 15.9 a	110 ± 70.2 b	40
K <sup>+</sup> (mg L <sup>-1</sup> )	10.1 ± 10.5 a	18.6 ± 6.9 b	7.4 ± 7.9 a	22.9 ± 13.0 b	40
Na <sup>+</sup> (mg L <sup>-1</sup> )	28.7 ± 10.6 a	144 ± 56.2 b	18.3 ± 4.3 a	298 ± 143 b	40
SAR	0.8 ± 0.2 a	3.2 ± 0.9 b	0.5 ± 0.1 a	5.2 ± 1.4 b	40
TDS (g L <sup>-1</sup> )	0.6 ± 0.2 a	1.2 ± 0.4 b	0.5 ± 0.2 a	2.3 ± 1.2 b	40
pH	7.6 ± 0.4 a	7.7 ± 0.3 a	7.7 ± 0.3 a	7.8 ± 0.3 a	40
EC (dS m <sup>-1</sup> )	0.9 ± 0.3 a	1.9 ± 0.7 b	0.8 ± 0.2 a	3.5 ± 1.8 b	40

Different lowercase letters mean significant differences at  $p < 0.05$  according to Mann-Whitney U test, between treatments for the same park.

### 2.3.3. Salt accumulation in soils

The main chemical characteristics of soils are presented in Table 2.4. Significant differences between both treatments were found for almost the same parameters than in the case of irrigation water and soil solution (Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup>, Na<sup>+</sup>, SAR and EC). This can be explained by the interaction between the irrigation water and the soil system (Lado and Ben-Hur, 2009). Na and EC values in PEMA\_RW were two times higher than in PGW\_RW. That could be explained by the fact that PEMA\_RW was RW irrigated 10 years more than PGW\_RW.

The increase in soils of four key parameters (Cl<sup>-</sup>, Na<sup>+</sup>, SAR and EC) along the study period is shown in Fig. 2.1. There are three issues that must be emphasized, the constant low values along the years for the parameters obtained in the DW treatment, the steady increase of values from PGW\_RW and the higher constant values for PEMA\_RW.

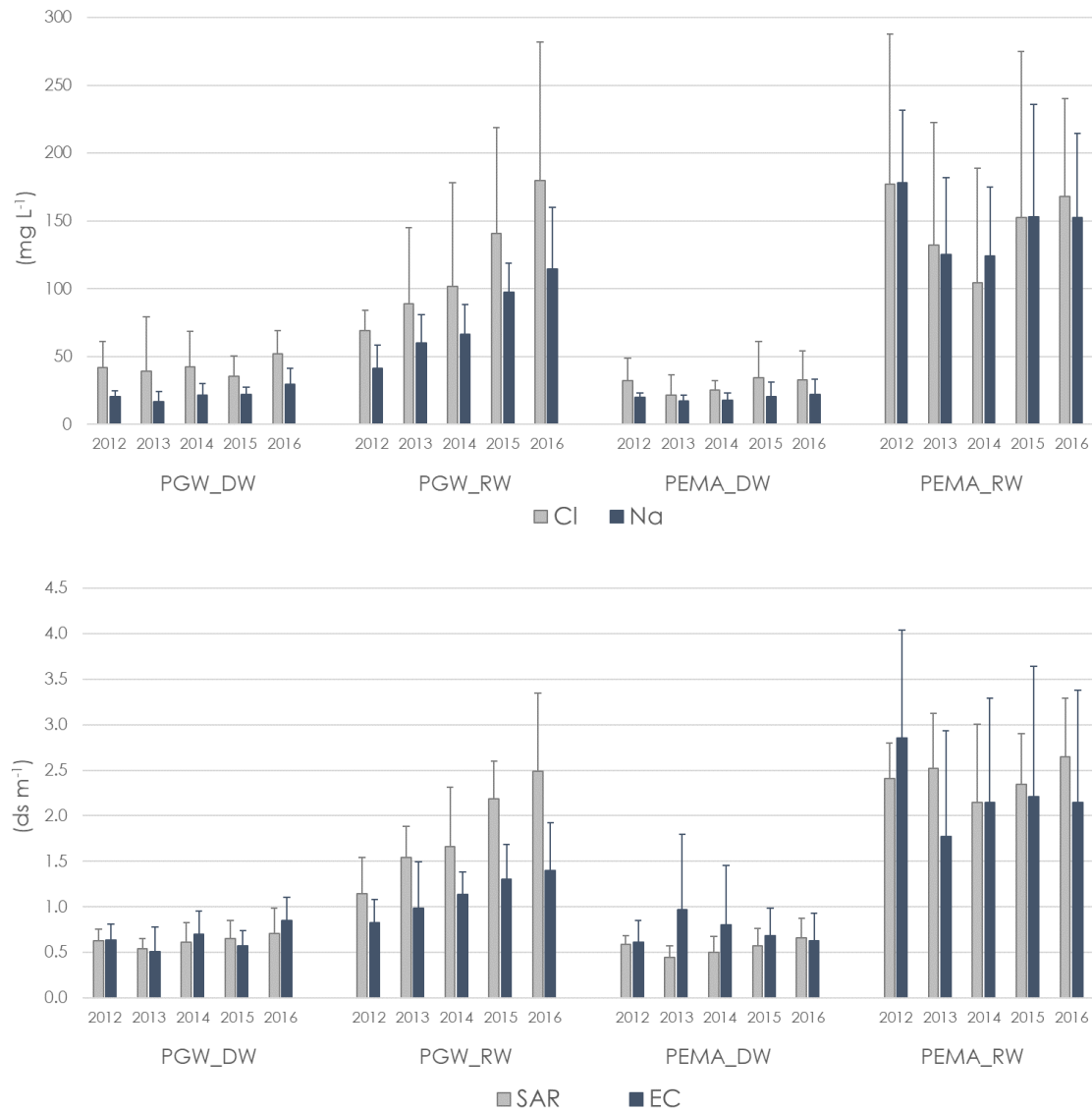
**Table 2.4.** Chemical characteristics of soils for both treatments in each park (2012 – 2016). Average, standard deviation (SD) and number of cases (n). EC-Electrical Conductivity.

Parameter	PGW_DW	PGW_RW	PEMA_DW	PEMA_RW	n
HCO <sub>3</sub> <sup>-</sup> (mg L <sup>-1</sup> )	181 ± 84 a	191 ± 120 a	150 ± 66.6 a	184 ± 139 a	40
Cl <sup>-</sup> (mg L <sup>-1</sup> )	42.1 ± 24.6 a	116 ± 78.9 b	29.1 ± 18.3 a	147 ± 96.3 b	40
NO <sub>3</sub> <sup>-</sup> (mg L <sup>-1</sup> )	46.4 ± 81.1 a	72.9 ± 120 a	47.6 ± 73.7 a	71 ± 149 a	40
PO <sub>4</sub> <sup>3-</sup> (mg L <sup>-1</sup> )	6.8 ± 13.7 a	5.2 ± 8.1 a	2.8 ± 3.8 a	4.5 ± 7.6 a	40
SO <sub>4</sub> <sup>2-</sup> (mg L <sup>-1</sup> )	66.7 ± 46.3 a	150 ± 104 b	166 ± 340 a	789 ± 815 b	40
Ca <sup>2+</sup> (mg L <sup>-1</sup> )	66.1 ± 30.2 a	88.0 ± 36.9 b	100 ± 110 a	244 ± 191 b	40
Mg <sup>2+</sup> (mg L <sup>-1</sup> )	19.6 ± 7.6 a	28.1 ± 17.2 b	12.9 ± 8.7 a	66.6 ± 62.8 b	40
K <sup>+</sup> (mg L <sup>-1</sup> )	14.4 ± 10.9 a	18.2 ± 10.5 b	14.7 ± 13.0 a	44.2 ± 59.6 b	40
Na <sup>+</sup> (mg L <sup>-1</sup> )	22.1 ± 8.6 a	76.0 ± 37.2 b	19.5 ± 7.4 a	147 ± 62.3 b	40
N <sub>TOT</sub> (mg kg <sup>-1</sup> )	1071 ± 1065 a	1426 ± 1260 a	925 ± 1116 a	1159 ± 1200 b	40
SAR	0.6 ± 0.2 a	1.8 ± 0.7 b	0.6 ± 0.2 a	2.4 ± 0.6 b	40
pH	7.9 ± 0.4 a	7.9 ± 0.3 a	7.6 ± 0.5 a	7.8 ± 0.4 a	40
EC (dS m <sup>-1</sup> )	0.7 ± 0.3 a	1.1 ± 0.4 b	0.7 ± 0.5 a	2.2 ± 1.2 b	40

Different lowercase letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test, between treatments for the same park.

Chloride concentration in DW plots were under 50 mg L<sup>-1</sup> during all the years. However, in PGW\_RW it showed a linear increase (157%) from 70 mg L<sup>-1</sup> in 2012 to 180 mg L<sup>-1</sup> in 2016. This linear increase was of 29% the first year and of 14%, 38% and 27% the following years. PGW\_RW reached the mean value observed in PEMA\_RW, which remained quite constant throughout the study period (around 150 mg L<sup>-1</sup>). The same pattern was shown for sodium concentration, although values were generally below the chloride concentrations.

SAR levels for PGW\_DW and PEMA\_DW were around 0.6 along the five years of study. SAR in PGW\_RW behaved in the same way as chloride and sodium, increasing linearly from 1.1 to 2.5 (127%). Despite this increase, SAR values are low and do not represent a risk to soil structure properties (Rengasamy and Olsson, 1991). In 2016, PGW\_RW reached and exceeded the mean value of PEMA\_RW (2.4), only after 5 years of reclaimed water irrigation.



**Fig. 2.1.** Cl<sup>-</sup>, Na<sup>+</sup>, SAR and EC concentrations in each plot throughout the study period (2012 – 2016).

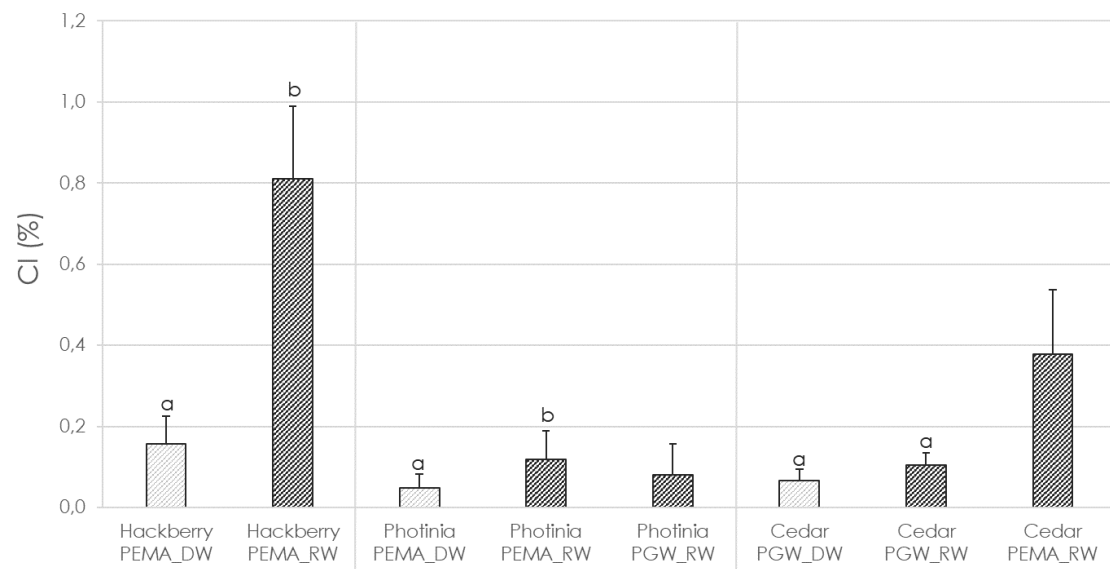
On the other hand, EC in PGW\_RW (1.4) in 2016 remained lower than in PEMA\_RW (2.2). According to Rengasamy (2010), soils which SAR is under 6 and its EC < 4 dS m<sup>-1</sup>, are categorized as non-salt affected soils as in the case of soils from the four study plots. This contrasts with most of the soils irrigated with reclaimed water, which tend to be classified as saline-sodic soils (Muyen et al., 2011; Pedrero et al., 2018). Overall, values of EC above 2 dS m<sup>-1</sup> show that there is a slight risk of soil salinization (Porta et al., 1994). PEMA\_RW after 10 years of reclaimed water irrigation reached and maintain this level the five years of study

(except in 2013). This is in accordance with Chen et al. (2013b) who concluded, in their study on parks of Beijing (humid continental climate and Fluvo-aquic and Cinnamon soils), that only one ( $2.01 \text{ dS m}^{-1}$ ) of the seven studied parks had a mild soil salinization ( $2\text{--}4 \text{ dS m}^{-1}$ ). This Beijing park was irrigated for 9 years with reclaimed water irrigation. However, the remaining six parks did not present soil salinization even after the same years under reclaimed water irrigation. Annual precipitation in Beijing was about 630 mm and more than 70% of the rainfall was concentrated in 3 months, which implies a rise of salt leaching and a decrease of the risk of soil salinization. Similarly, McLain and Williams (2012) in their short-term study (2 years) in an Arizona urban park (arid climate) did not find a soil EC increase in the first 30 cm of a sandy clay loam soil.

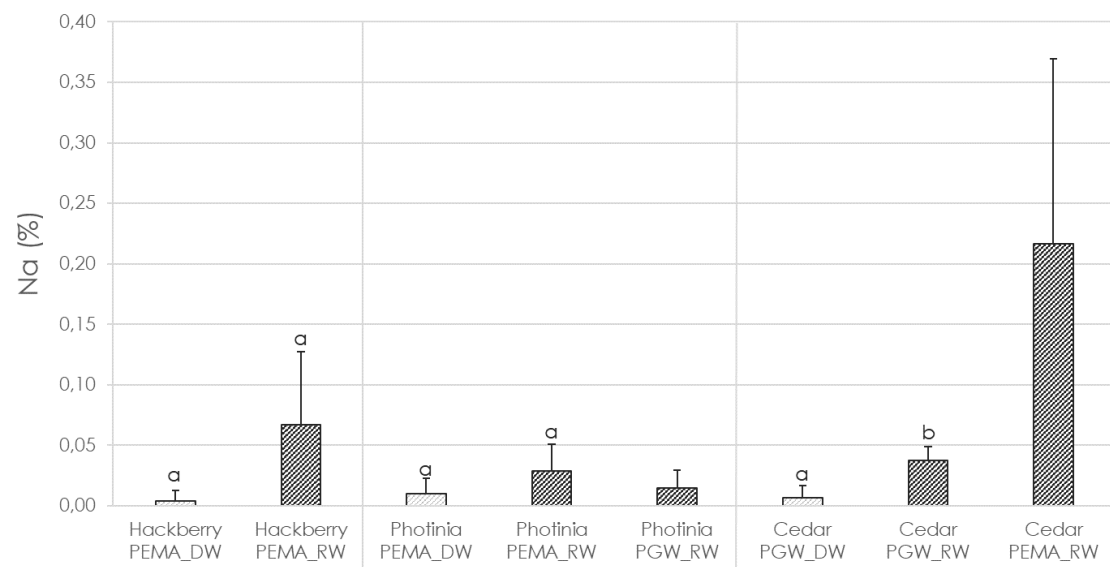
#### 2.3.4. Cl and Na accumulation in plant leaves

Chloride and sodium contents (% of dry weight) in leaves are presented in Fig. 2.2 and 2.3, respectively. Cl (%) content was significantly higher in those hackberries irrigated with reclaimed water in comparison with those irrigated with drinking water. Likewise, there were significant differences between *Photinia* plants in PEMA, obtaining higher values in those irrigated with reclaimed water. However, significant differences were not found between DW and RW in PGW for Cl (%) in cedars. It should be noted that  $\text{Cl}^-$  values in PGW\_RW cedars were higher than values obtained in PGW\_DW and lower than those obtained in PEMA\_RW. That may be due to the higher amount of years of reclaimed water irrigation in PEMA park.

In the case of Na (%), only cedars in PGW\_RW (0.04%) showed a significantly higher concentration than those in PGW\_DW (0.01%). It should be underlined that is necessary to compare our results with other reclaimed water irrigation studies that used different plant species due to the lack of this kind of studies in urban parks. PEMA\_RW values (0.22%  $\text{Na}^+$ ) were very close to the  $\text{Na}^+$  content obtained by Ali et al. (2013) after 18 months (0.25%  $\text{Na}^+$ ) in *Khaya senegalensis*. However, De Miguel et al. (2013) after one year of RW irrigation found values of 0.30% Na in *Jatropha curcas* leaves, notably above ours. That could be explained by the higher amount of Na ( $122 \text{ mg L}^{-1}$ ) present in their RW in contrast with the RW used for this study (77 and  $62 \text{ mg L}^{-1}$ ). On the other hand, Al-Hamaiedeh and Bino (2010) in their six-month study using treated grey water for irrigate olive trees, obtained values of Na 0.03% and Cl 0.21%, which are similar to our values for *Photinia* (PEMA\_RW and PGW\_RW) and Cedar (PGW\_RW).



**Fig. 2.2.** Cl concentrations in leaves (%). Error bars indicate standard deviation and different letters shows significance at  $p < 0.05$  according to Mann–Whitney U test between treatments for the same park.



**Fig. 2.3.** Na concentrations in leaves (%). Error bars indicate standard deviation and different letters shows significance at  $p < 0.05$  according to Mann–Whitney U test between treatments for the same park.

