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Departamento de Agronomía

Área Ingeniería Hidráulica

Optimización en el uso del agua y fertilizante para fertirriego de precisión con aguas regeneradas

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Water and fertilizer use optimization for a precision fertigation using reclaimed water

Tesis Doctoral presentada por

Carmen Alcaide Zaragoza

para la obtención del título de

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Directores

Dr. Juan Antonio Rodríguez Díaz
(Profesor Titular de la Universidad de Córdoba)

Dra. Irene García Fernández
(Profesor Contratado Doctor de la Universidad de Córdoba)

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AUTOR: *Carmen Alcaide Zaragoza*

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Campus de Rabanales
Ctra. Nacional IV, Km. 396 A
14071 Córdoba

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Tesis como compendio de publicaciones

Esta tesis se presenta como compendio de publicaciones, cumpliendo con los requisitos establecidos por la Universidad de Córdoba para este fin. Tres de los seis capítulos de esta tesis se corresponden con tres artículos científicos publicados en revistas incluidas en el primer y segundo cuartil según la última relación del Journal Citation Reports (2020).

1. Alcaide Zaragoza, C., Fernández García, I., González Perea, R., Camacho Poyato, E., Rodríguez Díaz, J.A., 2019. REUTIVAR: Model for precision fertigation scheduling for olive orchards using reclaimed water. Water (Switzerland). Índice de impacto: 3.103. 2º cuartil en el área de Recursos Hídricos, posición 39/98.

2. Alcaide Zaragoza, C., González Perea, R., Fernández García, I., Camacho Poyato, E., Rodríguez Díaz, J.A., 2020. Open-source application for optimum irrigation and fertilization using reclaimed water in olive orchards. Computers and Electronics in Agriculture. Índice de impacto: 5.565. 1er cuartil en el área de Agricultura, posición 2/57.

3. Alcaide Zaragoza, C., Fernández García, I., García Martín, I., Camacho Poyato, E., Rodríguez Díaz, J.A., 2021. Spatio-temporal analysis of nitrogen variations in an irrigation distribution network using reclaimed water for irrigating olive trees. Agricultural Water Management. Índice de impacto: 4.516. 1er cuartil en el área de Agronomía, posición 12/91.

TÍTULO DE LA TESIS: Optimización en el uso del agua y fertilizante para fertirriego de precisión con aguas regeneradas

DOCTORANDA: Carmen Alcaide Zaragoza

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

Las aguas regeneradas representan, cada vez más, una alternativa para mitigar los déficits hídricos existentes en el regadío. No obstante, su uso no es sencillo debido a su contenido en sales y nutrientes, que deben ser considerados en los programas de riego y de fertilización. Así, un manejo óptimo de la fertilización debería ser capaz de complementar los nutrientes que ya de por sí aporta el agua, permitiendo ahorrar costes de producción y reduciendo el impacto ambiental. Dicha programación es compleja para el regante y, por tanto, son necesarias herramientas que faciliten la programación del fertirriego, considerando estos aspectos.

La presente Tesis Doctoral se enmarca dentro del Proyecto Grupo Operativo REUTIVAR (Modelo de Riego Sostenible del Olivar Mediante el Uso de Aguas Regeneradas, GOP3I-SE-16-0005) en el que se pretendía avanzar en el uso sostenible de las aguas regeneradas en el riego de olivar, mediante la programación conjunta del riego deficitario y de la fertilización. Dicho proyecto fue coordinado por FERAGUA (Asociación de Regantes de Andalucía) y contó también como socios con la Fundación Centro de Nuevas Tecnologías del Agua (CENTA), la Universidad de Córdoba y la Comunidad de Regantes de Tintín. Dentro del mismo se han desarrollado diversas acciones técnicas y de demostración, las cuales se pueden consultar en la página web del proyecto (www.reutivar.eu). Gracias a la labor realizada, el proyecto fue galardonado con el Premio Medioambiente de Andalucía 2020 de la Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible de la Junta de Andalucía, en la modalidad de Gestión Sostenible del Agua.

La Tesis Doctoral se divide en tres grandes apartados claramente diferenciados, los cuáles abordan diferentes problemas relacionados con el fertirriego del olivar con aguas regeneradas, aportando soluciones y herramientas para facilitar su manejo óptimo. La Tesis se ha elaborado como compendio de artículos científicos, que han dado lugar a tres publicaciones en revistas con altos índices de impacto:

– Zaragoza, C. A., García, I. F., Perea, R. G., Poyato, E. C., & Díaz, J. A. R. (2019). REUTIVAR: Model for precision fertigation scheduling for olive orchards using reclaimed water. Water (Switzerland), 11(12) doi:10.3390/w11122632

En este trabajo, como primer paso de la Tesis, se desarrolla un modelo que determina en tiempo real las necesidades de riego y fertilización para olivar regado con aguas regeneradas. Para facilitar la toma de decisiones, el modelo integra información climática (datos históricos y predicciones), datos de suelo, configuración hidráulica del sistema de riego, disponibilidad de agua, estado nutricional del árbol y calidad del agua.

– Alcaide Zaragoza, C., González Perea, R., Fernández García, I., Camacho Poyato, E., & Rodríguez Díaz, J. A. (2020). Open source application for optimum irrigation and fertilization using reclaimed water in olive orchards. Computers and Electronics in Agriculture, 173 doi:10.1016/j.compag.2020.105407

En el segundo de los trabajos se desarrolla una aplicación para dispositivos Android, *Reutivar App*, que integra las metodologías desarrolladas en el primer trabajo. La aplicación constituye una herramienta sencilla y en un entorno amigable para el usuario. Además, *Reutivar App* es la primera herramienta desarrollada para la programación del fertirriego óptimo de olivar con aguas regeneradas.