Wu et al. (2001) made a list of the salt tolerance of 38 landscape woody plant species under sprinkler irrigation with low salt ( $500 \text{ mg L}^{-1} \text{ NaCl}$ ) and high salt ( $1500 \text{ mg L}^{-1} \text{ NaCl}$ ) concentrations in the irrigation water. The study concluded that Chinese Hackberry (*Celtis sinensis*) had low salt tolerance for both concentrations and Cedar (*Cedrus deodara*) had high



salt tolerance. They found that leaves of hackberries under high salt irrigation were severely damaged and at least 70% of them were affected by chlorosis. In our study, salt concentration was clearly less: 131 and 155 mg L<sup>-1</sup> NaCl, for PGW and PEMA, respectively. Hence, we did not find chlorosis in leaves of hackberries or cedars. Wu and Dodge (2005) expanded their study and classified several landscape tree and shrub species according to their tolerance to recycled water irrigation and soil salinity. They concluded that *Cedrus deodara* was highly tolerant to salt water spray irrigation, which means that no apparent salt stress symptoms were observed when plants were irrigated with water containing 600 mg L<sup>-1</sup> sodium and 900 mg L<sup>-1</sup> chloride and was also highly tolerant to soil salinity. Cedars did not develop any salt stress symptoms even when soil EC was greater than 6 dS m<sup>-1</sup>. According to that, we did not record chlorosis neither in *Cedrus deodara* specimens (PEMA\_RW) nor in *Cedrus atlantica* specimens (PGW\_RW).

Furthermore, Wu and Dodge (2005) found that Chinese Hackberry and Photinia (*Photinia fraseri* and *Photinia glabra*) were sensitive to salt spray (more than 20% of leaves develop symptoms when plants were irrigated with water containing 200 mg L<sup>-1</sup> sodium and 400 mg L<sup>-1</sup> chloride) and to soil salinity (acceptable soil EC less than 2 dS m<sup>-1</sup>). However, in our study, *Photinia* did not show salt (NaCl) accumulation in leaves even when soil EC was higher than 2 dS m<sup>-1</sup>. Hackberries in PEMA\_RW showed a NaCl accumulation in leaves, but no chlorosis was observed. This is in line with the results described by Dmuchowski et al. (2013), who found that leaves of *Tilia 'Euchlora'* with strong damage contained extremely high Na content (0.33%). Likewise, Ayers and Westcot (1985) stated that many tree crops begin to show injuries when Cl content in the leaf tissue is above 0.3 % or when Na content is 0.25-0.50 % (dry weight). In our case, most of the species had not reached these levels, except for cedars and hackberries (only for Cl) in PEMA\_RW, and no significant damage were found.

Wu and Guo (2006) also studied the effects of reclaimed water irrigation on other kind of conifer (coast redwood – *Sequoia sempervivens* Endl.). They concluded that RW irrigation should be strictly monitored to ensure that soil salinity does not exceed 2 dS m<sup>-1</sup>, the threshold for very sensitive landscape plants. Taking this into account, a status monitoring should be done in PEMA\_RW, where EC in soil has overcome this threshold. Likewise, Nackley et al. (2015) presented a similar study on coast redwood under RW irrigation. The results of their study suggested that its growth will be negatively impacted when EC from the irrigation water exceeds 1 dS m<sup>-1</sup>. This is in concordance with other study (Barnes et al.,

2007) of the same species, who concluded that keeping an EC in soil solution around 1 dS m<sup>-1</sup> would prevent the appearance of detrimental symptoms on redwood trees irrigated with recycled water. All these studies assessing the effects of RW irrigation in conifers have been conducted in California under a Mediterranean climate, which is similar to Madrid climate. Thus, according to the referred studies, levels of EC in soil solution > 1 dS m<sup>-1</sup>, could lead to adverse effects on conifers sited in PGW\_RW and PEMA\_RW.

The risk of crop affection due to salt accumulation in the root zone may be present even when irrigation water is of low conductivity (1 dS m<sup>-1</sup>) (Barnes et al., 2007). In these cases, it is necessary to take action and to apply corrective measures to prevent the accumulation of excessive salts in soils. More water than required to meet the evapotranspiration needs of the plants must pass through the root zone to leach the excess of soluble salts, which usually has been expressed as the leaching requirement (Letey et al., 2011). Leaching is one of the most practical ways to reduce and control toxic ions in the root zone. Therefore, it can be used to prevent or to correct a problem once it has been recognized from plant symptoms (Ayers and Westcot, 1985). With the aim of keeping salt levels under risk thresholds, this research team carried out a leaching pilot experience in an urban park in Madrid (Sastre-Merlín et al., 2016b). Drinking water was used with encouraging results such as a notable decrease in soil solution EC. Leaching requirement (LR) was calculated according to Ayers and Westcot (1985) formulation (Eq.1).

$$LR = \frac{ECw}{5 (ECe) - ECw} \quad [\text{Eq. 1}]$$

Where ECw is the electrical conductivity of the applied irrigation water and ECe is the plant specific threshold soil salinity. Tanji et al. (2007) estimated the salt tolerances of landscape plants. They concluded that *Cedrus deodara* tolerance was moderate (permissible soil ECe between 2 and 4 dS m<sup>-1</sup>) and *Celtis sinensis* and *Photinia fraseri* Dress were sensitive (permissible soil ECe less than 2 dS m<sup>-1</sup>). According to these classification (ECe = 2 dS m<sup>-1</sup>) we obtained a leaching requirement of 0.087 for PEMA and 0.098 for PGW. These values are similar to those values obtained and collected (0.08) in California by Corwin et al. (2007) through different models.

The relationship between water salinity, water application, plant tolerance and the amount of drainage water are essential to establish the optimal management strategy (Letey et al.,

2011). Thus, this practice should be part of the proper park management of the city in the near future in order to avoid salt accumulation in soils and plants in urban parks irrigated with reclaimed water. In addition to leaching, other actions could be implemented, such as blending reclaimed water with water sources that have lower EC and SAR (Wu et al., 2009). Likewise, planting salt-tolerant species (Cassaniti et al., 2009; Sevostianova and Leinauer, 2014) needs to be considered in order to achieve a sustainable environment in urban parks.

## 2.4. Conclusions

The high  $\text{Na}^+$  and  $\text{Cl}^-$  content in reclaimed water could imply a risk of salt accumulation in soils and plants. Level of salts in soil solution, soil and leaves of this study usually presented significant differences between both treatments (DW and RW). After 15 years of reclaimed water irrigation, PEMA\_RW showed higher values than PGW\_RW and a slightly soil salinization ( $\text{EC} > 2 \text{ dS m}^{-1}$ ). There was no soil sodification, although SAR and Na content in soils irrigated with RW was increasing (PGW\_RW) and consistently high (PEMA\_RW), but they were far from being a risk ( $\text{SAR}_{\text{soil}} > 6$ ). Overall, salt concentration (Cl and Na) in leaves was similar to the values found in the literature of reclaimed water irrigation. Cedars, hackberries, and *Photinia* were tolerant to sprinkler irrigation with reclaimed water. Likewise, no major salt stress symptoms were observed, despite the high values of Cl and Na in their leaf tissue. However, a proper park management should focus on preventing the appearance of adverse symptoms on sensitive plants. Thus, we recommend to use a leaching requirement of 8.7% for PEMA and 9.8% for PGW in order to wash out the excessive salt accumulation in soils.

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## CHAPTER 3

### **Influence of reclaimed water irrigation in soil physical properties of urban parks: A case study in Madrid (Spain)**

## Abstract

Reclaimed water irrigation has been a long-standing practice, especially among water deficit areas such as Spain. This kind of water, more mineralized than drinking water, could imply changes on structural soil features. The main aim of this study was to assess the impact of reclaimed water on aggregate stability, soil penetration resistance, infiltration rate and porosity in soils of one of the urban parks of Madrid. This research was carried out on five successive years (2012-2016) in two urban park plots: one irrigated with reclaimed water (RW) and another one with drinking water (DW).

Results showed that irrigation with reclaimed water increased microaggregate stability in the topsoil, probably because of higher values of soil organic matter (SOM). However, macroaggregate stability decreased after RW irrigation in the top and the deepest layer. Soil penetration resistance was significantly higher in the RW plot, probably due to a further development of the root system. Furthermore, a decrease on infiltration rate was observed for RW, apparently because of the influence of sodium. On the other hand, porosity results showed that there was no influence of the kind of irrigation water used. The prolonged use of reclaimed water to irrigate urban parks is potentially leading to a modification of some soil properties, which are key in urban parks soil system. Thus, to avoid future problems, the use of reclaimed water in urban parks irrigation should be continuously monitored.

### 3.1. Introduction

Nowadays, > 2 million hectares of farmland are irrigated with wastewater: treated, also known as reclaimed water, partially treated or untreated (Biggs and Jiang, 2009). This kind of irrigation has been developed since centuries, especially in arid or semi-arid areas (Mizyed, 2013). In the ancient Greece, the Minoan civilization used wastewater for irrigation in agriculture (Angelakis, 2005). Over time that practice was gradually extended, such as in the Middle Ages in the Mediterranean region of Valencia (Spain) and other North European countries as Germany and United Kingdom (Angelakis and Durham, 2008). The State of California was the frontrunner in the introduction of a regulation to control water reuse in 1918 (Asano and Levine, 1996). From the middle of the 20th century, there was an increase as well as an improvement of these practices associated to technological advances made in wastewater treatments and the rise of water deficit in many parts of the world (Bixio et al., 2006; Lyu et al., 2016). Semi-arid and arid areas, in particular, have been vulnerable to water scarcity due to a remarkable imbalance between water demands and the availability of water resources (O'Connor et al., 2008; Simons et al., 2015).

Within the European Union, there are two different water reuse realities: one in southern Europe where wastewater reuse is a growing source of irrigation water, and the other one in northern countries where is hardly practiced, but could be developed for other purposes (TYPESA, 2013). Furthermore, in southern Europe water reuse is mainly intended for agriculture (44% of the projects) and for urban or environmental uses (37% of the projects), while in northern Europe, reuse is focus on urban or environmental (51% of the projects) and industrial uses (33% of the projects) (Bixio et al., 2006). One of the pioneers in Europe in terms of including water reuse as one of its water resources was the Madrid City Council, together with other Spanish cities, such as Alicante (Melgarejo et al., 2016), Barcelona (Paranychianakis et al., 2015) and Vitoria-Gasteiz (Mujeriego, 1990). Hochstrat et al. (2006) found that Spain presented the highest projected reuse potential within the European Union, according to model calculations and some scenario assumptions. The Treated Water Reuse Plan for the City of Madrid was approved in 1997 (Iglesias and Ortega, 2008) and in 2015 a volume of 6.6 million m<sup>3</sup> of wastewater was reclaimed (Madrid City Council, 2018). Likewise, in the Madrid Region there are currently 24 municipalities which are using reclaimed water, mainly for parks irrigation, supplied by Madrid's water utility (Canal de Isabel II) through a reclaimed water network of 493 km (Community of Madrid, 2016). Hence, this research



team, through an agreement with the Madrid City Council, has been conducting research on this kind of irrigation in several parks of Madrid since 2009 (Sastre-Merlín et al., 2016).

On the other hand, soils play an essential role in global biogeochemical cycles, delivering and regulating vital ecosystem services (Keesstra et al., 2012; Pereira et al., 2018; Smith et al., 2015). Moreover, soil system is also the medium that supports plant roots and a reservoir of nutrients essential for plant growth (Janvier et al., 2007). Soil quality is necessary to support ecosystem functions and to promote plant, animal and human health (Wang et al., 2003). One of the key factors concerning soil quality is soil structure, because it affects water storage and movement, infiltration, erosion, root penetration and nitrogen and phosphorus recycling (Bronick and Lal, 2005; Levy, 2011). Poorly structured soils are prone to soil degradation (Morugán-Coronado et al., 2011). Aggregates are considered a major sign of soil structure, and their shape, distribution and stability hold influence over several soil processes, such as aeration, water and nutrient storage and transmission, and root penetration (Candan and Broquen, 2009; Shepherd et al., 2001). The decrease of soil organic matter causes a decrease in aggregate stability (Al-Kaisi et al., 2014; Duchicela et al., 2013). In addition, wetting and raindrop impact also contributes to the breakdown of the aggregates (Vaezi et al., 2017).

Some studies have shown that reclaimed water irrigation may potentially lead to a degradation of soil structure, e.g., a decrease of aggregate stability, a decrease in soil hydraulic conductivity, changes of water movement through the soil, etc. (Bhardwaj et al., 2007; Chávez et al., 2012; Herpin et al., 2007; Lado and Ben-Hur, 2009; Wallach et al., 2005). Some of these processes, such as clay dispersion, are caused by larger sodium adsorption ratio (SAR) in reclaimed water (Levy et al., 2014) or high salinity, what causes a decrease in aggregate stability (Adrover et al., 2012) together with several effects in landscape plants (Niu and Cabrera, 2010). Abedi-Koupai et al. (2006) found that salt and suspended solids contents of treated wastewater are the principal features affecting physical soil properties. The effects of reclaimed water irrigation in soil properties have been widely studied, but there is not a definitive conclusion because it largely depends on the quality of the reclaimed water, irrigation practices, soil texture and local climate conditions, among others (Chen et al., 2015).

Despite the potential effects, reclaimed water irrigation implies several benefits in arid and semi-arid areas. First, saving fresh water that can be used for other high-quality uses such as human consumption (Ahmed and Al-Hajri, 2009; Bedbabis et al., 2014). Secondly,

guaranteeing water availability along the year, regardless drought episodes or periods with low rainfall (Angelakis and Durham, 2008; Toze, 2006). Furthermore, reclaimed water irrigation could increase the available amount of nutrients for plants (Ali et al., 2013; Pedrero et al., 2015), as well as reduce fertiliser application and promote sustainability (Chen et al., 2013).

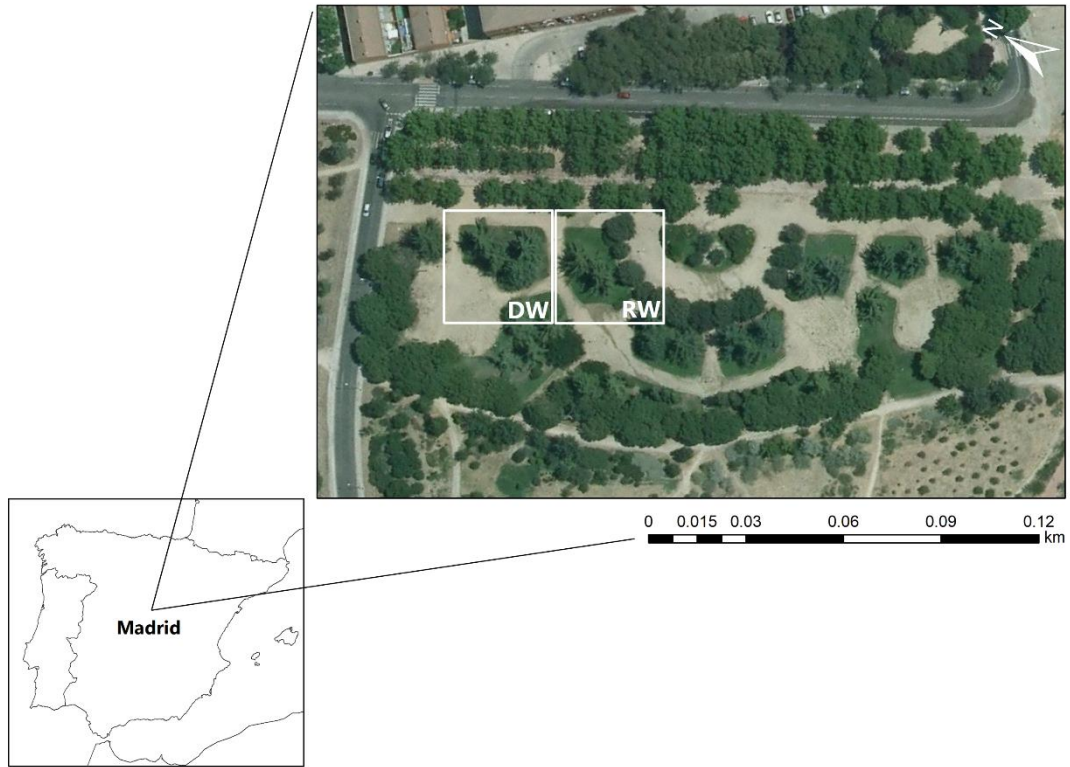
Water supply limitations for urban parks irrigation in areas with high evapotranspiration and low rainfall (e.g. Mediterranean region) force park managers to use alternative resources. Reclaimed water is the major of these alternative resources, although the use of it may lead to affect soil properties, especially its structure. Consequently, the objective of this work was to assess the influence of reclaimed water irrigation on soil physical properties of urban parks in a case study in Madrid.

## 3.2. Materials and methods

### 3.2.1. Study area

The study was carried out on five successive years (2012, 2013, 2014, 2015 and 2016) at the Garrigues Walker Park, a public urban park (40° 22' 11" N, 3° 39' 41" W) located in Madrid (Spain). 2012 was considered the starting point of the study, since it was the first year with reclaimed water irrigation on this park. Two adjacent plots were selected for the study (Fig. 3.1), one irrigated with reclaimed water (RW) and another one with drinking water (DW). Study plots were adjacent and its size was of 415 and 382 m<sup>2</sup> for DW and RW, respectively. The mean seasonal amount of irrigation was about 940 mm for each plot. Both irrigation waters were sampled once a year directly from the park's sprinklers. These samples were collected in plastic bottles, refrigerated and transferred to the laboratory for further analysis. Each water sample was analyzed following the procedures described by APHA (2012).

Climate in Madrid is classified as Mediterranean semi-arid by Martonne (Quan et al., 2013), characterized by warm and dry summers and cold winters. Average annual precipitation is 421 mm, annual mean temperature is 15 °C and average annual evapotranspiration  $ET_o$  (Penman-Monteith) is 930 mm (1981-2010) (AEMET, 2018).



**Fig. 3.1.** Location of the experiment site.

### 3.2.2. Soil parameters and soil sampling

#### 3.2.2.1. Bulk density & porosity

Four undisturbed soil samples (0–5 cm, 10–20 cm, 30–40 cm, 55–65 cm) per treatment were randomly collected using core stainless cylinders (51 mm long × 50 mm diameter). These undisturbed samples were used to determine bulk density, macro-, meso- and microporosity. First, the samples were saturated with water by capillarity in a sandbox to determine pF between 0 and 2.0 (0.1 to 10 kPa) by successive weight measurements, as the cores slowly dried in the sandbox. Schofield (1935) introduced the pF scale, which express the relationship between the amount of water in a soil and the force with which it is held (Eq.1). Where  $h$  is the height in cm of a column of water, which would give a pressure numerically equal to the suction.

$$pF = \log_{10} h \quad (\text{Eq.1})$$

Water retention between 2.54 and 4.2 pF (33 to 1500 kPa) was determined using a progressive drying process with pressure plate extractors (Richards, 1941). Finally, the samples were completely dried in oven (24h at 105 °C). The weight of these dried samples also allowed the determination of the bulk density.

The relationship between pore size and water retention capacity was established as follows: macropores ( $>60\ \mu\text{m}$ ) corresponding to matric potentials between pF 0 and 1.8; mesopores ( $60\text{ to }10\ \mu\text{m}$ ) correspond to pF values between 1.8 and 2.54 and micropores ( $<10\ \mu\text{m}$ ) having  $\text{pF} \geq 2.54$ . Pores smaller than  $0.2\ \mu\text{m}$  diameter correspond to matric potentials higher than pF 4.2 (1500 kPa). The categorization of these kind of pores is consistent with current literature (e.g. Bienes et al., 2016; Taboada et al., 2004).

#### *3.2.2.2. Soil chemical properties*

At each plot, soil samples were collected at four depths: 0–5 cm, 10–20 cm, 30–40 cm, 55–65 cm using a 6-cm Edelman-type auger. Soil sampling was carried out twice a year, once in March (before the irrigation season) and once in October (right after the irrigation season). Each soil sample contained approximately 1 kg of soil and was composed of three soil sub-samples randomly collected from each depth. These samples were air-dried, then passed through a 2 mm sieve and ground before analysis by ion chromatography and potentiometry determination of the saturated paste extract as described by Rhoades (1982).

#### *3.2.2.3. Aggregate stability and Soil organic matter*

Two kinds of aggregate stability analysis were carried out, the water stable aggregates (WSA) and the counting number drops (CND). WSA was used to assess microaggregate stability and CND to assess macroaggregate stability. The CND is a method which assess the number of drop impacts required to destroy a macroaggregate (Imeson and Vis, 1984). The CND test tries to imitate the impact of natural raindrops (Cerdà, 1998). In order to determine aggregate stability, 30 macroaggregates (size 4 to 4.75 mm diameter) of each air-dried sample were randomly selected to conduct this test (Boix-Fayos et al., 2001).

Water stable aggregates (WSA method) was expressed as the percentage of the microaggregates (0.25 to 2 mm) resistant to wet sieving (USDA, 2001). Aggregate samples were submerged and emerged over a 0.25 mm sieve at 30 oscillations per minute, for three

minutes. These calculations were corrected for sand content. Three subsamples of 5 g were evaluated.

Soil organic matter (SOM) was determined by wet oxidation (Walkley and Black, 1934).

#### *3.2.2.4. Infiltration rates*

To assess infiltration rates a single-ring infiltrometer (12 cm diameter) has been used, carrying out five repetitions per treatment. Before infiltration tests, vegetation cover was carefully removed by cutting it with scissors and then it was registered the time it takes to infiltrate 25 mm of distilled water. This was repeated 10 times in order to reach field capacity and obtain a constant infiltration rate. It was conducted in 2016.

#### *3.2.2.5. Penetration resistance*

A hand Eijkelkamp penetrometer (Mod.06.01) has been used to determine the penetration resistance of soils. This test was carried out 10 times randomly in each plot, in June 2012 and September 2016, aiming to check differences along time. Penetration resistance readings were made at the following soil depths: 2.5, 5, 10, 15, 20, 25, 30, 35, 40 and 45 cm.

#### *3.2.3. Statistical analysis*

All data were analyzed using IBM SPSS Statistics for Windows, version 22.0 (Armonk, NY: IBM Corp.). Normality was assessed by Kolmogorov-Smirnov test and Levene test was used to verify homogeneity of variance. The differences between the means of each parameter were established using a t-test and between different depths, using the one-way ANOVA and post hoc Bonferroni's multiple comparison tests at a 0.05 significance level. When data did not follow a normal distribution even after a data transformation, non-parametric Mann-Whitney U test was applied. Pearson correlation index was used to assess relationships between dependent variables.

### **3.3. Results**

#### *3.3.1. Irrigation water*

The main physico-chemical parameters for drinking water (DW) and reclaimed water (RW) are presented in Table 3.1. Reclaimed water increased significantly concentrations of most of

the ions, especially  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{K}^+$  and  $\text{Na}^+$  in comparison with drinking water. SAR and electrical conductivity (EC) also presented significantly greater values in reclaimed water.

**Table 3.1.** Physico-chemical characteristics of drinking and reclaimed water used during the experiment. Mean and standard deviation (SD) values were calculated from the five years of study (2012-2016). TDS-Total Dissolved Solids; EC-Electrical Conductivity; nd-not detected.

Parameter	DW	RW	n
$\text{HCO}_3^-$ (mg L <sup>-1</sup> )	29.8 ± 20.7 a	167 ± 98.5 b	5
$\text{Cl}^-$ (mg L <sup>-1</sup> )	16.8 ± 2.9 a	114 ± 23.6 b	5
$\text{NO}_3^-$ (mg L <sup>-1</sup> )	1.7 ± 1.2 a	15.5 ± 15.1 a	5
$\text{NO}_2^-$ (mg L <sup>-1</sup> )	0.2 ± 0.1 a	5.9 ± 8.4 a	5
$\text{PO}_4^{3-}$ (mg L <sup>-1</sup> )	nd	0.3 ± 0.6	5
$\text{SO}_4^{2-}$ (mg L <sup>-1</sup> )	14.1 ± 1.8 a	97.6 ± 28 b	5
$\text{NH}_4^+$ (mg L <sup>-1</sup> )	0.3 ± 0.5 a	18.7 ± 17.2 a	5
$\text{Ca}^{2+}$ (mg L <sup>-1</sup> )	13.1 ± 3.4 a	44.2 ± 9.5 b	5
$\text{Mg}^{2+}$ (mg L <sup>-1</sup> )	2.3 ± 0.6 a	11.1 ± 2.8 b	5
$\text{K}^+$ (mg L <sup>-1</sup> )	1.1 ± 0.1 a	19.7 ± 3.2 b	5
$\text{Na}^+$ (mg L <sup>-1</sup> )	8.2 ± 1.1 a	77 ± 13.9 b	5
SAR	0.3 ± 0.1 a	2.8 ± 0.6 b	5
TDS (g L <sup>-1</sup> )	0.1 ± 0.0 a	0.6 ± 0.1 b	5
pH	7.6 ± 0.2 a	7.5 ± 0.3 a	5
EC (dS m <sup>-1</sup> )	0.1 ± 0.02 a	0.9 ± 0.07 b	5

Different letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test between treatments.

### 3.3.2. Soil chemical properties

Table 3.2 shows the chemical characteristics of soils in both plots. Significant differences between both treatments were found for most of the main parameters,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ , SAR and EC, being higher for RW plot. Almost all these nutrients match with nutrients with higher values for reclaimed irrigation water. There was a significant correlation between nutrient concentration in irrigation water and in soils for  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , SAR and EC.

**Table 3.2.** Chemical characteristics of the saturated paste extract of soils for both treatments (2012 – 2016). Average, standard deviation (SD) and number of cases (n). EC-Electrical Conductivity.

Parameter	DW	RW	n
HCO <sub>3</sub> <sup>-</sup> (mg L <sup>-1</sup> )	181 ± 84 a	191 ± 120 a	40
Cl <sup>-</sup> (mg L <sup>-1</sup> )	42.1 ± 24.6 a	116 ± 78.9 b	40
NO <sub>3</sub> <sup>-</sup> (mg L <sup>-1</sup> )	46.4 ± 81.1 a	72.9 ± 120 a	40
PO <sub>4</sub> <sup>3-</sup> (mg L <sup>-1</sup> )	6.8 ± 13.7 a	5.2 ± 8.1 a	40
SO <sub>4</sub> <sup>2-</sup> (mg L <sup>-1</sup> )	66.7 ± 46.3 a	150 ± 104 b	40
Ca <sup>2+</sup> (mg L <sup>-1</sup> )	66.1 ± 30.2 a	88.0 ± 36.9 b	40
Mg <sup>2+</sup> (mg L <sup>-1</sup> )	19.6 ± 7.6 a	28.1 ± 17.2 b	40
K <sup>+</sup> (mg L <sup>-1</sup> )	14.4 ± 10.9 a	18.2 ± 10.5 b	40
Na <sup>+</sup> (mg L <sup>-1</sup> )	22.1 ± 8.6 a	76.0 ± 37.2 b	40
N <sub>TOT</sub> (mg kg <sup>-1</sup> )	1071 ± 1065 a	1426 ± 1260 a	40
SAR	0.6 ± 0.2 a	1.8 ± 0.7 b	40
pH	7.9 ± 0.4 a	7.9 ± 0.3 a	40
EC (dS m <sup>-1</sup> )	0.7 ± 0.3 a	1.1 ± 0.4 b	40

Different letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test between treatments.

### 3.3.3. Aggregate stability

The results of aggregate stability tests and soil organic matter are presented in Table 3.3. SOM values presented significant differences between depths for the same treatment, being higher in the topsoil (0-5 and 10-20 cm). Likewise, SOM shown statistically higher values in the RW treatment than in the DW one, for every depth except for the 55-65 cm thickness.

WSA test revealed significant differences between treatments in the topsoil (0-5 cm) and in the deepest (55-65 cm) layer. Microaggregate stability (WSA) was higher in RW treatment in the top layer. Nevertheless, in the 55-65cm layer WSA was statistically higher for DW treatment. In terms of differences between depths in DW, it was clearly shown two levels, 0-5 and 10-20 cm where percentage of WSA was significantly higher than values in 30-40 and 55-65 cm. The same occurred for RW, although intermediate levels did not show statistical differences between the top and the deepest layer.

**Table 3.3.** Soil Organic Matter (SOM), Na (mg L<sup>-1</sup>) in saturated paste extract, Microaggregate stability (WSA: Water stable soil aggregates) and Macroaggregate stability (CND: Counting Number Drops) for both treatments. Average, standard deviation (SD) and number of cases (n).

Treatment	Depth	SOM (%)	n	Na (mg L <sup>-1</sup> )	n	WSA (%)	n	CND	n
DW	0-5 cm	5.5 ± 0.9 aA	9	19.1 ± 6 aA	30	62.1 ± 3 aA	3	29 ± 34 aA	30
	10-20 cm	1.6 ± 0.3 abA	9	22.4 ± 6 aA	30	53.9 ± 8 aA	3	35 ± 48 aA	30
	30-40 cm	0.4 ± 0.1 bcA	9	24.2 ± 12 aA	30	33.7 ± 4 bA	3	19 ± 14 aA	30
	55-65 cm	0.3 ± 0.1 cA	9	22.8 ± 9 aA	30	32.3 ± 4 bA	3	40 ± 44 aA	30
RW	0-5 cm	6.9 ± 1.0 aB	9	67.5 ± 34 aB	30	70.0 ± 4 aB	3	18 ± 17 abB	30
	10-20 cm	2.6 ± 0.6 abB	9	79.9 ± 27 aB	30	53.5 ± 8 abA	3	19 ± 12 aA	30
	30-40 cm	0.9 ± 0.5 bcB	9	80.3 ± 40 aB	30	37.2 ± 15 bcA	3	42 ± 53 aA	30
	55-65 cm	0.4 ± 0.3 cA	9	76.3 ± 44 aB	30	22.4 ± 2 cB	3	17 ± 33 bB	30

Different lowercase letters mean significant differences at  $p < 0.05$  between depths for the same treatment. Different uppercase letters mean significant differences at  $p < 0.05$  between treatments for the same depth.

Regarding macroaggregate stability (CND test), it was significantly higher for DW in the topsoil and in the deepest layer. Furthermore, there were no differences between the four layers in DW, whereas for RW there were only differences between the 55-65 cm layer and the two intermediate layers.

There was a significant correlation between SOM and microaggregate stability (WSA). However, no significant correlation was found between SOM and CND or between CND and WSA (Table 3.4).

**Table 3.4.** Correlation matrix between: Soil Organic Matter (SOM), Microaggregate stability (WSA: Water stable soil aggregates) and Macroaggregate stability (CND: Counting Number Drops).

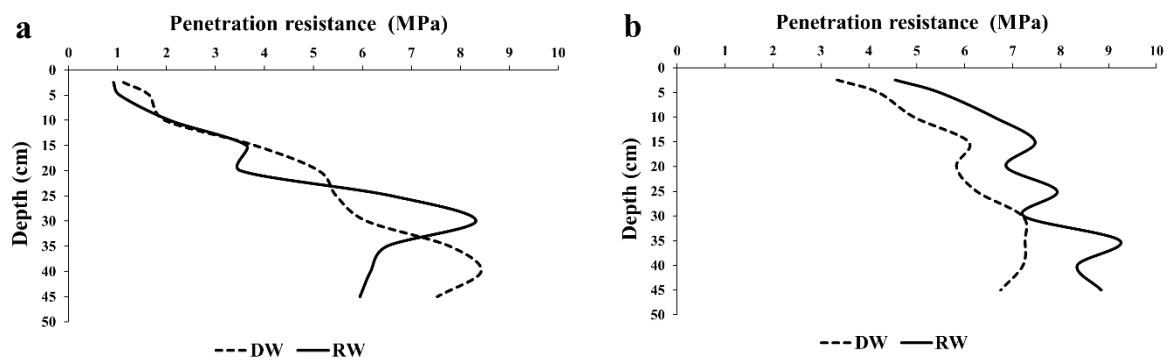
Variable	SOM	WSA	CND
SOM	1	0.821*	-0.085
WSA	0.821*	1	-0.028
CND	-0.085	-0.028	1

\* Significant at statistical level of  $p < 0.01$



### 3.3.4. Soil penetration resistance

Soil penetration resistance (MPa) for 2012 and 2016 in both plots is shown in Fig. 3.2 and Table 3.5. In 2012 soil penetration resistance was similar for both plots, although it was significantly different in surface versus deeper layers, being higher in the last ones, for both treatments. Fig. 3.2b shows the results of the test carried out 4 years later, in 2016. These results were clearly different in comparison with those obtained in 2012 (Fig. 3.2a). Penetration resistance values had strongly increased in surface and slightly in deep soil layer.



**Fig. 3.2.** Soil penetration resistance (MPa) in 2012 (Fig. 3.2a) and 2016 (Fig. 3.2b).

In order to compare soil penetration resistances, it was considered useful to cluster results by depth (Bienes et al., 2016) (Table 3.5). Thus, we considered two layers: a superficial one (0-10 cm) strongly affected by the root zone of the grass, and a deeper one (15-45 cm). We obtained significant higher values of soil penetration resistance in 2016 in comparison with 2012, except for the 15-45 cm layer in DW plot that remained stable. Moreover, in 2016, significant differences were found between treatments in both layers, being always higher for RW. Whereas in 2012 there were only significant differences for the superficial layer (0-10 cm), being higher for DW.

**Table 3.5.** Penetration resistance (MPa) after 5 years of reclaimed water irrigation. Average, standard deviation (SD) and number of cases (n).

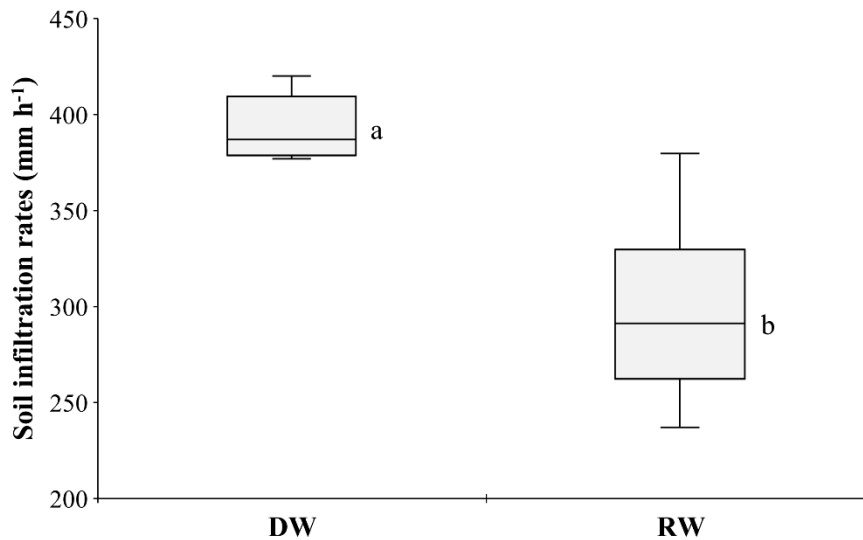
Year	Treatment	Penetration resistance (MPa)			
		0 – 10 cm	n	15 – 45 cm	n
2012	DW	1.58 ± 0.77 aA	36	6.01 ± 3.15 aA	61
	RW	1.38 ± 1.22 bA	32	5.16 ± 3.16 aA	41
2016	DW	4.16 ± 1.64 aB	36	6.55 ± 2.30 aA	61
	RW	5.54 ± 2.06 bB	30	7.11 ± 1.90 bB	45

Different lowercase letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test, between treatments for the same year and depth.