– Alcaide Zaragoza, C., Fernández García, I., Martín García, I., Camacho Poyato, E., & Rodríguez Díaz, J. A. (2021). Spatio-temporal analysis of nitrogen variations in an irrigation distribution network using reclaimed water for irrigating olive trees. Agricultural Water Management, doi.org:10.1016/j.agwat.2021.107353

En el tercer trabajo se analizan las repercusiones de la variación espacio-temporal de la calidad del agua regenerada en las necesidades de fertilización. Se hace un seguimiento de la variación del contenido de nutrientes en el agua durante toda la campaña de riego en varios puntos de la red de distribución de la Comunidad de Regantes de Tintín, comprobando cómo existen diferencias importantes entre las cantidades de nutrientes recibidas dependiendo de la localización.

En su conjunto, la investigación realizada representa un claro avance al estado del conocimiento actual en esta temática, sobre la cual prácticamente no existían trabajos previos. Además, la investigación desarrollada puede tener importantes repercusiones en el sector del riego, cada vez más interesado en el uso de las aguas regeneradas como fuente alternativa de recursos hídricos.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 10 de diciembre de 2021

Firma de los directores

RODRIGUEZ DIAZ JUAN ANTONIO - 44350701P

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Fecha: 2021.12.10 20:03:19 +01'00'

FERNANDEZ GARCIA IRENE ROSA - 26495846F

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Nombre de reconocimiento (DN): c=ES, serialNumber=IDCES-26495846F, givenName=IRENE ROSA, sn=FERNANDEZ GARCIA, cn=FERNANDEZ GARCIA IRENE ROSA - 26495846F
Fecha: 2021.12.09 12:29:17 +01'00'

Fdo.: Juan Antonio Rodríguez Díaz Fdo.: Irene Fernández García

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Summary

Irrigated agriculture is the main user of freshwater resources worldwide, using more than 70% of the available water resources. This makes the agricultural sector especially susceptible to drought periods, which are expected to increase in the next few years because of the growing extreme event occurrence caused by climate change. This situation is particularly critical in Andalusia (Southern Spain) since irrigated agriculture is a key sector in its economy. Olive orchard is the most representative crop in this region as well as the most water demanding crop, even with very deficit irrigation strategies. On the other hand, fertilization is frequently imprecise, which leads to overfertilization of the olive trees, especially of nitrogen. In this context, the use of reclaimed water for olive orchard irrigation arises as an alternative to traditional water sources, which alleviates the pressure on water resources and reuses the nutrients carried by the water. However, its management is complex due to the water nutrient content, which, additionally, is variable throughout the year. For these reasons, new studies are required to understand the spatio-temporal variability effects of the water nutrients, as well as the development of tools to ease the proper application of this type of water for both farmers and technicians.

This thesis is organized in 6 chapters, all of them focused on the particularities of olive orchard fertigation using reclaimed water. Thus, the different chapters include from the creation of a model for optimal fertigation using reclaimed water and its implementation in a user-friendly mobile app to the changes produced in water quality spatially and seasonally in irrigation networks due to its characteristics. Chapter 1 contextualizes the reason of this thesis and Chapter 2 describes the objectives pursued in this thesis and the structure of the rest of the document.

Chapter 3 presents a model which determines in real-time the irrigation and fertilization scheduling, using reclaimed water, for olive groves. This model considers weather information, both historical and forecast, soil characteristics, irrigation system characteristics, water allocation, tree nutritional status, most susceptible crop development stages, electricity tariff and water quality. Different scenarios were simulated, showing the need for a more sustainable management when fertigating olive trees with reclaimed water, since farmers tend to overfertilize.

Chapter 4 integrates the model developed in Chapter 3 into a mobile application for Android devices. This app aims to provide technicians and farmers with a user-friendly tool that eases the olive orchard fertigation management when using reclaimed water. This application was tested in a commercial farm, showing that no additional fertilizer application was necessary thanks to the nutrients provided by reclaimed water, saving 100% of the fertilizer applied by the farmer. This provides benefits not only for the farmer, who can reduce his total economic costs, but also for society as it avoids the intensive and unnecessary use of fertilizers and the associated pollution.

In Chapter 5, a temporal and spatial study of the quality of reclaimed water in an irrigation distribution network is carried out, paying especial attention to nitrogen. This study showed that both the total concentration and the form in which nitrogen reaches the farms change over time and through the irrigation network. Seasonally, total nitrogen content was reduced in the summer months. Spatially, there was a clear nitrification process from the pumping station to the farms. These variations demonstrate the importance of continuous water quality monitoring in order to adjust the fertilization plan to the nitrogen content in the water.

Finally, Chapter 6 contains the general conclusions obtained from this thesis and the avenues for future research.

The use of reclaimed water for olive orchard fertigation in Andalusia can play a key role in reducing the water resource pressure and, simultaneously, recovering the water nutrients for fertilization. This thesis highlights the importance of a continuous water quality control and a proper management to avoid the impacts of an excessive fertilizer use when using reclaimed water. For this reason, tools which make easier reclaimed water management are presented as well as the changes occurring in the quality of this water source. All this contributes to achieve a more efficient use of both water and fertilizer.

Resumen

La agricultura de regadío es el principal consumidor de agua en el mundo, empleando más del 70% de los recursos hídricos disponibles. Esto provoca que la agricultura sea especialmente vulnerable a los periodos de sequía, los cuales se espera que aumenten en los próximos años debido al incremento de los fenómenos extremos causados por el cambio climático. Esta situación es especialmente crítica en Andalucía (sur de España) ya que la agricultura es un sector clave en su economía. El olivar es el cultivo más representativo de esta región, además del cultivo que más agua demanda, pese a seguir estrategias de riego deficitarias. Por otro lado, la fertilización del olivar es con frecuencia imprecisa, lo que ocasiona en muchos casos que se produzca una sobrefertilización, especialmente de nitrógeno. En este contexto, la utilización de agua regenerada para el riego del olivar surge como una alternativa a las fuentes de agua tradicionales, la cual permite aliviar la presión en los recursos hídricos y reutilizar los nutrientes que lleva el agua. Sin embargo, su gestión es más compleja debido a esa concentración de nutrientes que lleva, la cual es, además, variable a lo largo del año. Por ello, es necesario llevar a cabo nuevos estudios para conocer los efectos de la variabilidad temporal y espacial de los nutrientes que aporta el agua, así como el desarrollo de herramientas que faciliten la aplicación adecuada de este tipo de aguas tanto para agricultores como técnicos.