Different uppercase letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test, between years for the same treatment and depth.

### 3.3.5. Soil infiltration rates

Soil infiltration rate was significantly higher in DW ( $392 \pm 16 \text{ mm h}^{-1}$ ) compared to RW ( $296 \pm 40 \text{ mm h}^{-1}$ ) (Fig. 3.3). Furthermore, there was a high degree of variability in the results for soil infiltration rates in RW.



**Fig. 3.3.** Box-plot diagram of infiltration rate ( $\text{mm h}^{-1}$ ) in DW and RW. Different letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test.

### 3.3.6. Porosity and bulk density

Soil texture (0-65 cm) was classified as sandy clay loam according to USDA soil classification for both plots. After five years of reclaimed water irrigation, there was no significant difference in porosity neither soil bulk density between the two plots. Table 3.6 shows the results of several fractions of porosity in both plots (0-65 cm), without significant differences between the two treatments.

**Table 3.6.** Average, standard deviation (SD) and number of cases (n) of bulk density (BD, g cm<sup>-3</sup>) and volumetric percentage of micro, meso, macroporosity and total porosity (TP) (2016 sampling).

Treatment	% Clay	% Sand	% Silt	Soil texture	BD (g cm <sup>-3</sup> )	Microporosity (<10µ)	Mesoporosity (10-60 µ)	Macroporosity (>60 µ)	TP	n
DW	21	56	23	Sandy clay loam	1.3 ± 0.2 a	30.0 ± 3.1 a	7.2 ± 1.4 a	15.2 ± 8.9 a	52.3 ± 7.6 a	4
RW	25	54	21	Sandy clay loam	1.5 ± 0.4 a	30.4 ± 1.6 a	5.8 ± 2.9 a	8.9 ± 6.9 a	45.1 ± 9.6 a	4

Different letters mean significant differences at  $p < 0.05$  according to t-test.

## 3.4. Discussion

Overall, both irrigation waters were adequate for irrigation according to Westcot and Ayers (1984). However, some of the physicochemical characteristics of reclaimed water were significantly higher than those obtained in drinking water, especially Na<sup>+</sup> and Cl<sup>-</sup>. That could imply soil salinization after long term reclaimed water irrigation (Zalacáin et al., 2019). Comparing with other studies, [e.g. Lubello et al. (2004); Pedrero et al. (2012); Pereira et al. (2011)] the studied reclaimed water agronomic parameters were within average of tertiary treated wastewaters.

SOM has shown statistically higher values in the RW treatment than in the DW one (Table 3.3). These results were in concurrence with those obtained by Walker and Lin (2008) and Qian and Mecham (2005), who found an increase of SOM content in soils irrigated by wastewater and recycled wastewater for over 40 and 5 years, respectively. Furthermore, SOM accumulation plays a significant role improving soil physical properties, such as soil structure, which is positive for soil development (Li et al., 2015).

Soil aggregate stability is a critical property that affects soil sustainability (Amézketa, 1999) and is often used as an indicator of soil structure (Six et al., 2000). The stability of soil micro- and macroaggregates may be affected by several soil internal factors and external factors, such as climate, biological features and agricultural management, among others (Amézketa, 1999). This property is usually well correlated with soil organic matter content (Six et al., 2004; Tisdall and Oades, 1982). Table 3.3 showed that microaggregate stability was higher for RW treatment in the top layer. Mainly due to the higher content of SOM (6.9%) in the topsoil of this plot compared with DW. Microaggregate stability (WSA) was strongly influenced by the content of SOM, due to the existence of a significant correlation between them (Table 3.4). That was in accordance with Boix-Fayos et al. (2001), who concluded that small aggregates (< 1 mm) were positively correlated with organic matter and clay content. Other factor affecting the higher microaggregate stability in the topsoil of RW plot was calcium. There is general acceptance that calcium is a critical element for the stabilization of microaggregates through its role in the formation clay–polyvalent cation–organic matter complexes (Six et al., 2004). Bivalent cations ( $\text{Ca}^{2+}$  and  $\text{Mg}^{+2}$ ) improve soil structure through cationic bridging with clay particles (Bronick and Lal, 2005). This could explain that in our study, calcium, which was significantly higher in RW, could have played a relevant role in the higher stability of microaggregates in the topsoil irrigated with RW. However,  $\text{Na}^+$  percolates down through the soil and it reaches the deepest level (55-65 cm) with a higher concentration in RW than in DW (Table 3.3). This, together with a significant decrease in SOM with depth, caused that microaggregates (WSA) were less stable in RW than in DW treatment in the deepest level (55-65 cm).

For coarse and medium textured soils (< 25% clay) the stability of aggregates was unaffected by the quality of the irrigation water (Levy and Mamedov, 2002). In those soils, treated wastewater irrigation, usually with high sodicity that induces conditions which promote clay dispersion, seemed to play a minor role in determining aggregate stability (Levy, 2011). Likewise, Morugán-Coronado et al. (2011) and Bhardwaj et al. (2007) said that in their studies on treated wastewater irrigation, there were not significant differences in the stability of aggregates according to the irrigation treatment. However, Levy and Torrento (1995) found that an increase in sodicity (SAR) caused a decrease in macroaggregate stability. The  $\text{Na}^+$  is a highly dispersive agent which affects directly the breakup of aggregates (Bronick and Lal, 2005). Exchangeable  $\text{Na}^+$  in the soil solution and at exchange sites contribute to repulse

charges that disperse clay particles, which could end up in the breakup of macroaggregates. Thus, we obtained lower significant values in macroaggregate stability (CND) for RW in the top and the deepest layer (Table 3.3). That could be due to the sodium content was significantly higher in RW than in DW treatment (Tables 3.1 and 3.2).

Soil penetration resistance was higher after 4 years in both plots. This increase was statistically significant in the RW plot for both considered depths. A low root density often implies a higher soil penetration resistance, as in the case of crops (Pardo et al., 2000). However, in our case, when a cover of grass was present, the root density per unit of surface was so high, that the penetrometer must break the roots to go down the soil. Consequently, the values obtained were higher. Therefore, the significant increase that occurred in the superficial layer (0-10 cm) after four years could be due to a further development of the root system, especially in RW and slightly in DW. This fact is consistent with the greater biomass production of grass after reclaimed water irrigation (Sastre-Merlín et al., 2015). Additionally, it could be also a sign of soil compaction (Cambi et al., 2017; Demuner-Molina et al., 2013), as bulk density in RW ( $1.5 \text{ g cm}^{-3}$ ) was slightly higher than in DW ( $1.3 \text{ g cm}^{-3}$ ).

Infiltration is a dynamic process and one of the key factors in the soil phase of the hydrological cycle (Lado and Ben-Hur, 2009). After four years of reclaimed water irrigation, the steady-state infiltration rate was significantly lower in the RW plot rather than in DW (Fig. 3.3). These results match with those obtained by Bedbabis et al. (2014), which using a double-ring infiltrometer, also observed a significant decrease of soil infiltration rate after four years of treated wastewater irrigation. Likewise, this decrease in soil infiltration rates has also been described by other authors (Abo-Ghobar, 1993; Lado et al., 2005; Sou-Dakouré et al., 2013; Tunc and Sahin, 2015). Although SAR values were not as high as in other studies (Bedbabis et al., 2014; Sou-Dakouré et al., 2013), they could be slightly affecting the infiltration rate (Suarez et al., 2006). The proportion of sodium in relationship with calcium was around 2.8 times higher in reclaimed water than in drinking water (Table 3.1). This negative effect of  $\text{Na}^+$  could be related with the lower macroaggregate structural stability for RW treatment (0-5 and 55-65 cm) and, consequently, with the lower infiltration rate in RW plot. It should be noted that even a small percentage of unstable aggregates may have an important effect on infiltration (Imeson and Vis, 1984). This decrease of infiltration rate in RW could be also a consequence of the slightly lower macroporosity in this plot (Table 3.6).

However, infiltration rate for both treatments was classified as rapid according to USDA classification (USDA, 2001).

The overall increase in bulk density on the topsoil has been a common outcome in areas irrigated with reclaimed water (Aiello et al., 2007; Coppola et al., 2004; Wang et al., 2003). We obtained bulk density values slightly higher in RW than in DW (Table 3.6), without a statistical significance. Micro-, meso- and macroporosity results showed that in five years of treatment with reclaimed water, there was no influence of irrigation treatment. These results were in accordance with those obtained by Abedi-Koupai et al. (2006). In their study in an arid region (Iran), they found no significant difference for the average soil porosity between the wastewater and groundwater irrigation treatments. However, other authors have shown a decrease in soil porosity after long-term reclaimed water irrigation (Wang et al., 2003) via narrowing meso- and macropores (Bardhan et al., 2016).

### 3.5. Conclusions

Reclaimed water from Madrid was within average of tertiary treated wastewaters in comparison with other studies. Irrigation with reclaimed water increased microaggregate stability (WSA) in the topsoil for the RW plot, apparently because of the higher values of SOM. However, the other layers remained overall stable. Higher significant values were found in the topsoil and in the deepest layer of DW for macroaggregate stability (CND). That could be due to the higher presence of  $\text{Na}^+$  in RW, which operates as a highly dispersive agent affecting directly the macroaggregate stability. In summary, irrigation with RW increased the amount of water-stable microaggregates (WSA) in the topsoil, but decreased the resistance of macroaggregates (CND).

Soil penetration resistance was significantly higher in the RW plot, probably due to a further development of the root system. Moreover, reclaimed water irrigation also led to a decrease in infiltration rate, mainly because of the influence of sodium. On the other hand, porosity results showed that there was no significant influence of the kind of irrigation water used, although bulk density obtained was slightly higher in RW than in DW.

Results support that reclaimed water irrigation in urban parks is potentially leading to a modification of some soil properties, which are key in the urban parks soil systems. Thus, to avoid future problems, the use of reclaimed water for urban parks irrigation should be

continuously monitored. More studies are required to assess the influence of irrigation water and to determine the long-term effects on the soil system in urban parks.

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## CHAPTER 4

**Turfgrass biomass production  
and nutrient balance of an urban park  
irrigated with reclaimed water**



## Abstract

The increasing demand for water resources in arid and semiarid countries has stimulated the use of non-conventional water resources such as reclaimed water. Consequently, turfgrass irrigation with reclaimed water has become a regular practice in these regions. The main goal of this research was to assess the effects of reclaimed water (RW) irrigation in Madrid urban parks by studying changes in grass nutrient balance and its biomass production.

Irrigation with reclaimed water led to a grass biomass increase, mainly due to the high proportion of nutrients received through the irrigation water. The main nutrient input in RW irrigation were of Cl, S, K and Na. RW also contributed to a significant increase in nutrient removal by grass.

Thus, all this information generated should be taken into account by park managers in order to fulfill the grass aesthetic value and its nutritional requirements in those urban parks irrigated with RW.

## 4.1. Introduction

The increasing demand for water resources in arid and semiarid countries has led water managers to look for new measures to provide water continuously throughout the year, regardless meteorology. This search, enhanced by climate change, has stimulated the use of non-conventional water resources, such as reclaimed water (Bdour et al., 2009; Norton-Brandão et al., 2013; Tram VO et al., 2014). Since the old times wastewater was reused for agricultural irrigation (Angelakis et al., 2005). Nevertheless, unplanned reuse together with a lack of adequate potable water and wastewater treatments caused catastrophic epidemics, such as cholera (Asano and Levine, 1996). However, the advances in water treatment technologies in the last century have enabled the quick development of this resource, mainly in countries with this technological expertise (Battilani et al., 2010; Z. Chen et al., 2013).

Agriculture is the main use of reclaimed water, and it has been expanded all over the world (Pedrero et al., 2010; Sato et al., 2013). Moreover, reclaimed water is also used for golf courses (Benlouali et al., 2017; Lockett et al., 2008; Murakami and Ray, 2000), urban parks and garden irrigation (Chen et al., 2015; Furumai, 2008). Even Harivandi (2000) held that turfgrasses may be the best plants for reclaimed water irrigation. One of the major leaders in water reuse is the State of California (USA). Since the late 1920s this State has been using reclaimed water for agricultural and landscape irrigation, groundwater recharge and industrial use (Asano and Levine, 1996; Wu et al., 2001). Urban reuse in California is mainly intended for turfgrasses irrigation in both golf courses and lawns (O'Connor et al., 2008). Thus, grass irrigation is a major water consumer activity in the country as a whole (Sidhu et al., 2015).

Use of reclaimed water carries several advantages, which are the main reasons to promote water reuse all over the world. The main advantages lies in keeping fresh water to be used in high-quality practices, such as human consumption (Meneses et al., 2010) and its feasibility as a continuous source throughout the year, regardless the rainfall pattern (Toze, 2006). Moreover, reclaimed water irrigation could increase the available amount of nutrients for plants (Ali et al., 2013; Pedrero et al., 2015). Turfgrasses, in particular, can absorb relatively large amounts of nitrogen and other nutrients often found in higher concentrations in reclaimed water. That reduces the risk of groundwater contamination (Harivandi, 2000) as well as the dependence on fertilizer application and, accordingly, promotes sustainability (Angelakis and Durham, 2008; W. Chen et al., 2013b).

However, public opinion usually opposes to water reuse projects due to the idea that exposure to reclaimed water is unsafe (Buyukkamaci and Alkan, 2013; Garcia-Cuerva et al., 2016). Furthermore, some landscapers and farmers are reluctant to use reclaimed water (Tanji et al., 2007), mainly by their concern about salinity damage in soil and plants. Soil salinization could result in direct injury to turfgrass and may lead to problems of soil structure loss (Evanylo et al., 2010; Marcum, 2006). Likewise, reclaimed water could cause soil health degradation and provoke a heavy metal accumulation if it is not properly managed (Rahman et al., 2016).

Nowadays water reuse has become a key resource in water management in arid and semiarid parts of the world (Ait-Mouheb et al., 2018; Kellis et al., 2013; Mizyed, 2013). Consequently, landscape irrigation with reclaimed water is becoming a regular practice in these areas (Han et al., 2016; Nouri et al., 2013a; Palacios et al., 2017; Qian and Mecham, 2005). In Spain, there are several examples of water reuse in park and golf course irrigation, especially in the Mediterranean Rim (Candela et al., 2007; Iglesias et al., 2010). Furthermore, it is expanding all over the country and more than 2300 hectares of land are irrigated with reclaimed water in the whole Madrid region (Community of Madrid, 2016). One of the main projects is sited in its capital, where the Madrid City Council began to irrigate most of its urban parks with reclaimed water since the first years of this century. Nowadays, the City Council of Madrid has settled a vast system of more than 150 km of pipes and 65 deposits in order to irrigate its parks with reclaimed water (Madrid City Council, 2019).

Garden and park irrigation are among the largest consumers of water in cities (Nouri et al., 2013b). The use of municipal reclaimed water to irrigate green areas and urban parks is a valuable attempt to maximize the existing water resources (Hassanli, 2013) and to promote the development of a circular economy (Lyu et al., 2016). This new paradigm implies the identification, description and matching of the input-output nutrient flows in terms of quantity and quality (Wielemaker et al., 2018). Nutrient balance (N, P, K and other elements) refers to the total amount of effective nutrients entering into the system through reclaimed water irrigation, which can be absorbed and used by plants as nutrients (Xu et al., 2016). Salinity often affects this nutritional balance of plants by several mechanisms, including osmotic effects of salts, competitive interactions among ions in the substrate and effects on membrane selectivity (Azza Maher et al., 2007). Thus, the accumulation of nutrients by grass

over the growing season is dependent upon harvest interval, water availability and applied nutrients (Allhands and Overman, 1995).

Conversely, few studies have assessed the effects of reclaimed water irrigation in grass (Ahmad et al., 2010; Evanylo et al., 2010; Lockett et al., 2008) and we do not know that someone has done it for urban-park turfgrass. Therefore, the main goal of this research was to assess the effects of reclaimed water irrigation in urban parks by studying changes in grass nutrient balance and its biomass production. This research also aimed to acquire reliable and useful information to help municipal managers in their decision-making process for maintaining urban parks in a good environmental status.

## 4.2. Materials and methods

### 4.2.1. Study area

The study was carried out in the city of Madrid (Spain) and was performed during three consecutive years (2015, 2016 and 2017) at Garrigues Walker Park (40° 22' 11" N, 3° 39' 41" W). This urban public park has been irrigated with reclaimed water since 2012. Two adjacent plots were selected for the study, one irrigated with reclaimed water (RW) and another one with drinking water (DW). Each plot had low-pressure sprinklers (Hunter PGP ultra, Hunter Industries) at a spacing of 7 m and operating within manufacturer's specifications. Specifically, DW plot had 11 sprinklers evenly distributed within 415 m<sup>2</sup> and RW plot had 10 sprinklers distributed in 382 m<sup>2</sup>. Soil texture (0-0.65 m) was classified as sandy clay loam according to USDA soil classification for both plots (Table 4.1). Soils were classified as Terric Anthrosols (IUSS Working Group WRB, 2015).