Esta tesis se estructura en 6 capítulos, todos ellos enfocados a las particularidades del fertirriego usando aguas regeneradas en el olivar. Así, los distintos capítulos contemplan desde la creación de un modelo y su implementación en una aplicación de entorno amigable para la gestión óptima del agua y el fertilizante usando estas aguas, hasta los cambios que se producen en la calidad del agua tanto espacial como temporalmente en la red riego debido a sus características. En el capítulo 1 se expone el contexto en el cual se enmarca esta tesis y se justifica la necesidad de la misma. En el capítulo 2 se encuentran los objetivos perseguidos en esta tesis, así como la estructura del resto del documento.

El capítulo 3 presenta un modelo que determina en tiempo real la programación del riego y la fertilización del olivar usando aguas regeneradas. Este modelo considera información agroclimática, tanto histórica como futura, características del suelo, características del sistema de riego, dotación, estado nutritivo del árbol, etapas más susceptibles del desarrollo del cultivo, tarifa eléctrica y calidad del agua aplicada. Se simularon diferentes escenarios, evidenciando la necesidad de una gestión más sostenible cuando se fertirriega el olivar con aguas regeneradas ya que los agricultores tienden a sobrefertilizar.

En el capítulo 4 se integra el modelo desarrollado en el capítulo 3 en una aplicación móvil para dispositivos Android. Esta app tiene como objetivo proporcionar a técnicos y agricultores una herramienta fácil de usar que facilite la gestión del fertirriego del olivar cuando se utilizan aguas regeneradas. Esta aplicación se utilizó en una finca comercial, mostrando que gracias a los nutrientes que aporta el agua regenerada, no era necesaria la aplicación de fertilizante adicional, ahorrando el 100% del fertilizante que aplica el agricultor. Esto proporciona beneficios no solo para el agricultor, el cual puede reducir sus costes totales, sino también para la sociedad, ya que evita el uso intensivo e innecesario de fertilizantes y la contaminación que lleva asociada.

En el capítulo 5, se lleva a cabo un estudio temporal y espacial de la calidad del agua regenerada en una red de distribución de riego. Este estudio demostró que tanto la concentración de nitrógeno total como la forma en la que llega a la finca cambia con el tiempo y a lo largo de la red de riego. Estacionalmente, el contenido total de nitrógeno se redujo en los meses de verano. Espacialmente, se produjo una clara nitrificación desde la salida del agua en la estación de bombeo hasta las distintas parcelas. Estas variaciones demuestran la importancia de un continuo control de la calidad del agua para poder ajustar el programa de fertilización al contenido de nitrógeno en el agua.

Por último, el capítulo 6 recoge las principales conclusiones obtenidas de esta tesis, así como las líneas futuras de investigación

La utilización de agua regenerada para el fertirriego del olivar en Andalucía puede jugar un papel fundamental para disminuir la presión en los recursos

hídricos y, al mismo tiempo, utilizar los nutrientes que contiene para la fertilización. Esta tesis destaca la importancia de un control continuo de la calidad del agua y de una gestión adecuada para evitar los problemas que puede ocasionar el uso excesivo de los fertilizantes. Por ello, en esta tesis se presentan herramientas que facilitan la gestión de este tipo de aguas, teniendo en cuenta aspectos técnicos y agronómicos y se estudian los cambios que se pueden producir en la calidad de las mimas. Todo esto contribuye a conseguir un uso más eficiente y sostenible tanto del agua como del fertilizante.

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Table of Contents

List of Tables

List of Figures

List of Symbols and Abbreviations

A:	Sector Area
AEMET:	Agencia Estatal de Meteorología
AM:	Actual Management Scenario
AM-ND:	Actual Management Scenario considering hypothetical olive Nutrient Deficiency
API REST:	Application Programming Interface REpresentational State Transfer
BOD_5:	Biochemical Oxygen Demand
CHG:	Confederación Hidrográfica del Guadalquivir
Chl-a:	Chlorophyll a
COD:	Chemical Oxygen Demand
d:	Irrigation day
D:	Average Canopy Diameter
D_d:	Daily Deep Percolation
dm:	Number of days of the month

DO	Dissolved Oxygen
D_r:	Root Zone Depletion
EC:	Electrical Conductivity
ET_0:	Reference evapotranspiration
$ET_{c,adj}$:	Crop Adjusted Evapotranspiration
ET_c:	Crop evapotranspiration
EU:	European Union
FAO:	Food and Agriculture Organization
FC:	Field Capacity
FI:	Full Irrigation
FSI:	Filtration System Inlet
FSO:	Filtration System Outlet
ICT:	Information and Communication Technologies
id:	Number of days from the current day to the next irrigation event
IDE:	Integrated Development Environment
IE:	Irrigation Efficiency

IFAPA: Instituto de Investigación y Formación Agraria y Pesquera

$IN_{historical}$: Monthly Average Irrigation Needs

IN_d: Daily Irrigation Needs

IWT: Irrigation Water Thresholds

k_c: Crop coefficient

k_r: Tree canopy coefficient

$k_{strategy}$: Irrigation Strategy Coefficient

MVC: Model View Controller

MVVM: Model-View-ViewModel

n: Next irrigation day chosen by the user

N: Plant density

n_e: Emitter number

NN: Real Nutritional Needs

OS: Operation System

OWAF: Optimal Water and Fertilization management scenario

OWAFE: Optimal Water, Fertilization and Electricity cost management scenario

OWAFE-ND:	Optimal water, Fertilization and Electricity Cost management scenario considering hypothetical olive nutrient deficiency
p:	Fraction of Total Available Water in which the crop can extract water
P:	Precipitation
P_{eff}:	Effective Precipitation
PWP:	Permanent Wilting Point
q_e:	Emitter flow
RAW:	Readily Available Soil Water
R_d:	Runoff
RDI:	Regulated Deficit Irrigation
RM ANOVA:	Repeated Measures Analysis of Variance
RW:	Reclaimed Water
S_c:	Cultivated area
SDI:	Sustained Deficit Irrigation
SWC_d:	Daily Soil Water Content
SWCT:	Soil Water Content Threshold

t_d:	Daily Irrigation Time
TAW:	Total Available Water
TID:	Tintín Irrigation District
USDA:	United States Department of Agriculture
UV:	Ultraviolet
WWTP:	Wastewater Treatment Plant
Z_r:	Rooting Depth
θ_{FC}:	Water Content at Field Capacity
θ_{PWP}:	Water Content at Permanent Wilting Point

1 Introduction

1.1 Background

The current world population is expected to increase from nearly 8 billion of people to around 10 billion by 2050 (United Nations, 2015). Driven by this population growth, food demand is also predicted to significantly rise in the upcoming years. Irrigated agriculture can double or even triple yield in comparison with rainfed land, so the irrigated area is also expected to grow in the next few years (FAO, 2011). On the other hand, fertilizers increase the nutrient availability for crops and contribute, directly and indirectly, to 95 percent of global food production (FAO, 2019). Therefore, both irrigation and fertilization are fundamental for achieving the require food production growth.

At present, more than 70% of all freshwater withdrawals worldwide are used for agricultural irrigation (FAO, 2017). For this reason, irrigated agriculture is considerably constrained by water scarcity. If climate change is considered, the pressure on water resources will be aggravated in the future since alterations in temperature and rainfall patterns as well as higher occurrence probability of extreme events are expected (Beniston et al., 2007).

On the other hand, world's fertilizer demand is also expected to increase in the next years (FAO, 2019) due to the need to feed the world's growing population. However, an excessive and inappropriate use of fertilizers is proven to generate numerous environmental and ecological impacts such as water eutrophication, air pollution or even crop productivity reduction (Foley et al., 2005).

Considering the existing and the expected pressure on water resources together with the problems associated to an improper use of fertilizers, irrigated agriculture will need to face the challenge of ensuring food production using these resources in a more sustainable way. The use of both nutrients and water from recycled resources arises as an opportunity to address these problems, integrated in the new circular economy paradigm.

1.2 Water Reuse Worldwide

The use of reclaimed water is gaining momentum as a solution to mitigate the global water scarcity problem. Treated wastewater is water from domestic, industrial or commercial activities that has been processed in a wastewater treatment plant to remove contaminants (International Organization for Standardization, 2018). However, to make it appropriate for reuse, an additional treatment is necessary. This treatment will depend on the required water quality which is related to the final water use. Then, the former wastewater is called reclaimed or recycled water and it can be used for different purposes (Raschid-sally and Jayakody, 2008)

According to Sato et al. (2013), the countries across the world that reuse treated wastewater the most are USA (6.4 hm^3/day), Egypt (1.9 hm^3/day), Syria (1.5 hm^3/day), Spain (1.5 hm^3/day), Israel (0.7 hm^3/day) and Saudi Arabia (0.4 hm^3/day). The uses of the reclaimed water vary considerably, even within the same country, depending on the climate, country's development, main economic activities, etc. In general, it is estimated that, in developed countries and after secondary treatment, the main destination of this water is agricultural irrigation (33%), followed by irrigation of green areas (20%) and industrial uses (8%) (Prats-Rico, 2016).

Spain is one of the most water stressed countries in the EU and this situation is forecasted to be heightened in a climate change context (Bisselink et al., 2018; Maddock et al., 2015). The most recent available data, published by the National Statistics Institute at the end of 2018, quantified the total volume of treated wastewater in 13.7 hm^3/day throughout the Spanish territory. Of this volume, and despite the fact that Spain is the country with the highest rates of wastewater reuse in the EU (Prats-Rico, 2016), only 11% (1.54 hm^3/day) was reused. However, this percentage varies largely depending on the region of the country. Figure 1.1 shows the proportion of reuse water out of the total treated water. In the first place is Murcia Region, which reuses 95% of its wastewater, followed by the Valencian Community, with 43% and the Balearic Islands with 34%. Although a large percentage of treated water is reused in these territories, most regions still have much scope for improvement.

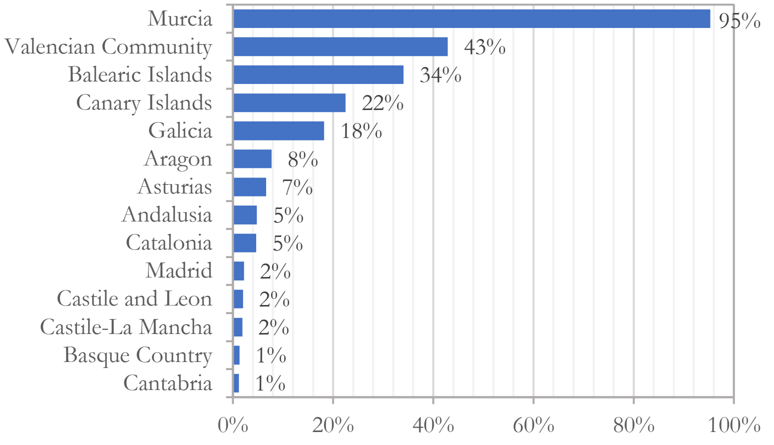

Figure 1.1 Treated wastewater that is reused classified by Autonomous Regions in Spain
* Author's elaboration based on INE (2018)

The main uses of reclaimed water in Spain, according to INE (2018a), are irrigated agriculture (66%), gardens and recreational sport areas (21%), industry (4%) and sewer cleaning and street sweeping (2%). This makes sense given the importance of the agricultural sector in the country and the associated water requirements. The usable agricultural area in Spain represents more than M 23 hectares, almost half of its territory, and nearly M 17 hectares are already under cultivation. Of the total cultivated area, 77% is dedicated to rainfed crops and 23% to irrigated crops (Spanish Government, 2020). Despite the irrigated area is lower, more than 75% of the freshwater resources in the country are used for irrigation (INE, 2018b). Arable crops cover most of the irrigated area in this territory (24%), followed by olive orchards (22%) and vineyard (10%) (Spanish Government, 2020).