Average annual precipitation in Madrid (1981-2010) is 421 mm, annual mean temperature is 15 °C (AEMET, 2019) and average annual evapotranspiration ET (Penman) is 930 mm. According to these data, Madrid's climate is classified as arid by Lang aridity index and as Mediterranean semi-arid by Martonne (Quan et al., 2013). It is characterized by dry and warm summers and cold winters. The most precipitation is concentrated in spring and autumn.

**Table 4.1.** Particle size distribution, pH, Soil Organic Matter (SOM) and soil texture in the plots at the beginning of the study (2015).

Study plot	Depth	pH	% SOM	% Clay	% Sand	% Silt	Soil texture
<b>DW</b>	0-0.05 m	8.2	5.3	18	57	25	Sandy loam
	0.10-0.20 m	8.2	1.6	29	51	21	Sandy clay loam
	0.30-0.40 m	8.2	0.4	25	56	20	Sandy clay loam
	0.55-0.65 m	7.9	0.3	21	63	17	Sandy clay loam
<b>RW</b>	0-0.05 m	8.0	7.4	21	63	17	Sandy clay loam
	0.10-0.20 m	8.2	2.7	31	48	21	Sandy clay loam
	0.30-0.40 m	8.0	1.3	28	52	21	Sandy clay loam
	0.55-0.65 m	7.8	0.6	24	57	20	Sandy clay loam

#### 4.2.2. Irrigation water sampling and analysis

Irrigation season usually lasted from March to October (8 months) and plots were irrigated on a daily basis, except on weekends (Table 4.2). Differences of irrigation amounts between DW and RW may be caused by water leaks or meter inaccuracies on water meters installed in both plots. The irrigation amount (mm) was calculated to be the same for both plots. Once a year, in July, reclaimed water and drinking water were sampled directly from the park's sprinklers. Samples were collected in 125 ml plastic bottles, refrigerated and transferred to the laboratory for further analysis. The parameters evaluated were: Electrical Conductivity (EC), Total Dissolved Solids (TDS), pH and concentrations of  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\text{PO}_4^{3-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{NH}_4^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$  and  $\text{Na}^+$ . Ion concentration was determined by ion chromatography, except for bicarbonates and pH that were potentiometrically determined. Each water sample was analyzed following the procedures described by APHA (2012).

#### 4.2.3. Grass sampling and analysis

Grass biomass was weighed after each mowing, with a portable weighing scale (Silvercrest, Germany). There were eight harvests per year as an average. Samples of grass were collected from each plot every time the landscaping staff mowed the grass. Each sample contained approximately 500 g of fully developed mown grass. Samples were placed in paper bags and transferred to the laboratory, where they were rinsed with distilled water, oven dried at 60 °C, and finally crushed. Following acid digestion with nitric acid in a microwave system

(Kalra, 1998), nutrient concentration (Ca, K, Mg, Na, P, S, B, Cu, Fe, Mn and Zn) was determined by inductively coupled plasma mass spectrometry (Agilent 7700x ICP-MS, USA). Cl was analyzed by potentiometry and Total Nitrogen (TN) by Dumas method (Watson and Galliher, 2001).

**Table 4.2.** Total rainfall (mm), March-October rainfall (mm), evapotranspiration (ET), mean temperature (°C) and irrigation (mm) from the three years of study in both plots: drinking water (DW) and reclaimed water (RW).

Year	Total rainfall (mm)	March-October rainfall (mm)	Total ET (mm)	Mean temperature (°C)	Irrigation DW (mm)	Irrigation RW (mm)
2015	311	238	1306	16.6	949	971
2016	486	287	1222	15.8	877	898
2017	256	163	1310	16.7	1012	1131

#### 4.2.4. Statistical analysis

All data were analyzed using IBM SPSS Statistics for Windows, version 22.0 (Armonk, NY: IBM Corp.). Normality was assessed by Kolmogorov-Smirnov test and Levene test was used to verify homogeneity of variance. The differences between the means of each parameter were established using a t-test at a 0.05 significance level. When data did not follow a normal distribution, even after a data transformation, non-parametric Mann–Whitney U test was applied.

### 4.3. Results and discussion

#### 4.3.1. Irrigation water quality

Table 4.3 shows the main physico-chemical parameters analyzed for drinking and reclaimed water used for irrigation. Most of the ion concentrations showed a statistically significant increase in reclaimed water in comparison with drinking water, specially  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$  and B. Sodium adsorption ratio (SAR), total dissolved solids and electrical conductivity also presented significantly greater values in reclaimed water. Both irrigation

waters were adequate for irrigation according to FAO water quality standards (Ayers and Westcot, 1985). However, some parameters ( $\text{Cl}^-$ ,  $\text{Na}^+$ , EC and TDS) could mean a slight to moderate degree of restriction on use.

**Table 4.3.** Physico-chemical characteristics of drinking and reclaimed water used during the experiment. Mean and standard deviation (SD) values were calculated from the three years of study (2015-16-17). SAR-Sodium adsorption ratio; TDS-Total Dissolved Solids; EC-Electrical Conductivity; nd-not detected.

Parameter	DW	RW	n
$\text{HCO}_3^-$ ( $\text{mg L}^{-1}$ )	$38.4 \pm 16.8$ a	$72.1 \pm 12.7$ b	3
$\text{Cl}^-$ ( $\text{mg L}^{-1}$ )	$18.2 \pm 2.6$ a	$129 \pm 18.5$ b	3
$\text{NO}_3^-$ ( $\text{mg L}^{-1}$ )	$1.5 \pm 1.6$ a	$19.1 \pm 16.5$ a	3
$\text{NO}_2^-$ ( $\text{mg L}^{-1}$ )	$0.3 \pm 0.1$ a	$0.1 \pm 0.2$ a	3
$\text{PO}_4^{3-}$ ( $\text{mg L}^{-1}$ )	nd	$0.9 \pm 1.6$	3
$\text{SO}_4^{2-}$ ( $\text{mg L}^{-1}$ )	$15.9 \pm 2.1$ a	$117 \pm 16.1$ b	3
$\text{NH}_4^+$ ( $\text{mg L}^{-1}$ )	$0.5 \pm 0.6$ a	$0.03 \pm 0.06$ a	3
$\text{Ca}^{2+}$ ( $\text{mg L}^{-1}$ )	$13.2 \pm 4.8$ a	$51.5 \pm 6.6$ b	3
$\text{Mg}^{2+}$ ( $\text{mg L}^{-1}$ )	$2.4 \pm 0.6$ a	$13.2 \pm 1.6$ b	3
$\text{K}^+$ ( $\text{mg L}^{-1}$ )	$1.3 \pm 0.2$ a	$22.0 \pm 1.8$ b	3
$\text{Na}^+$ ( $\text{mg L}^{-1}$ )	$8.6 \pm 1.4$ a	$83.6 \pm 11.8$ b	3
B ( $\text{mg L}^{-1}$ )	$0.02 \pm 0.04$ a	$0.11 \pm 0.04$ b	3
Cu ( $\text{mg L}^{-1}$ )	$0.003 \pm 0.003$ a	$0.018 \pm 0.011$ a	3
Fe ( $\text{mg L}^{-1}$ )	$0.073 \pm 0.064$ a	$0.057 \pm 0.023$ a	3
Mn ( $\text{mg L}^{-1}$ )	$0.008 \pm 0.005$ a	$0.035 \pm 0.022$ a	3
Zn ( $\text{mg L}^{-1}$ )	$0.003 \pm 0.005$ a	$0.156 \pm 0.151$ a	3
TDS ( $\text{g L}^{-1}$ )	$0.09 \pm 0.01$ a	$0.5 \pm 0.02$ b	3
pH	$7.4 \pm 0.6$ a	$7.3 \pm 0.3$ a	3
SAR	$0.4 \pm 0.1$ a	$2.4 \pm 0.3$ b	3
EC ( $\mu\text{S cm}^{-1}$ )	$139 \pm 24.1$ a	$830 \pm 32.6$ b	3

Means with different letters in each column shows significance at  $p < 0.05$  according to t-test.

The concentration of total nitrogen in RW of  $4.38 \text{ mg L}^{-1}$  was below the typical concentration (10 to  $20 \text{ mg L}^{-1}$ ) of reclaimed water originated from secondary treatment plants (W. Chen et al., 2013a). A TN concentration lower than  $5 \text{ mg L}^{-1}$  does not represent a restriction on use

(Ayers and Westcot, 1985). The low concentration obtained could be due to the fact that tertiary treatment was applied in water reclamation plants of Madrid (Madrid City Council, 2019). Many of these reclamation plants employ nitrogen removal to meet water quality criteria (Asano et al., 2007). It should be noted that this TN concentration obtained in RW is under the TN estimated level that has to be in irrigation water (between 10 and 25 mg L<sup>-1</sup>) to meet total annual nitrogen requirements of turfgrasses (Sevostianova and Leinauer, 2014). This water quality, in terms of nitrogen, may be used as a valuable source for irrigation, preventing groundwater contamination, despite it cannot be considered a major source of nitrogen for plants (Rahil and Antonopoulos, 2007). With regard to P and K levels in reclaimed water, they yielded an average value of 0.9 and 22 mg L<sup>-1</sup> in irrigation water applied, respectively. However, the average PO<sub>4</sub><sup>3-</sup> concentration was not detected and was significantly lower for K (1.3 mg L<sup>-1</sup>) in drinking water. These results are consistent with those obtained by other authors for reclaimed water after tertiary treatment (Pedrero et al., 2015; Qureshi et al., 2016). K<sup>+</sup> concentration in this study (22 mg L<sup>-1</sup>) was very similar to the obtained by Qureshi et al. (2016), Bañón et al. (2011) and Valdés et al. (2012): 20.7, 23 and 24.6 mg L<sup>-1</sup>, respectively. Concerning PO<sub>4</sub><sup>3-</sup>, the concentration obtained in this research was similar to other concentrations of tertiary-treated waters. For instance, Pedrero et al. (2015) got a mean PO<sub>4</sub><sup>3-</sup> concentration slightly lower (0.63 mg L<sup>-1</sup>) than ours in three years of study (2008-2010). However, other authors [Valdés et al. (2012), Qureshi et al. (2016) and (Nicolás et al., 2016)] gained higher PO<sub>4</sub><sup>3-</sup> concentrations in the reclaimed water used for irrigation: 1.44, 2.42 and 2.5 mg L<sup>-1</sup>, respectively. In terms of microelement concentration, all of them were below the recommended maximum concentrations of trace elements in irrigation water (Carrow, 2012).

#### 4.3.2. Herbaceous biomass production

Biomass production according to the area of each plot and throughout the entire study period is shown in Fig. 4.1. In most of the harvests (82.6%), wet biomass collected in RW plot was higher than the collected in DW plot. Although both plots presented a high variability in the results, RW was significantly higher altogether (Table 4.4). This is in accordance with several studies that have conducted research on grass growth under RW irrigation (Heidarpour et al., 2007; Rahman et al., 2016). These results are also consistent with those obtained by Ganjegunte et al. (2017), who found that switchgrass produced considerable biomass even under highly saline and sodic conditions. Biomass production is a key factor



in agriculture, but it is not an important concern in landscape plants, where visual appearance and aesthetic value are, in fact, the key features (Cassaniti et al., 2012; Tanji et al., 2007). In the case of landscape plants, maximum growth is not essential and visual quality is not directly related to biomass production (Acosta-Motos et al., 2014). However, a growth reduction may reduce the visual appeal of herbaceous landscape plants (Zollinger et al., 2006).

Generally, reclaimed water and wastewater irrigation lead to a plant biomass increase (Adrover et al., 2008; De Miguel et al., 2013; Tabari and Salehi, 2009). This increase is mainly due to the high proportion of nutrients received through the irrigation water (Rusan et al., 2007). That explains that we had usually found greatest differences between DW and RW in harvests collected during summer months (Fig. 4.1), although there were not statistically significant. However, Evanylo et al. (2010) found that bermudagrass produced greater biomass under potable water irrigation than under reclaimed water irrigation. Nonetheless, bentgrass used in the same study produced higher biomass under reclaimed water irrigation, even being a less salt-tolerant species. Castro et al. (2013) observed that RW irrigation caused a decrease of plant biomass production in a horticultural crop, such as lettuce. It was due to an accumulation of  $\text{Na}^+$  in plant tissues and because lettuce is moderately salt sensitive. Likewise, Ben-Gal et al. (2008) concluded that irrigation water salinity decrease biomass production in bell peppers.

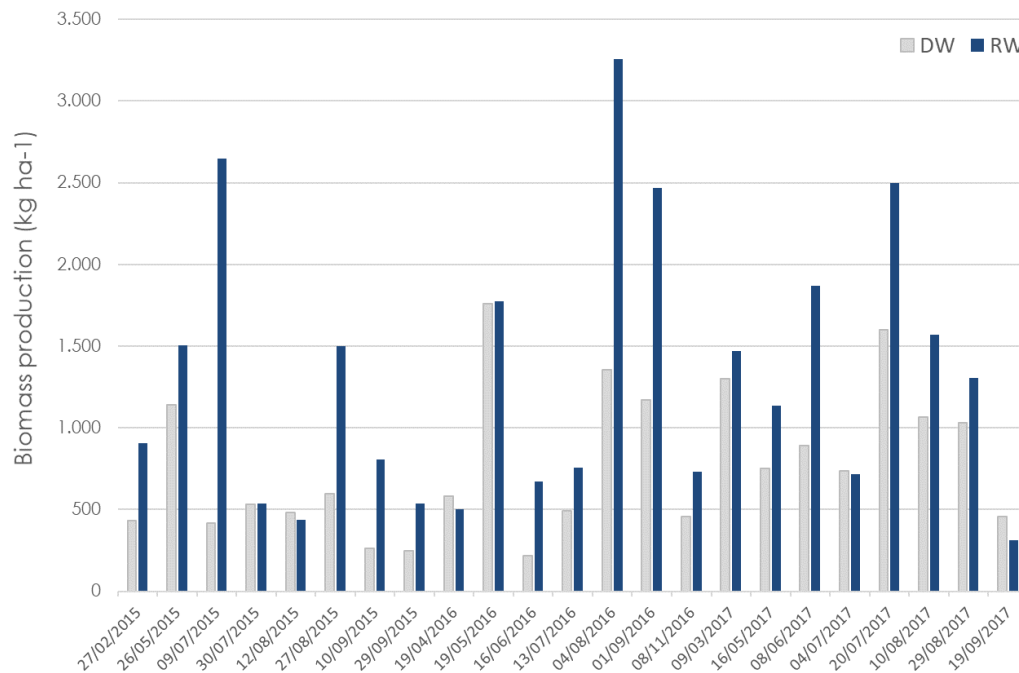
Conversely, this biomass increase could lead to some economic problems, such as the increase of the moving needs, the management of a higher volume of mown grass, and eventually it would require more labor time.

**Table 4.4.** Total herbaceous biomass production in both plots (drinking water (DW) and reclaimed water (RW)). Mean and standard deviation (SD) values of biomass per harvest were calculated for the three years of study (2015-16-17).

Plot	Biomass per harvest ( $\text{kg ha}^{-1}$ )	n	Total biomass ( $\text{kg ha}^{-1}$ )		
			2015	2016	2017
DW	$781 \pm 443$ a	23	4110	6032	7820
RW	$1300 \pm 811$ b	23	8873	10158	10874

Different letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test.

In 2017, biomass production reached a peak in both plots (7820 kg ha<sup>-1</sup> for DW and 10874 kg ha<sup>-1</sup> for RW) due to a higher irrigation amount, a higher mean temperature and a large number of sunshine hours (3001) during 2017. Biomass production in 2016 was higher than in 2015 (Table 4.4). That could be produced by the fact that rainfall from March to October was the highest of the study period together with lower ET than usual (Table 4.1).



**Fig. 4.1.** Herbaceous biomass production (wet weight) in both plots (drinking water (DW) and reclaimed water (RW)) along the study period (27/02/2015 – 19/09/2017).

#### 4.3.3. Nutrient balance

Nutritional input by irrigation water and output by grass extraction are shown in Table 4.5. We considered the irrigation amount (mm) in each plot to evaluate the nutrient input into the system. Other sources of nutrients, such as atmospheric deposition or organic matter decomposition, were not considered. In terms of nutrient input, significant differences between both treatments were found for almost all the parameters, except for micronutrients and TN (Table 4.5). The main nutrient input in RW irrigation were of Cl, S, K and Na. This is according with Ozturk et al. (2011), who concluded that reclaimed water is rich in plant main macronutrients such as potassium and phosphorus. Nutrients in RW could lead to a substantial reduction in fertilizer application, reducing the cost of unnecessary nutrients and

preventing soil contamination (Fan et al., 2014; Murakami and Ray, 2000; Pedrero et al., 2014). Comparing nutrient inputs of several studies in Brazil (Pereira-Leal et al., 2011) with the present research, their results showed a five times lower input for Ca, three times lower for Mg, and three times higher input for Na than in the present study. This was in concordance with Pedrero et al. (2018), who also obtained lower nutrient inputs from RW (300 kg Ca ha<sup>-1</sup> and 60 kg Mg ha<sup>-1</sup>). However, their results showed an increase in P input through reclaimed water, 13 times higher than in the present study.