However, the uses to which reclaimed water is destined differ across the country (Figure 1.2). In most cases, the main use of the reclaimed water matches the main activity of the autonomous community, as is evident in the cases of Murcia, devoted to the agricultural sector, and the Basque Country, used mainly in industrial processes. However, the case of Andalusia stands out since, even though agriculture is a fundamental sector, the use of reclaimed water for this purpose is very low.

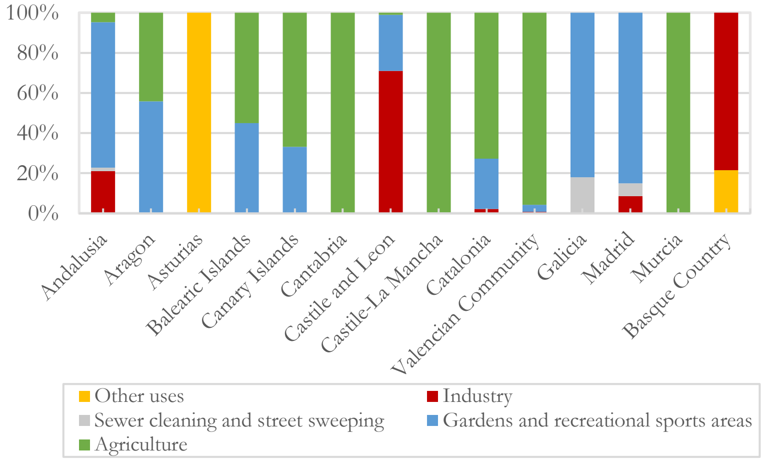

Figure 1.2 Uses of the reclaimed water in Spain

* Author's elaboration based on INE (2018)

In Spain only a fraction of the water that is treated is reused. Considering that it is one of the driest countries in the EU and that irrigated agriculture is the main user of freshwater, it is clear that this non-conventional resource offers a major opportunity in this country. However, its management can be complex and some considerations must be taken into account.

1.3 Reclaimed Water Characteristics

The reclaimed water management complexity is mainly caused by the peculiarities of this type of water. First, it is crucial to meet the water quality requirements for the particular use and also to monitor that those are maintained at appropriate levels over time. In Spain, the minimal water quality requirements for reuse are regulated by the Royal Decree 1620/2007 and by the recently approved EU Regulation 2020/741 (Spain Government, 2007; The European Parliament and the Council of the European Union, 2020). These water quality limits have been established with the objective of ensuring public health, preventing the use of reclaimed water from causing any harm.

The temporal variability is also an important factor to consider in the reclaimed water management. For example, in the case of reclaimed water from a municipal source, the volume and quality of the water is usually not uniform throughout the year since it is strongly influence by holiday periods. On the other hand, water requirements can also change during the year, as in the case of irrigated agriculture, which may require water storage. Climatic conditions can also cause chemical reactions in the water, modifying some parameters such as nitrogen content, dissolved oxygen, etc. Depending on the final water use, these modifications will have different consequences. For example, if reclaimed water is used for enhancing water bodies, the dissolved oxygen content would be essential for ensuring the aquatic ecosystem biodiversity (Kramer, 1987). In the case of irrigated agriculture, the temporal variability could cause imbalances in the fertilization plans leading to lack or excess of nutrients.

As previously mentioned, irrigated agriculture is the main user of reclaimed water in the world. Thanks to the nutrients carried by the water, considerable fertilizer reductions can be achieved, increasing also the farm profitability (Maestre-Valero et al., 2019). However, the use of reclaimed water for irrigation can also produce certain problems. For example, the presence in water of ions (Na^+, B^{3+} and Cl^-) that may cause toxicity is frequent; therefore, water and soils must be analyzed regularly to ensure their long-term sustainability. These ions may cause salinity problems which affect the nutrient assimilation by the crop, the microbial activity of soils and even the water absorption (Orgaz et al., 2017). If necessary, in these cases, irrigation with freshwater can be alternated to avoid the salinization of these soils. Finally, it is important to mention that, frequently, farmers apply additional fertilizers without considering the nutrients in the water, which leads to overfertilization. This may cause important environmental problems, such as diffuse pollution caused by nitrate leaching which leads to the quality deterioration and eutrophication of water bodies (Lee and Jones-Lee, 2005). Overfertilization, produces negative impacts on both yield and crop quality. For example, a nitrogen excess can produce a decrease in the frost tolerance of the crop or cause a delay in the fruit ripening (Fernández-Escobar et al., 2010; Kozlowski and Pallardy, 1997). In the phosphorus case, it could cause zinc blockages, leading to Zn deficiency in the crop (Fernández-Escobar, 2017).

1.4 Use of reclaimed water for fertigation

The joint management of water and fertilizers, fertigation, using reclaimed water can be challenging for farmers due to the characteristics of this type of water. Different methodologies have been developed to optimize the water and fertilizer use. For example, Pérez-Castro et al. (2017) created a mobile application for fertigation management: *cFertigUAL*. This mobile App aimed to calculate the optimal fertilizer quantity considering the crop type and the irrigation system. Nevertheless, it was only developed for greenhouse crops. Some other authors have developed methodologies to determine the most economic fertilizer (Bueno-Delgado et al., 2016; Pagán et al., 2015). Both works considered the quality of the irrigation water, but the optimal nutrient solution was also required to run the model. This information is usually unknown by farmers, which hinders its use. The Institute for Agricultural and Fisheries Research and Training (IFAPA) developed a website application whose objective was to recommend a fertigation schedule for olive orchards. These recommendations are based on monthly average agroclimatic records and, consequently, they do not consider real-time data. The optimum fertigation programs are provided monthly, which sometimes is not the most useful option in the day to day irrigation management. However, there are not tools for optimal fertigation management which considers the particularities of reclaimed water and in a user-friendly format.

On the other hand, the nutritional aspects and impacts of using reclaimed water for irrigation has already been studied by different authors. Some authors have focused their research on horticultural crops and citrus. For example, Pereira et al. (2011) studied the effect of using recycled water on citrus crop nutrition. Lu et al. (2016)) studied how reclaimed water could influence the development or quality of the tomato. All of them agreed that irrigation with recycled water could lead to significant fertilizer savings as well as environmental benefits as long as this resource is properly managed.

Given its importance in the Mediterranean countries, previous works have evaluated the use of reclaimed water for irrigating olive orchards. Erel et al. (2019) studied the olive nutrient requirements when reclaimed water is used, finding that no additional fertilizers are needed to obtain the same yield. Other authors studied the impacts of reclaimed water on tree development, oil and fruit quality and land contamination (Ayoub et al., 2016; Bourazanis et al., 2016; Erel et al., 2019). They all agreed that reclaimed water did not produce any negative impacts as long as the water was properly controlled and managed. Pedrero et al. (2020) undertook a review analyzing the advantages and limitations of different water sources and their qualities for olive tree irrigation. They affirmed that, in Mediterranean countries and in a long-term period, olive orchards irrigated with reclaimed water are likely to enhance its yield thanks to the nutrients dissolved in the water. However, they highlighted that these nutrients could also generate negative effects on both olive yield and oil quality if given in excess.

In summary, reclaimed water is expected to play an essential role in the new circular economy paradigm. Its use will alleviate the pressure on water resources and will allow to recover nutrients from the water for crop application. However, this water already carries a large amount of nutrients which are, furthermore, variable along the season. For this reason, a continuous control and proper management are particularly important if problems associated with an excessive use of fertilizers are to be avoided. Thus, new studies are required to know the effects of both the temporal variability along the season and the spatial variability throughout the irrigation network of nutrients in reclaimed water and the implications they have on the crops as well as the development of new tools which make easier the proper use of this type of water for both farmers and managers.

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2 Objectives and thesis structure

2.1 Objectives

The overall objective of this thesis is to deepen the knowledge of the management of olive orchards fertigation with reclaimed water and to develop new tools to simplify the management and scheduling of olive orchard fertigation using reclaimed water.

To achieve this aim, the specific objectives are detailed below:

1. Development of a model to schedule in real-time olive orchard fertigation using reclaimed water considering water quality, crop data and irrigation network characteristics.
2. Creation of a user-friendly mobile app to ease the optimal olive orchard fertigation using reclaimed water for technicians and farmers.
3. Spatio-temporal analysis of the reclaimed water quality variability in the irrigation network.

2.2 Thesis structure

To achieve these aims, this thesis is organised in six chapters. **Chapter 1** and **Chapter 2** are the introduction and the objectives pursued, respectively.

Chapter 3 consists of a model to determine the real-time irrigation and fertilization scheduling using reclaimed water for irrigating olive trees. The model considers weather information, soil characteristics, hydraulic characteristics of the system, water allocation, tree nutrient status and irrigation water quality. This chapter has been published under the title "REUTIVAR: Model for precision fertigation scheduling for olive orchards using reclaimed water" (2019) by Alcaide Zaragoza C., Fernández García I., González Perea R., Camacho Poyato E. and Rodríguez Díaz J.A. in *Water*.

Chapter 4 integrates the above-mentioned precision model into a user-friendly mobile app. This chapter has been as "Open source application for optimum irrigation and fertilization using reclaimed water in olive orchards" (2020) by Alcaide Zaragoza C., González Perea R., Fernández García I., Camacho Poyato E. and Rodríguez Díaz J.A. in *Computers and Electronics in Agriculture*.

In **Chapter 5**, both spatial and temporal analyses of the reclaimed water quality in an irrigation distribution network were performed. This chapter corresponds to the paper "Spatio-temporal analysis of nitrogen variations in an irrigation distribution network using reclaimed water for irrigation olive trees" (2021) Alcaide Zaragoza C., Fernández García I., Martín García I., Camacho Poyato E. and Rodríguez Díaz J.A. in *Agricultural Water Management*.

Finally, **Chapter 6** presents the conclusions drawn from this thesis as well as the avenues for future research in the field of reclaimed water used for irrigation.

3 REUTIVAR: Model for precision fertigation scheduling for olive orchards using reclaimed water

This chapter has been published entirely in the journal "Water", Alcaide Zaragoza C., Fernández García I., González Perea R., Camacho Poyato E. and Rodríguez Díaz J.A. (2019)

Abstract. Olive orchard is the most representative and iconic crop in Andalusia (Southern Spain). It is also considered one of the major economic activities of this region. However, due to its extensive growing area, olive orchard is also the most water-demanding crop in the Guadalquivir River Basin. In addition, its fertilization is commonly imprecise, which causes over-fertilization, especially nitrogen. This leads to pollution problems in both soil and water, threating the environment and the system sustainability. This concern is further exacerbated by the use of reclaimed water to irrigate since water is already a nutrient carrier. In this work, a model which determines the real-time irrigation and fertilization scheduling for olive orchard, applying treated wastewater, has been developed. The precision fertigation model considers weather information, both historical and forecast data, soil characteristics, hydraulic characteristics of the system, water allocation, tree nutrient status, and irrigation water quality. As a result, daily information about irrigation time and fertilizer quantity, considering the most susceptible

crop stage, is provided. The proposed model showed that by using treated wastewater, additional fertilization was not required, leading to significant environmental benefits but also benefits in the total farm financial costs.