Moreover, in order to achieve the desired aesthetic appearance and an optimal performance, turfgrass areas require nitrogen inputs (Sevostianova and Leinauer, 2014). Current N fertilization recommendations for maintenance of some turfgrasses in Florida (US) include a range of rates from 98 to 294 kg ha<sup>-1</sup> per year, depending on region and level of aesthetic preference (Trenholm et al., 2012). However, in the present study, TN input was considerably less than this number. It showed a slight difference between both irrigation waters, but was not statistically significant. That was in line with Rahil and Antonopoulos (2007), who said that generally the input of nitrogen on account of reclaimed water is small, due to the advanced treatment processes of activated sludge and nitrification/denitrification. Regarding Na input from RW (832 kg ha<sup>-1</sup>), it was slightly higher than others found in bibliography. Such as De Miguel et al. (2014), who got an input of 542 kg Na ha<sup>-1</sup> in their research of a vegetation filter with poplars.

On the other hand, uptake by vegetation represents an important pathway for nutrient removal, mainly when regular harvesting and removal of biomass is practiced (Tzanakakis et al., 2009). Nutrient removal by grass (Table 4.5) showed statistically significant differences between DW and RW for all the elements, including micronutrients, except for potassium and phosphorus. Pereira-Leal et al. (2011), in their research with sugarcane and 'Tifton 85' bermudagrass, concluded that both crops extracted small amounts of P, due to the low P content of the irrigation water. These results are coincident with those obtained in the present study. Likewise, reclaimed water irrigation introduced large amounts of Na into the system. However, grass only extracted small amounts compared with the total Na input, despite being significantly higher than in DW. This result is in accordance with the results obtained by Pereira-Leal et al. (2011).

High concentrations of Cl<sup>-</sup> in irrigation water reduce NO<sub>3</sub><sup>-</sup> uptake by plants and high concentrations of NO<sub>3</sub><sup>-</sup> inhibit phosphate uptake (Azza Maher et al., 2007). That could explain

the behavior of these elements in the present study, where the Cl input was higher in RW, and nutrient removal of TN was not as high as expected.

**Table 4.5.** Elements of the nutrient input by irrigation water, the nutrient removal by grass biomass (mowing) and the nutrient balance for both plots (drinking water (DW) and reclaimed water (RW)). Mean and standard deviation (SD) values were calculated from the three years of study (2015-2017). nd: not detected.

Parameter	Nutrient input by irrigation water			Nutrient removal by grass biomass (mowing)			Nutrient Balance	
	DW	RW	n	DW	RW	n	DW	RW
Cl (kg ha <sup>-1</sup> )	172 ± 30 a	1281 ± 146 b	3	2.0 ± 1.8 a	5.2 ± 6.3 b	23	170	1275
TN (kg ha <sup>-1</sup> )	7.4 ± 2.7 a	42.6 ± 36 a	3	6.6 ± 4.5 a	12.0 ± 9.5 b	23	0.8	30.5
P (kg ha <sup>-1</sup> )	nd	3.3 ± 5.7	3	1.2 ± 1.1 a	1.5 ± 1.3 a	23	-1.2	1.8
S (kg ha <sup>-1</sup> )	50.6 ± 9.8 a	388 ± 45 b	3	0.8 ± 0.5 a	1.4 ± 1.1 b	23	49.8	387
Ca (kg ha <sup>-1</sup> )	126.6 ± 50 a	513 ± 75 b	3	2.9 ± 2.6 a	4.3 ± 3.1 b	23	123.8	509
Mg (kg ha <sup>-1</sup> )	22.5 ± 5.2 a	131 ± 8.2 b	3	0.8 ± 0.7 a	1.6 ± 1.4 b	23	21.7	129
K (kg ha <sup>-1</sup> )	11.8 ± 2.3 a	218 ± 9.5 b	3	6.6 ± 5.8 a	11.5 ± 12.0 a	23	5.2	207
Na (kg ha <sup>-1</sup> )	82 ± 16.7 a	832 ± 114 b	3	0.2 ± 0.1 a	0.9 ± 1.1 b	23	81.8	831
B (kg ha <sup>-1</sup> )	0.2 ± 0.4 a	1.1 ± 0.4 b	3	0.004 ± 0.003 a	0.01 ± 0.01 b	23	0.2	1.1
Cu (kg ha <sup>-1</sup> )	0.03 ± 0.03 a	0.2 ± 0.1 a	3	0.003 ± 0.002 a	0.01 ± 0.01 b	23	0.03	0.17
Fe (kg ha <sup>-1</sup> )	0.72 ± 0.6 a	0.6 ± 0.2 a	3	0.204 ± 0.174 a	0.62 ± 0.69 b	23	0.52	-0.06
Mn (kg ha <sup>-1</sup> )	0.08 ± 0.04 a	0.3 ± 0.2 a	3	0.014 ± 0.010 a	0.03 ± 0.02 b	23	0.06	0.31
Zn (kg ha <sup>-1</sup> )	0.03 ± 0.05 a	1.5 ± 1.4 a	3	0.013 ± 0.008 a	0.02 ± 0.02 b	23	0.02	1.5

Different letters mean significant differences at  $p < 0.05$  according to Mann–Whitney U test, between treatments.

Data analyzed for irrigation water and for grass nutritional status was used to elaborate a nutrient balance (Table 4.5). A few authors have performed nutrient balance in order to assess the nutritional status of plants irrigated with reclaimed water (Acosta-Motos et al., 2017; Lal et al., 2015). Nutrient balance showed higher differences between inputs and removals for RW treatment than for DW (Table 4.5). Nutrient input for RW plot was higher for Cl > Na > Ca > S, whereas in DW was Cl > Ca > Na > S. The main elements were the same for both irrigation treatments. Negative values were obtained (higher removals than inputs) for the nutrient balance of P in DW and for Fe in RW. That could be explained by a deficit of these elements related to the irrigation water input. Moreover, the amount of TN removed

by harvested grass increases when higher nutrient load is provided by irrigation water (Geber, 2000). This concurs with our data. TN extraction in RW was higher than in DW, due to a larger TN input in RW irrigation water. Therefore, information generated by this study should be taken into account by park managers in order to fulfill the nutritional requirements of grasses in those urban parks irrigated with reclaimed water.

#### 4.4. Conclusions

Reclaimed water irrigation led to a grass biomass increase in most of the harvests, which could contribute to improve the aesthetic value of grass. This increase was mainly due to the high proportion of nutrients received through the irrigation water. By contrast, this biomass increase may involve some inconveniences in park management, such as the increase of the mowing needs, the management of a higher volume of mown grass and the requirement of more labor time.

The main nutrient input in RW irrigation were of Cl, S, K and Na. Reclaimed water led to a statistically significant increase in nutrient removal by grass for almost all elements. Positive values were obtained (higher inputs than removals) in the nutrient balance for most of the elements, except for P in DW and for Fe in RW, which could be explained by a deficit of these elements in the irrigation water input. Thus, all the information generated by this study should be taken into account by park managers in order to fulfill the grass aesthetic value and its nutritional requirements in those urban parks irrigated with reclaimed water.

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## CHAPTER 5

Effects of reclaimed water irrigation  
on micronutrient concentration  
in soils and cedars of urban parks



## Abstract

The use of reclaimed water to cope with water scarcity has become one of the main alternative resources in water-deficit countries. Reclaimed water represents a significant component in the integrated water resources management in the city of Madrid (Spain). The City Council replaced the usual drinking water irrigation system by a reclaimed water one, in most of its green areas. That could be altering soil physico-chemical properties and vegetation development. This study assessed the effects of reclaimed water irrigation on micronutrient concentration (B, Cu, Fe, Mn and Zn) in the water-soil-plant system, of two urban parks in Madrid. Micronutrient concentrations in irrigation water, soils and cedar leaves were analyzed. Results showed that reclaimed water used in Madrid was adequate for irrigation regarding the studied micronutrients. Lower values of micronutrient concentration in soils were obtained when compared with other studies on reclaimed water irrigation in urban parks. Likewise, foliar micronutrient content of cedar leaves were nearly always within the optimum parameters. As there was no correlation between micronutrient concentration in irrigation water and cedar leaves, cedar decline cannot be attributed to the input of these micronutrients by reclaimed water.

## 5.1. Introduction

In many regions of the world, the increasing demand of water resources and the situation of water deficit has created a water stress state. To cope with this water scarcity, the use of reclaimed water has become one of the main alternative resources in water-deficit countries (Garcia and Pargament 2015), such as Spain (Angelakis and Durham 2008). Nowadays, Spain is one of the European leaders in water reuse regarding volume of reclaimed water production as well as legislation (Kirhensteine et al. 2016). Reuse of treated wastewater is ruled in Spain since 2007, by the Royal Decree 1620/2007 (BOE 2007). Furthermore, Spain produced 531,000,000 m<sup>3</sup> of reclaimed water in 2014, 60% of it was intended for agriculture irrigation (INE 2019).

The city of Madrid (3.2 million inhabitants) has developed a huge system of reclaimed water to irrigate most of its urban parks, as other large cities in the world, such as Beijing (China) (Chen, Lu, Pan, et al. 2013; Yi et al. 2011), Denver and San Diego (USA) (Qian and Mecham 2005; San Diego City Council 2019), Adelaide (Australia) (Nouri et al. 2013), Tokyo (Japan) (Furumai 2008). The first thoughts of water reuse in Madrid were in the mid-90s when a severe drought jeopardized the subsistence of the capital's green areas (Iglesias and Ortega 2008). Nowadays, in Madrid there are over 30 green areas irrigated with reclaimed water coming from water reclamation plants. In 2015, 6,600,000 m<sup>3</sup> of wastewater were reclaimed, 78% was intended for green areas irrigation and the 22% remaining for street and sewage cleaning (Madrid City Council 2019).

Irrigation with reclaimed water has significant benefits: its reliability as a continuous water source (Biggs and Jiang 2009; Toze 2006) and the decrease of the pressure on sensitive water bodies (Miller 2006). There have been reported other benefits of reclaimed water use. For instance, the reduction of dependence on other sources of fertilization (Chen, Lu, Peng, et al. 2013; Toze 2006) and a decrease of the pollution load of wastewater discharge (Pedrero and Alarcón 2009). In spite of that, the safety of reclaimed water irrigation has sometimes been questioned, because it may produce adverse effects in soil, soil solution and in plants (Aiello et al. 2007; Castro et al. 2013; Herpin et al. 2007; Jueschke et al. 2008; Rezapour et al. 2012). Some authors had exposed risk of soil salinization (Biggs and Jiang 2009; Lado et al. 2012), as well as an excess of micronutrients and heavy metal accumulation (Farahat and Linderholm 2015; Kim et al. 2015).

Reclaimed water is a source of micronutrients, including B, Cu, Fe, Mn and Zn (Pereira et al. 2012). Although micronutrient concentrations in reclaimed water are regularly low –albeit higher than in drinking water– long-term use of this kind of water could result in an accumulation of these microelements on soils and plants, due to its build-up capacity (Hu et al. 2018; Mujeriego 1990). Some of them had been reported to accumulate in soils and plants after long-term irrigation, depending on the reclaimed water quality, irrigation rate, soil properties and plant uptake (Pedrero et al. 2010; Rusan et al. 2007; Singh et al. 2009). Toxicity of metals depends on many more factors aside from its total concentration, such as their mobility and reactivity with other components of the ecosystem (Abollino et al. 2002). Therefore, low solubility and limited plant uptake cause micronutrients and metals to accumulate in surface soil (Kim et al. 2015).

Several micronutrients as B, Cu, Fe, Mn and Zn have been recognized as essential for plant growth in low concentrations. Nevertheless they can be phytotoxic in higher concentrations (Avci and Deveci 2013). These micronutrients are absorbed and found in lower concentrations in plant tissues, and their function is to supply the nutritional exigency of the plant (da Silva Lobato et al. 2016). These elements have received less attention, compared with macronutrients, in terms of the development and growth of trees (Hagen-Thorn and Stjernquist 2005). Most of the studies about micronutrient accumulation have been carried out in agriculture (Chang et al. 2014; Kalavrouziotis and Koukoulakis 2009; Qureshi et al. 2016), but they do not take into account the effects in urban green areas and its landscape. Despite the fact that there are a few research groups working on the effects of micronutrients in urban green areas irrigated with reclaimed water (Chen et al. 2015; Lyu and Chen 2015), the lack of this kind of studies lead us to put some light on this topic. It should be noted the difficulty to quantify the exact contribution of each single source to the load of trace elements in urban soils because of recurrent disturbances, such as landscaping, construction and irrigation, among others (E. De Miguel et al. 1998). Due to the decline of several cedars in some parks irrigated with reclaimed water, the Madrid City Council wanted to undertake an in-depth study on this issue. Thus, the purpose of this research was to evaluate the effects of five major micronutrients, Boron (B), Copper (Cu), Iron (Fe), Manganese (Mn) and Zinc (Zn) in soils and cedars of two Madrid urban parks after several years of reclaimed water irrigation.

## 5.2. Materials and methods

### 5.2.1. Study area

The study was carried out in the city of Madrid (Spain), where most of its parks are irrigated with reclaimed water. This water comes from water reclamation plants after a tertiary treatment of the wastewater produced by the city. The technology used is microfiltration followed by a combined disinfection process using sodium hypochlorite and ultraviolet irradiation.

Average annual precipitation is 421 mm, the annual mean temperature is 15 °C (1981-2010) (AEMET 2018) and average annual evapotranspiration ET (Penman) is 930 mm, which illustrates the water stress situation. Moreover, the climate in Madrid is classified as Mediterranean semi-arid by Martonne (Quan et al. 2013). It is characterized by warm and dry summers and cold winters, getting nearly all their precipitation during spring and autumn.

The experiment was performed along five consecutive years (2012-2016) in two public urban parks of Madrid: Emperatriz María de Austria Park (hereafter PEMA, 40° 22' 53" N, 3° 43' 16" W) and Garrigues Walker Park (hereafter PGW, 40° 22' 11" N, 3° 39' 41" W). These two parks were irrigated with reclaimed water since 2002 (PEMA) and 2012 (PGW). Two plots irrigated with reclaimed water (PGW\_RW and PEMA\_RW) and other two irrigated with drinking water (PGW\_DW and PEMA\_DW) from each park were selected for the study. Soil texture (0-0.6 m) was classified as sandy clay loam according to USDA soil classification for the four plots, except for PEMA\_DW which was sandy loam.

### 5.2.2. Irrigation water sampling and analysis

The average irrigation volume was about 940 mm per year for each plot. The irrigation season was usually extended through 8 months, from March to October. Once a year, in July, reclaimed water (RW) and drinking water (DW) were sampled directly from the park's sprinklers. These samples were collected in 125 ml plastic bottles, refrigerated and transferred to the laboratory for further analysis. Each water sample was analyzed following the procedures described by APHA (2012). The concentration of micronutrients was determined by inductively coupled plasma mass spectrometry (ICP-MS), except for B, which was measured using ultraviolet-visible spectrophotometry (UV-Vis).

### 5.2.3. Soil sampling and analysis

At each plot, soil samples were collected at four depths: 0-0.05 m, 0.10-0.20 m, 0.30-0.40 m, 0.55-0.65 m using a 6-cm Edelman-type auger. Each soil sample contained approximately 1 kg of soil and was composed of three soil sub-samples randomly collected from each depth. Soil sampling was carried out twice a year, once in spring (before the irrigation season) and once in autumn (right after the irrigation season).

The soil samples were air-dried, then passed through a 2mm sieve and ground before analysis. Cu, Fe, Mn and Zn in soil samples were extracted with DTPA according to Lindsay and Norvell (1978), whereas B in soil samples were extracted with  $\text{CaCl}_2$  solution. Micronutrient concentration was determined as previously mentioned for water samples.

### 5.2.4. Leaves sampling and analysis

Composite samples of cedar leaves (*Cedrus atlantica* [PGW] and *Cedrus deodara* [PEMA]) were collected in July, at irrigation season highpoint. It must be stressed that there were no cedars in PEMA\_DW. Each leaf sample contained approximately 500 g of fully green developed leaves, composed of several sub-samples collected from different specimens present in each plot. Samples were collected around the canopy of each cedar at a height nearly 2 m above the ground. Leaves were placed in paper bags and transferred to the laboratory, where they were rinsed with distilled water, oven dried at 60°C and crushed after that. Following acid-digestion with nitric acid in a microwave system (Kalra 1998), micronutrient concentration was determined by inductively coupled plasma mass spectrometry (ICP-MS).

### 5.2.5. Statistical analysis

The Kolmogorov-Smirnov test was used to evaluate the normality of distribution of the data and Levene's test was used to verify homogeneity of variance. To identify significant differences within the studied variables, a t-test was performed at a 0.05 significance level. When data did not follow a normal distribution, even after a data transformation, a non-parametric Mann-Whitney U test was applied. Differences in the study parameters were compared between the two treatments for each park. Statistical analyses were conducted using IBM SPSS Statistics for Windows, version 22.0 (Armonk, NY: IBM Corp.). Pearson correlation index was used to assess relationships dependent variables. These analyses were performed using the STATISTICA 10 software package (Statsoft, Inc., 2010).

## 5.3. Results

### 5.3.1. Irrigation water

The analysis of both irrigation water types (RW and DW) showed differences in their composition (Table 5.1). Reclaimed water used for irrigation in the studied parks contained larger amounts of micronutrients than drinking water: 3 and 5 times larger for B, 10 and 5 times for Cu, 1.4 and 16 times for Fe, 4 and 10 times for Mn, 10 times higher for Zn, in PGW and PEMA respectively. Nevertheless, there were only significant differences in B content at PEMA site.