Keywords: reclaimed water; fertigation scheduling; precision irrigation; olive orchard.

3.1 Introduction

Freshwater resources are mainly used for agricultural irrigation, accounting for more than 70% of all water withdrawals worldwide (FAO, 2017). This makes agriculture especially vulnerable to drought periods. This problem is emphasized in a context of climate change since alterations in temperature and rainfall patterns and an increase in the occurrence probability of extreme events have been forecasted (Beniston et al., 2007). Consequently, in arid and semi-arid areas where irrigation agriculture is a major activity, such as Mediterranean countries, extremely high water stress is predicted (Bisselink et al., 2018; Maddock et al., 2015). This will lead to an increase in water demand and potential soil moisture deficit. This situation is particularly critical in Andalusia (Southern Spain), since irrigated agriculture plays a key role in its economy. Olive is the most representative and iconic crop in this region, not only for its importance in the landscape and culture, but also for being considered one of its major economic activities. However, due to its extensive area, olive orchard is the most water demanding crop in the Guadalquivir River Basin, with a water demand higher than 580 hm^3/year for more than one and a half million hectares, which implies about 20% of the total agricultural water demand in that region (CHG, 2016). On the other hand, olive fertilization is commonly imprecise, which causes over-fertilization, especially nitrogen. This leads to pollution problems in atmosphere, soil, and water, threating the environment and the biosystem sustainability. Thus, irrigated agriculture will need to face the challenge of ensuring production using water and fertilizers in a more sustainable way.

Strategies to improve the efficient use of water and fertilizer, increasing the irrigation districts sustainability, have been proposed. The significant development of information and communication technologies (ICTs) has also encouraged the application of these strategies. For instance, González Perea et al. (2017) developed a mobile and desktop application for farmers (*IrriFresa App*) which incorporated the precision irrigation principles for strawberry crop. Its use in commercial farms led to significant water savings which ranged from 11% to 33%. Other authors developed ICT applications focused on irrigation and fertilization management. Thus, Bueno-Delgado et al. (2016) and Pagán et al. (2015) proposed methodologies to determine the most economic fertilizer considering the water quality of the irrigation system. However, in both works, the optimal nutrient solution, which is usually unknown by farmers, was needed as a model input. Pérez-Castro et al. (2017) developed a mobile application with Android Studio IDE (integrated development environment) to determine the fertilizer quantity depending on the crop type and the irrigation system conditions. Nevertheless, this mobile application was only available for greenhouse vegetables. The Institute for Agricultural and Fisheries Research and Training (IFAPA) developed a tool for irrigation and fertigation (fertigation) scheduling for olive orchard. This management tool considers average historic agroclimatic information and determines a monthly fertigation scheduling for olive orchard. However, it is only available online which, sometimes, is not functional for farmers in the day to day irrigation management. It neither considers real-time weather information nor weather forecast. This could cause an inaccurate recommendation because of climate variability.

On the other hand, in order to reduce the pressure on water resources, the use of treated water as an alternative to conventional water sources has also been addressed. Treated wastewater is defined as water arising from any combination of domestic, municipal, or industrial origin that has been processed in a wastewater treatment plant (International Organization for Standardization, 2018). Reclaimed or reused water is formerly treated wastewater with an additional treatment which makes it suitable for reusing in different purposes, such as agriculture, landscape irrigation, or recharge of groundwater aquifers, among others (Arizona Department of Environmental Quality, n.d.; Raschid-sally and Jayakody, 2008). Chen et al. (2013) and Ródenas and Albacete (2014) assured that the use of this water constitutes a strategy both for the water scarcity problem and the sustainability of the irrigated agriculture improvement. After long-term research about citrus trees and horticultural crops irrigated with reclaimed water, Pedrero et al. (2016) and Maestre-Valero et al. (2019) determined that the use of reclaimed water for irrigating citrus trees and horticultural crops generates significant fertilizer savings without posing a risk for human health. Due to its importance and extensive cultivation in Mediterranean areas, different authors have studied the impacts of using reclaimed water as irrigation water in olive orchards on soil pollution (Petousi et al., 2015; Segal et al., 2011), tree development (Ayoub et al., 2016; Bedbabis et al., 2010), and oil quality (Bedbabis et al., 2010; Bourazanis et al., 2016). They concluded that negative impacts were not found when reclaimed water was properly controlled and managed. Erel et al. (2019) compared olive crop irrigation using reclaimed water and freshwater for eight irrigation seasons. Their work showed that fertilizer applications were not required when reclaimed water was used as irrigation water since the water already satisfied the olive nutrient requirements. Their study also highlighted the importance of a regular water quality control to consider nutrients provided with the water. Therefore, the use of reclaimed water in irrigated agriculture could reduce both the intensive use of fertilizer and the associated energy and economic costs. However, special attention must be paid when reclaimed water is used for irrigation because water is already a nutrient carrier and its nutrient content is variable along the year. Nevertheless, when reclaimed water is properly managed and supported by new advances in the ICT, this non-conventional water source can become a strategic solution to the problem raised (Trinh et al., 2013)

In this work, a new model which determines the precision fertigation scheduling in real-time for olive orchard, considering the particularities of applying reclaimed water, has been developed. The innovation of this model was the integration of the irrigation and fertilization olive management techniques combined with weather forecast and agroclimatic records, updated in real-time, and adapted for the specific case of irrigation with reclaimed water. This model aims to improve the irrigation system sustainability, applying nutrients according to the crop needs alone and concentrating the water application on the most critical crop stages to water stress. This model is intended for farmers and technicians to manage water and fertilizer in the most efficient way. The model has been tested in an olive orchard commercial farm located in Córdoba (Southern Spain).