**Table 5.1.** The average concentration of micronutrients in irrigation water (mg L<sup>-1</sup>), standard deviation (SD) and number of cases (n).

Treatment	B	Cu	Fe	Mn	Zn	n
PGW_DW	0.03 ± 0.06 a	0.001 ± 0.001 a	0.13 ± 0.11 a	0.01 ± 0.01 a	nd	4
PGW_RW	0.10 ± 0.07 a	0.01 ± 0.01 a	0.18 ± 0.14 a	0.04 ± 0.03 a	0.09 ± 0.14	5
PEMA_DW	0.03 ± 0.05 a	0.002 ± 0.003 a	0.01 ± 0.01 a	0.004 ± 0.002 a	0.003 ± 0.01 a	5
PEMA_RW	0.15 ± 0.04 b	0.01 ± 0.02 a	0.16 ± 0.16 a	0.04 ± 0.03 a	0.03 ± 0.03 a	5
Recommended maximum concentration *	0.7 – 3	0.2	5	0.2	2	

nd: not detected \*Ayers and Westcot (1985)

Different letters in each column mean significant differences at  $p < 0.05$  according to Mann–Whitney U test for each park.

### 5.3.2. Micronutrient concentration in soils

Soils showed significant differences for every micronutrient in PEMA and only for Cu in PGW (Table 5.2). The higher Fe concentration took place in PEMA\_DW, where the mean reached 68.1 mg kg<sup>-1</sup>. Likewise, Mn concentration was significantly higher in PEMA\_DW. On the other hand, soil organic matter (SOM) content and pH did not show any significant differences, despite the fact that SOM was slightly higher in the two plots irrigated with reclaimed water.

**Table 5.2.** Soil organic matter (SOM), pH values and micronutrient concentrations in soil (mg kg<sup>-1</sup>), standard deviation (SD) and number of cases (n).

Treatment	SOM (%)	pH	B	Cu	Fe	Mn	Zn	n
PGW_DW	1.9 ± 2.2 a	7.9 ± 0.4 a	0.3 ± 0.2 a	2.1 ± 1.5 a	12.2 ± 12.4 a	10.5 ± 12 a	5.8 ± 6.4 a	36
PGW_RW	2.7 ± 2.7 a	7.9 ± 0.3 a	0.3 ± 0.3 a	3.3 ± 1.9 b	16.4 ± 16.9 a	6.8 ± 7.5 a	7.2 ± 7.8 a	36
PEMA_DW	1.8 ± 2.4 a	7.6 ± 0.5 a	0.2 ± 0.2 a	1.1 ± 1.2 a	68.1 ± 96.9 a	25.9 ± 33 a	3.1 ± 3.8 a	36
PEMA_RW	2.1 ± 2.4 a	7.8 ± 0.4 a	0.3 ± 0.2 b	2.8 ± 2.5 b	28.5 ± 61.2 b	17.2 ± 33 b	5.7 ± 3.7 b	34

Different letters in each column mean significant differences at  $p < 0.05$  according to Mann–Whitney U test for each park.

### 5.3.3. Micronutrient concentration in cedars

Average micronutrient concentrations in cedar leaves during the five years of study are shown in Table 5.3. The Mn concentration presented significant differences between the two treatments, being higher in the drinking water irrigation plot (PGW\_DW). According to Munson (1998) classification, every parameter concentration was sufficient, except for the deficient levels for Cu in PGW\_DW and for Mn in both plots irrigated with reclaimed water (PGW\_RW and PEMA\_RW). None of the studied element was excessive or toxic according to Munson (1998).

**Table 5.3.** Micronutrient concentrations in cedar leaves (mg kg<sup>-1</sup>), standard deviation (SD) and number of cases (n).

Treatment	B	Cu	Fe	Mn	Zn	n
PGW_DW	51 ± 29 a	4 ± 3 a	309 ± 122 a	48 ± 26 b	24 ± 4 a	6
PGW_RW	64 ± 20 a	5 ± 3 a	223 ± 157 a	10 ± 5 a	23 ± 7 a	6
PEMA_RW <sup>(1)</sup>	67 ± 12	7 ± 5	262 ± 102	19 ± 8	21 ± 5	6
Sufficient content *	10 – 200	5 – 30	100 – 500	20 – 300	20 – 100	

\* Munson (1998). Means with different letters in each column shows significance at  $p < 0.05$  according to t-test.

<sup>(1)</sup> There were not cedars in PEMA\_DW

### 5.3.4. Relationship between variables

There was not significant correlation between micronutrient concentration in irrigation water and in cedar leaves (Table 5.4). However, there were four significant correlations ( $p<0.05$ ) for Cu I – Zn I and for B CL – Fe CL, but they did not show any relationship between irrigation water and cedar leaves micronutrient concentration.

**Table 5.4.** Correlation matrix with micronutrient concentration in irrigation water and in cedar leaves. B I: B concentration in irrigation water; Cu I: Cu concentration in irrigation water; Fe I: Fe concentration in irrigation water; Mn I: Mn concentration in irrigation water; Zn I: Zn concentration in irrigation water; B CL: B concentration in cedar leaves; Cu CL: Cu concentration in cedar leaves; Fe CL: Fe concentration in cedar leaves; Mn CL: Mn concentration in cedar leaves; Zn CL: Zn concentration in cedar leaves.

	B I	Cu I	Fe I	Mn I	Zn I	B CL	Cu CL	Fe CL	Mn CL	Zn CL
B I	1.00	0.28	-0.37	0.22	0.32	0.50	0.32	0.21	-0.07	-0.28
Cu I	0.28	1.00	-0.01	0.27	0.61*	0.32	-0.27	-0.12	0.02	-0.19
Fe I	-0.37	-0.01	1.00	0.48	-0.18	-0.04	-0.15	0.25	-0.02	0.28
Mn I	0.22	0.27	0.48	1.00	0.31	0.52	-0.46	0.36	0.37	-0.37
Zn I	0.32	0.61*	-0.18	0.31	1.00	0.30	-0.19	0.13	0.21	-0.30
B CL	0.50	0.32	-0.04	0.52	0.30	1.00	-0.07	0.55*	0.38	-0.18
Cu CL	0.32	-0.27	-0.15	-0.46	-0.19	-0.07	1.00	0.22	-0.08	0.38
Fe CL	0.21	-0.12	0.25	0.36	0.13	0.55*	0.22	1.00	0.22	0.10
Mn CL	-0.07	0.02	-0.02	0.37	0.21	0.38	-0.08	0.22	1.00	-0.09
Zn CL	-0.28	-0.19	0.28	-0.37	-0.30	-0.18	0.38	0.10	-0.09	1.00

Marked correlations (\*) are significant at  $p<0.05$ .

## 5.4. Discussion

Reclaimed water used in this study was adequate for irrigation according to the observed micronutrient concentrations (Table 5.1). This is due to the five parameters that were within the limits and widely below the maximum concentration suggested by Ayers and Westcot (1985) for irrigation water. Comparing these micronutrient contents with average data from the bibliography (e.g. Ali et al. 2013b; Bedbabis et al. 2015; Díaz et al. 2013), it has been shown that the studied micronutrient content in reclaimed water produced by Madrid wastewater reclamation plants is low. However, the higher contents in RW in comparison with DW



might be causing a long-term accumulation in soils and cedars, as suggested by Chen et al. (2015).

B concentration in the trial plot soils was about  $0.3 \text{ mg kg}^{-1}$  (Table 5.2). These levels were very low according to Ahmad et al. (2012), which establishes as normal values of B concentrations between 2 to  $200 \text{ mg kg}^{-1}$ , but only 5-10% is in a form available to plants. Values  $<0.5 \text{ mg kg}^{-1}$  were reported as deficient by Ahmad et al. (2012). B in form of borate is adsorbed by the clay and hydroxides of Fe and Al, with greater strength as the pH increases. Maximum adsorption is found for pH 8-9 (Goldberg 1997), and soluble B decreases strongly and is not available for plants. The pH of the trial plots was very similar in all of them, fluctuating between 7.6 and 7.9. These pH values were very close to the pH at which the highest adsorption and minimum availability takes place. In addition, in wet or irrigated areas soluble borate is easily leached from the soil profile and this leaching is more intense in coarse-textured soils (Shorrocks 1997). Therefore, it might had been a deficit of B in trees, but the greater contribution of borate due to reclaimed water allowed a greater absorption of this micronutrient by trees. This would justify the greatest concentration of B found in cedar leaves in the RW plots.

There were significant differences for Cu in PEMA soils (Table 5.2). Since both plots (PEMA\_DW and PEMA\_RW) had similar pH, this difference must be attributed to the greater contribution of Cu by reclaimed water with respect to drinking water. A significantly higher content of Cu in soil was observed in PGW\_RW with respect to PGW\_DW plot. Likewise, there were no differences in pH between both PGW trial plots (pH = 7.9). It could be that the higher content of SOM (2.7 in PGW\_RW versus 1.9 in PGW\_DW) was responsible for a lower solubility of Cu (Zeng et al. 2011) in PGW\_DW. This is in accordance with Madrid et al (2004), who found that the accumulation of Cu and Zn in soils studied in the urban area of Sevilla was clearly favored by organic matter.

Like Cu, Zn decreases its bioavailability by increasing the pH (Martínez and Motto 2000; Planquart et al. 1999). The largest contribution of Zn by reclaimed water was responsible of the highest concentration of this element in the soil (Table 5.2), which became significantly higher in both plots irrigated with reclaimed water (PGW\_RW and PEMA\_RW). That is in accordance with results obtained by Roca et al (2007), who concluded that  $\text{Zn}_{(\text{DPTA})}$  remained adsorbed in soil without vertical displacement.

In both parks, plots treated with reclaimed water received more Fe than those treated with drinking water. However, this extra contribution in PEMA\_RW was not reflected in a higher Fe concentration in soils. In summary, once recognized the difficulty of comparing miscellaneous studies, the obtained values were lower than those found in bibliography, such as those of Lu et al. (2016). In a 2-year study, they obtained values of Cu and Zn almost seven times higher, respectively, than ours. Likewise, Chen et al. (2015), in their study of seven urban parks of Pekin after 9 years of reclaimed water irrigation, found contents of Cu and Zn almost fifteen times higher than ours in Madrid urban parks. These results were probably due to the different quality of reclaimed water used for irrigation.

The foliar micronutrient concentrations of *Cedrus atlantica* (PGW) and *Cedrus deodara* (PEMA) were mostly within the optimum parameters according to Munson (1998). It is worth to say that no significant differences were found between the two treatments, except for Manganese. Some of these micronutrients, as Fe, Mn and Zn, presented higher concentrations in cedar leaves irrigated by DW instead of those irrigated by RW. That is in accordance with Al-Nakshabandi et al. (1997), who reported a similar trend in their study on eggplants irrigated by treated wastewater in Jordan. The iron values from our study were quite similar to the described by Ali et al. (2011) who, in their 18-month study, found levels of 280 ppm of Fe for woody trees seedlings irrigated by a secondary effluent. Nonetheless, in a parallel study for *Khaya senegalensis* seedlings, the same author (H. M. Ali et al. 2013) described Fe foliar contents of 130 ppm, half than ours. Both studies used for irrigation an effluent with higher content in Fe (8.6 ppm) than in the present research.

Moreover, Nicolás et al. (2016) obtained foliar B contents significantly higher (>100 ppm) in mandarin trees irrigated during six years with saline reclaimed water. It was probably due to a progressive increase in B concentration in the irrigation water, as well as a higher B concentration in reclaimed water (0.67 mg L<sup>-1</sup>) than ours. On the other hand, Pedrero et al. (2012) obtained in their 3-year study in lemon trees a mean B leaf content of 4.3 ppm. This result was substantially lower than in the present work (64 and 67 mg kg<sup>-1</sup> for PGW\_RW and PEMA\_RW, respectively), despite a B concentration of 0.5 ppm in reclaimed water. As discussed earlier, the lower amount of B was probably due to the pH influence in B assimilation, which is especially difficult in alkaline mediums. In addition, a high frequency use of a fertigation system causes the leaching of the borate ion. Pereira et al. (2012) found that a B phytotoxicity problem for citrus plants was not likely to happen until RW irrigation

was extended for more than 50 years. It should be noted that the critical level of B toxicity to citrus plants was  $1.3 \text{ mg kg}^{-1}$ , considerably lower than the values obtained in the current study. However, Stone (1990) gathered toxic levels from several studies and concluded that the estimated B concentration when damage occurs in some conifers is  $200 \text{ mg kg}^{-1}$ .

On the other hand, De Miguel et al. (2013) and Petousi et al. (2015) in their *Jatropha curcas* and olive trees studies, respectively, reported similar foliar levels of Cu ( $8.4$  and  $7.4 \text{ mg kg}^{-1}$ ) and Zn ( $20$  and  $19.1 \text{ mg kg}^{-1}$ ) in plants irrigated by reclaimed water after one and three years of irrigation. Furthermore, Zn concentrations in *Jatropha curcas* and *Olea europea* leaves, irrigated by groundwater and drinking water, were higher than those irrigated by reclaimed water, as in the present study.

Several features as climate, atmospheric depositions, microelements concentrations in soil and the nature of soil influence the bioaccumulation of microelements in plants (H. Ali et al. 2013; Bhargava et al. 2012). The presence of micronutrients in cedar leaves cannot be related to irrigation water, due to the inexistence of significant correlations between these two variables (Table 5.4). Therefore, cedar decline cannot be attributed to the input of these micronutrients by reclaimed water.

## 5.5. Conclusions

Micronutrient concentration in reclaimed water produced by Madrid water reclamation plants was within the limits for an irrigation water in terms of the studied micronutrients. Nevertheless, micronutrient concentration was higher in RW than DW. SOM and pH had strong influence in the micronutrient concentration in soils from the parks. Compared with other studies of RW irrigation, lower values of micronutrient concentration in soils were obtained. Moreover, foliar concentration of the studied micronutrients did not exceed toxic limits. There was no correlation between micronutrient concentration in irrigation water and cedar leaves. Therefore, it was discarded that cedar decline was produced by the influence of studied micronutrients present in reclaimed water. Eventually, reclaimed water irrigation plots did not show major differences between the two parks, despite PEMA has been irrigated with reclaimed water 10 years more than PGW.

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## CHAPTER 6

### Conclusions

Reclaimed water of Madrid was adequate for irrigation according to international water quality standards. Furthermore, it was within average of tertiary treated wastewaters in comparison with other studies and within the limits for an irrigation water in terms of the studied micronutrients.

Results achieved showed that reclaimed water irrigation in urban parks is potentially leading to a modification of some soil properties, which are key in the urban parks soil systems. For instance, slightly soil salinization ( $EC_{\text{soil}} > 2 \text{ dS m}^{-1}$ ) appeared after 15 years of reclaimed water irrigation in one of the parks. There was also a steady increase of  $Cl^-$  (157%),  $Na^+$  (180%), SAR (127%) and EC (69%) in soils that were irrigated for 5 years with reclaimed water. Whereas in plots irrigated with drinking water significant lower values ( $p < 0.05$ ) for these parameters were observed. Regarding soil physical properties, irrigation with reclaimed water increased the amount of water-stable microaggregates in the topsoil but decreased the resistance of macroaggregates after RW irrigation in the top and the deepest layer. Likewise, soil penetration resistance was significantly higher ( $p < 0.05$ ) in the reclaimed water plot, probably due to a further development of the herbaceous root system. Moreover, reclaimed water irrigation also led to a decrease in infiltration rate, mainly because of the influence of sodium.

On the other hand, soil porosity results showed that there was no influence of the kind of irrigation water used. Furthermore, there was no soil sodification in RW plots. Although SAR and Na content in soils irrigated with RW were increasing in PGW\_RW and consistently high in PEMA\_RW, they were far from being a risk ( $SAR_{\text{soil}} > 6$  and  $EC_{\text{soil}} > 4 \text{ dS m}^{-1}$ ). Lower values of micronutrient concentration in soils were obtained when compared with other studies on reclaimed water irrigation in urban parks.

As for the vegetation,  $Cl$  (%) leaf content was significantly higher ( $p < 0.05$ ) in those hackberries and *Photinias* irrigated with RW in comparison with those irrigated with DW. However, for  $Na$  (%) leaf content, there were only significant differences for cedars irrigated with RW versus DW in PGW. In general, salt concentration in leaves was similar to the values found in the literature, being in most of the cases below the threshold when plants start to show injuries. Thus, no major salt stress symptoms were observed, despite the high values of  $Cl$  and  $Na$  in their leaf tissue in comparison with those irrigated with DW. Likewise, foliar micronutrient content of cedar leaves was nearly always within the optimum parameters. The statistical analysis showed no correlation between micronutrient concentration in

irrigation water and in cedar leaves, so cedar decline could not be attributed to the input of these micronutrients by reclaimed water.

Moreover, irrigation with reclaimed water led to a grass biomass increase (on average of 66%) in most of the harvests, mainly due to the high proportion of nutrients received through the irrigation water, which acted as a fertilizer. That could contribute to improve the aesthetic value of grass and, consequently, of the parks. Reclaimed water led to a statistically significant increase in nutrient removal by grass for almost all elements.

To sum up, prolonged reclaimed water irrigation may be altering the features of the soil-plant system of urban parks. For that reason, and in order to avoid future problems, the use of reclaimed water in urban parks irrigation should be continuously monitored. One of the recommended measures proposed is to use an adequate leaching requirement (10%) in order to wash out the excessive salt accumulation in parks irrigated with reclaimed water. Eventually, the transfer of these research results to municipal managers may contribute to a better management of reclaimed water irrigation in urban parks, with the aim to prevent the likely appearance of adverse symptoms on sensitive plants.

## Conclusiones

El agua regenerada de Madrid es adecuada para el riego conforme a los parámetros internacionales de calidad del agua de riego. Además, se sitúa dentro de la media de las aguas regeneradas sometidas a tratamiento terciario en comparación con las referidas en otros estudios y dentro de los límites establecidos para un agua de riego en cuanto a la concentración de los micronutrientes estudiados.

Los resultados obtenidos han mostrado que el uso de agua regenerada en el riego de parques urbanos puede conducir potencialmente a una modificación de las propiedades fisicoquímicas del suelo. Por ejemplo, se ha observado una ligera salinización del suelo (conductividad eléctrica  $> 2 \text{ dS m}^{-1}$ ) tras quince años de riego con agua regenerada en uno de los parques. También se ha producido un aumento constante del  $\text{Cl}^-$  (157%),  $\text{Na}^+$  (180%), SAR (127%) y de la conductividad eléctrica (69%) de los suelos regados con agua regenerada durante cinco años, mientras que, en las parcelas regadas con agua potable, se han obtenido unos valores significativamente inferiores ( $p < 0.05$ ) para estos mismos parámetros. En cuanto a las propiedades físicas del suelo, el riego con agua regenerada ha incrementado la estabilidad de los microagregados en superficie, mientras que la estabilidad de los macroagregados ha disminuido después del riego con agua regenerada en la capa más superficial y en la más profunda. De la misma manera, la resistencia a la penetración del suelo ha sido significativamente mayor ( $p < 0.05$ ) en la parcela regada con agua regenerada, probablemente debido a un mayor desarrollo del sistema radicular de las plantas. Asimismo, el riego con agua regenerada ha conducido al descenso de la tasa de infiltración, principalmente por la influencia del incremento en la concentración de sodio.

Por otra parte, los resultados relativos a la porosidad del suelo no han mostrado ninguna influencia en relación con el tipo de agua de riego utilizada. Además, no hubo sodificación del suelo en las parcelas regadas con agua regenerada. A pesar de que el SAR y el contenido en  $\text{Na}^+$  de los suelos regados con agua regenerada ha ido en aumento en el caso de PGW\_RW y ha sido constantemente alto en el caso de PEMA\_RW, han estado lejos de ser un riesgo ( $\text{SAR}_{\text{soil}} > 6$  y conductividad eléctrica  $> 4 \text{ dS m}^{-1}$ ). Asimismo, la concentración de micronutrientes ha sido inferior que la descrita en otros estudios con este tipo de riego en parques urbanos.

En cuanto a la vegetación, se han obtenido valores significativamente superiores ( $p < 0.05$ ) de  $\text{Cl}$  (%) en las hojas de los almeces y *Photinias* regados con agua regenerada en comparación

con aquellos regados con agua potable. Sin embargo, para el contenido foliar de Na (%), sólo ha habido diferencias significativas entre los cedros regados con agua regenerada y agua potable en el PGW. En general, la concentración de sales en las hojas ha sido similar a los valores encontrados en la bibliografía, estando en la mayoría de casos por debajo del umbral en el que las plantas empiezan a mostrar daños. Por lo tanto, no se ha observado ningún síntoma significativo de estrés salino, a pesar de los altos valores de Cl y Na en el tejido foliar en comparación con las regadas con agua potable. De la misma manera, la concentración de micronutrientes en las hojas de los cedros se ha situado casi siempre dentro de los valores óptimos. En lo relativo a estos micronutrientes, el análisis estadístico realizado no ha mostrado correlación entre su concentración en el agua de riego y en las hojas de los cedros, por lo que el decaimiento que viene observándose en algunos ejemplares de esta especie no ha podido ser atribuido a la aportación de estos micronutrientes en el agua de riego.

Por otra parte, el riego con agua regenerada ha producido un incremento de la biomasa herbácea en la mayoría de las siegas (de un 66% de media), fundamentalmente debido a la mayor proporción de nutrientes aportada por el agua de riego regenerada, que ha actuado como fertilizante. Este hecho puede contribuir a mejorar el valor estético del césped y, en consecuencia, de los parques. El riego con agua regenerada también ha contribuido al significativo aumento en la eliminación de nutrientes por parte de la cubierta herbácea.

En suma, el riego prolongado con agua regenerada podría estar alterando las características del sistema suelo-planta de los parques urbanos. Por ello, a fin de evitar futuros problemas, el uso de este tipo de agua en el riego de parques urbanos debería ser controlado constantemente. Una de las medidas recomendadas que se propone es utilizar una fracción de lavado del suelo en torno al 10%, al objeto de lixiviar el exceso de acumulación de sales en los parques regados con este tipo de agua. Finalmente, la transferencia de los resultados de la investigación a los gestores municipales puede contribuir a un mejor manejo del riego con agua regenerada de los parques urbanos; y ello con el fin de dar prioridad a prevenir la posible aparición de síntomas adversos en aquellas especies de plantas más sensibles.





# Appendices

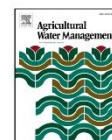
## Appendix 1

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### Salt accumulation in soils and plants under reclaimed water irrigation in urban parks of Madrid (Spain)


David Zalacáin<sup>a,\*</sup>, Silvia Martínez-Pérez<sup>a</sup>, Ramón Bienes<sup>b</sup>, Andrés García-Díaz<sup>b</sup>, Antonio Sastre-Merlín<sup>a</sup>
<sup>a</sup> Department of Geology, Geography and Environment, School of Sciences, University of Alcalá, Ctra Madrid-Barcelona Km 33.6, 28871, Alcalá de Henares, Madrid, Spain  
<sup>b</sup> Applied Research Dept., Madrid Institute for Research and Rural Development in Food and Agriculture (IMIDRA), Apdo 127, 28800, Alcalá de Henares, Madrid, Spain

#### ARTICLE INFO

**Keywords:**  
Reclaimed water  
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Chloride

#### ABSTRACT

Reclaimed water irrigation in urban parks is expanding all over the world and could cause salt accumulation in soil and plants. Since the beginning of the 2000s, the city of Madrid (Spain) has been using reclaimed water to irrigate its parks. The main aim of this study was to estimate salt accumulation in soils and plants due to reclaimed water irrigation in two urban parks of Madrid. It was conducted over five consecutive years and the chemical properties in soil solution, soil and plant leaves of four species were analyzed. Two plots from each park were selected, one irrigated with reclaimed water (RW) and another one irrigated with drinking water (DW). There was a steady increase of  $\text{Cl}^-$ ,  $\text{Na}^+$ , SAR and electrical conductivity (EC) in soils that were RW irrigated for 5 years, while in DW plots lower values for these parameters were observed. Likewise, there was no soil sodification in RW plots. On the contrary, the park which has been RW irrigated for 15 years showed a slight soil salinization ( $\text{EC} > 2 \text{ dS m}^{-1}$ ). There were significant differences for the Cl and Na (%) leaf content between species irrigated with RW versus DW. Overall, salt concentration in leaves was similar to the values found in the literature, being in most of the cases below the threshold when plants start to show injuries. However, an adequate leaching requirement (9%) is advisable in order to wash out the excessive salt accumulation in parks irrigated with reclaimed water.

#### 1. Introduction

Soil salinization associated with irrigation is a global problem (Dehaan and Taylor, 2002; Rengasamy, 2006; Szabolcs, 1989; Yu et al., 2010). Almost 20% of irrigated land is threatened by salinization, and this percentage is still on the rise (Li et al., 2014). One of the processes that promotes soil salinization is reclaimed water irrigation (Chen et al., 2013a; Klay et al., 2010; Sou-Dakouré et al., 2013; Urbano et al., 2017). Due to water deficit, reclaimed water and wastewater irrigation is expanding all over the world (Bixio et al., 2006; Chu et al., 2004; Hamilton et al., 2007). Reclaimed water is defined as treated wastewater after an additional or complementary treatment that adjusts its quality for its intended use (BOE, 2007). Salinity levels in reclaimed water are usually high due to common tertiary treatment processes do not remove most mineral salts, unless it is combined with expensive desalination processes, such as reverse osmosis (Haruvy, 2006; Rebhun, 2004). Sodium and other forms of salinity are the most persistent in reclaimed water and are among the most difficult to remove from water, which usually requires the use of expensive cation exchange

resins or reverse osmosis membranes (Toze, 2006). After municipal use, water increases its salinity, mainly due to sodium salts and chlorides (Rebhun, 2004). These can originate from many sources such as detergents, soaps and washing material, as well as some chemicals used during the water treatment process (water chlorination) and other sources (Elgallal et al., 2016; Qadir and Scott, 2010).

Reclaimed water irrigation in urban parks is an increasing trend all over the world (Chen et al., 2013b; Furumai, 2008; Qian and Mecham, 2005; Yi et al., 2011). This increase is due to two critical factors: technological advances made in wastewater treatments and a rise of water deficit in many parts of the world (Lyu et al., 2016). This kind of irrigation implies a series of benefits such as its reliability as a water source along the time and mainly during drought episodes (Hanjra et al., 2012; Wilcox et al., 2016). The reduction of fertilizers use due to its high nutrient content (Montemurro et al., 2017) and the possibility of keeping fresh water resources for high-quality uses (Sastre-Merlín et al., 2016a) are other advantages associated with their use.

Salinization derived of a low-quality irrigation water had been widely studied for agricultural areas (Cassaniti et al., 2009; Letey et al.,

\* Corresponding author.

E-mail addresses: [zalacain.david@gmail.com](mailto:zalacain.david@gmail.com), [david.zalacain@uah.es](mailto:david.zalacain@uah.es) (D. Zalacáin).

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## Appendix 2

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### Influence of reclaimed water irrigation in soil physical properties of urban parks: A case study in Madrid (Spain)



David Zalacáin<sup>a,\*</sup>, Ramón Bienes<sup>b</sup>, Antonio Sastre-Merlín<sup>a</sup>, Silvia Martínez-Pérez<sup>a</sup>,  
Andrés García-Díaz<sup>b</sup>

<sup>a</sup> Department of Geology, Geography and Environment, School of Sciences, University of Alcalá, Ctra Madrid-Barcelona Km 33.6, 28871, Alcalá de Henares, Madrid, Spain

<sup>b</sup> Applied Research Dept., Madrid Institute for Research and Rural Development in Food and Agriculture (IMIDRA), Apdo 127, 28800, Alcalá de Henares, Madrid, Spain

#### ARTICLE INFO

**Keywords:**  
Water reuse  
Reclaimed water  
Urban park  
Soils  
Aggregate stability  
Infiltration rate

#### ABSTRACT

Reclaimed water irrigation has been a long-standing practice, especially among water deficit areas such as Spain. This kind of water, more mineralized than drinking water, could imply changes on structural soil features. The main aim of this study was to assess the impact of reclaimed water on aggregate stability, soil penetration resistance, infiltration rate and porosity in soils of one of the urban parks of Madrid. This research was carried out on five successive years (2012–2016) in two urban park plots: one irrigated with reclaimed water (RW) and another one with drinking water (DW).

Results showed that irrigation with reclaimed water increased microaggregate stability in the topsoil, probably because of higher values of soil organic matter (SOM). However, macroaggregate stability decreased after RW irrigation in the top and the deepest layer. Soil penetration resistance was significantly higher in the RW plot, probably due to a further development of the root system. Furthermore, a decrease on infiltration rate was observed for RW, apparently because of the influence of sodium. On the other hand, porosity results showed that there was no influence of the kind of irrigation water used. The prolonged use of reclaimed water to irrigate urban parks is potentially leading to a modification of some soil properties, which are key in urban parks soil system. Thus, to avoid future problems, the use of reclaimed water in urban parks irrigation should be continuously monitored.

#### 1. Introduction

Nowadays, > 2 million hectares of farmland are irrigated with wastewater: treated, also known as reclaimed water, partially treated or untreated (Biggs and Jiang, 2009). This kind of irrigation has been developed since centuries, especially in arid or semi-arid areas (Mizyed, 2013). In the ancient Greece, the Minoan civilization used wastewater for irrigation in agriculture (Angelakis et al., 2005). Over time that practice was gradually extended, such as in the Middle Ages in the Mediterranean region of Valencia (Spain) and other North European countries as Germany and United Kingdom (Angelakis and Durham, 2008). The State of California was the frontrunner in the introduction of a regulation to control water reuse in 1918 (Asano and Levine, 1996). From the middle of the 20th century, there was an increase as well as an improvement of these practices associated to technological advances made in wastewater treatments and the rise of water deficit in many parts of the world (Bixio et al., 2006; Lyu et al., 2016). Semi-arid and arid areas, in particular, have been vulnerable to water scarcity due to a

remarkable imbalance between water demands and the availability of water resources (O'Connor et al., 2008; Simons et al., 2015).

Within the European Union, there are two different water reuse realities: one in southern Europe where wastewater reuse is a growing source of irrigation water, and the other one in northern countries where is hardly practiced, but could be developed for other purposes (TYPESA, 2013). Furthermore, in southern Europe water reuse is mainly intended for agriculture (44% of the projects) and for urban or environmental uses (37% of the projects), while in northern Europe, reuse is focus on urban or environmental (51% of the projects) and industrial uses (33% of the projects) (Bixio et al., 2006). One of the pioneers in Europe in terms of including water reuse as one of its water resources was the Madrid City Council, together with other Spanish cities, such as Alicante (Melgarejo et al., 2016), Barcelona (Paranychianakis et al., 2015) and Vitoria-Gasteiz (Mujeriego, 1990). Hochstrat et al. (2006) found that Spain presented the highest projected reuse potential within the European Union, according to model calculations and some scenario assumptions. The Treated Water Reuse Plan for the City of Madrid

\* Corresponding author.

E-mail address: [david.zalacain@uah.es](mailto:david.zalacain@uah.es) (D. Zalacáin).

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## Appendix 3

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### Turfgrass biomass production and nutrient balance of an urban park irrigated with reclaimed water

David Zalacáin <sup>a,\*</sup>, Silvia Martínez-Pérez <sup>a</sup>, Ramón Bienes <sup>b</sup>, Andrés García-Díaz <sup>b</sup>, Antonio Sastre-Merlín <sup>a</sup>

<sup>a</sup> Department of Geology, Geography and Environment, School of Sciences, University of Alcalá, Ctra Madrid-Barcelona Km 33.6, 28871, Alcalá de Henares, Madrid, Spain

<sup>b</sup> Applied Research Dept., Madrid Institute for Research and Rural Development in Food and Agriculture (IMIDRA), Apdo 127, 28800, Alcalá de Henares, Madrid, Spain

#### HIGHLIGHTS

- Reclaimed water irrigation led to a grass biomass increase.
- The main nutrient input in reclaimed water irrigation were of Cl, S, K and Na.
- Reclaimed water led to an increase in nutrient removal by grass.
- Positive nutrient balance was obtained for almost all elements.

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#### ABSTRACT

The increasing demand for water resources in arid and semiarid countries has stimulated the use of non-conventional water resources such as reclaimed water. Consequently, turfgrass irrigation with reclaimed water has become a regular practice in these regions. The main goal of this research was to assess the effects of reclaimed water (RW) irrigation in Madrid urban parks by studying changes in grass nutrient balance and its biomass production.

Irrigation with reclaimed water led to a grass biomass increase, mainly due to the high proportion of nutrients received through the irrigation water. The main nutrient input in RW irrigation were of Cl, S, K and Na. RW also contributed to a significant increase in nutrient removal by grass.

Thus, all this information generated should be taken into account by park managers in order to fulfill the grass aesthetic value and its nutritional requirements in those urban parks irrigated with RW.

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#### 1. Introduction

The increasing demand for water resources in arid and semiarid countries has led water managers to look for new measures to provide water continuously throughout the year, regardless meteorology. This search, enhanced by climate change, has stimulated the use of non-conventional water resources, such as reclaimed water (Bdour et al., 2009; Norton-Brandão et al., 2013; Tram VO et al., 2014). Since the old times wastewater was reused for

agricultural irrigation (Angelakis et al., 2005). Nevertheless, unplanned reuse together with a lack of adequate potable water and wastewater treatments caused catastrophic epidemics, such as cholera (Asano and Levine, 1996). However, the advances in water treatment technologies in the last century have enabled the quick development of this resource, mainly in countries with this technological expertise (Battilani et al., 2010; Z. Chen et al., 2013a).

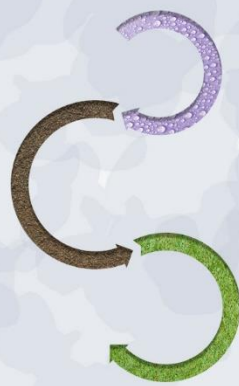
Agriculture is the main use of reclaimed water, and it has been expanded all over the world (Pedrero et al., 2010; Sato et al., 2013). Moreover, reclaimed water is also used for golf courses (Benlouali et al., 2017; Lockett et al., 2008; Murakami and Ray, 2000), urban parks and garden irrigation (Chen et al., 2015; Furumai, 2008). Even Harivandi (2000) held that turfgrasses may be the best plants for

\* Corresponding author.

E-mail address: [david.zalacain@uah.es](mailto:david.zalacain@uah.es) (D. Zalacáin).







**David Zalacáin Domench**

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