3.2 Methodology

The methodology focused on the development of a precision fertigation model for olive orchard, called REUTIVAR, using reclaimed water as water source. The model was developed considering both historical and forecast weather information, soil characteristics, hydraulic characteristics of the irrigation system, irrigation water quality, water allocation, and soil and tree nutrient status. A detailed description of the model, the required inputs, and the case study are provided below.

3.2.1 Model Description

The model aims to provide the optimal real-time fertigation scheduling in an easy and simple way. It is made up of four independent but interconnected modules: (1) farm characteristics, (2) climate data, (3) irrigation scheduling, and (4) fertilization scheduling (Figure 3.1). The model was implemented in MATLAB™ (MathWorks Inc., MA, USA) (Pratap, 2017).

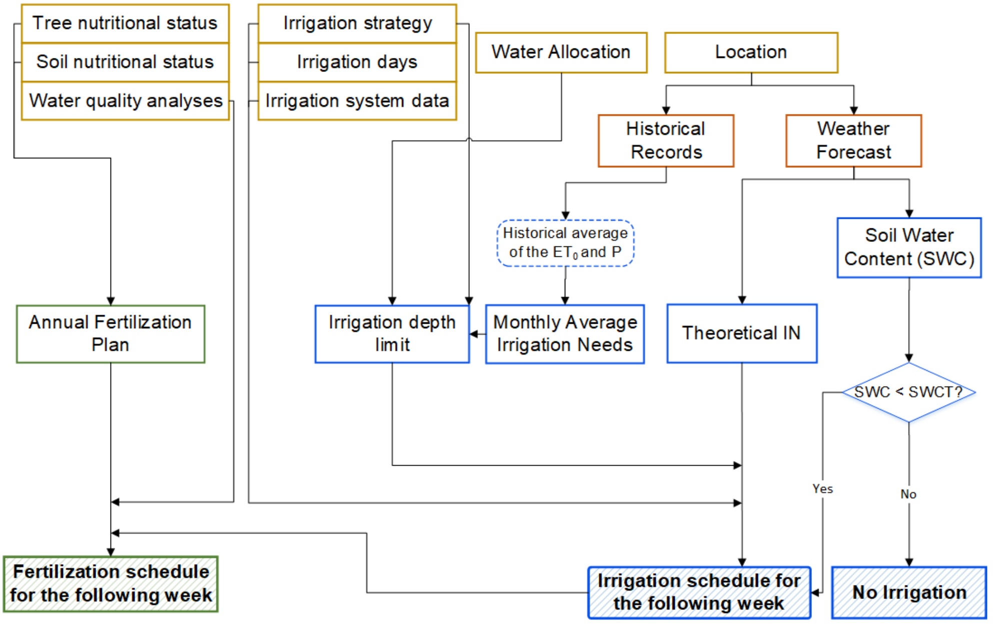


Figure 3.1 *REUTIVAR* flow chart

3.2.1.1 Farm Characteristics

Data of the farm is required in this module: location, area, planting pattern, soil texture, water allocation, irrigation system (flow and spacing of emitters), irrigation scheduling, and crop nutritional status. Soil texture was obtained using the USDA (US Department of Agriculture) soil texture triangle. Subsequently, using the ROSETTA model (Schaap, 1999), the soil moisture retention curves were calculated. Growing cycle, crop coefficient, and crop nutrient uptake were also needed, although they were embedded in the model. Water quality analyses are vital when reclaimed water is used for irrigation since the nutrient water content can be different depending on the case. Hence, water quality analyses were carried out regularly. Finally, soil nutritional status was also evaluated to improve the precision of the fertigation scheduling. This input variable was considered as an optional variable to take into account those cases in which soil nutritional status data are not available.

3.2.1.2 Climate Data

This module considered two aspects: historical agroclimatic data and weather forecasting data, both related to farm location. Firstly, the nearest agroclimatic station to the farm, selected from the available stations in the Agroclimatic Stations Network of the Regional Government of Andalusia (Junta de Andalucía, n.d.), was determined. From this agroclimatic station, using *web scraping* techniques (i.e., an automated process to extract data from websites), the daily values of precipitation (P) and reference evapotranspiration (ET_0) of the available entire time series were obtained.

Then, the daily average values of P and ET_0 were computed as well as the monthly average irrigation needs ($IN_{historical}$). $IN_{historical}$ were calculated as the difference between the crop evapotranspiration (ET_c) and the effective precipitation (P_{eff}) according to Allen (1998). ET_c and P_{eff} are defined later in Section 3.2.1.3.

The daily weather prediction of the study area one-week forward was obtained using AEMET (Agencia Estatal de Meteorología) OpenData. AEMET OpenData is the API REST (application programming interface representational state transfer) of the Spanish State Meteorological Agency (Agencia Estatal de Meteorología (AEMET), 2015). The climate data obtained were: mean temperature (°C), maximum temperature (°C), minimum temperature (°C), maximum relative humidity (%), minimum relative humidity (%), wind speed (km/h), and cloudiness index (%). From these climate variables, the value of ET_0 was calculated by the FAO (Food and Agriculture Organization) Penman–Monteith equation (Allen, 1998). Finally, by web scraping techniques, forecasted precipitation was obtained from eltiempo.es (Pelmorex Corp, 2017). Both weather forecasting and historical data were used to schedule the irrigation events.

3.2.1.3 Irrigation Scheduling

Irrigation scheduling was determined based on theoretical daily irrigation requirements for the following week (IN_d). However, parameters such as monthly water thresholds, soil water content, irrigation system, and irrigation scheduling options were also considered.

Firstly, because of water scarcity problems, monthly water thresholds for irrigation (*IWT*) were established to ensure water availability at the most critical crop stage. *IWT* were determined considering the irrigation strategy and $IN_{historical}$, and the total water allocation according to the volume of reclaimed water in the treatment plant and the water allocation established by the water agency (CHG, 2016). However, although the initial approach was based on historical records, the weekly irrigation recommendations were determined according to weather forecast. Therefore, fortnightly, REUTIVAR checked if the water initially scheduled, considering historical data, had been consumed, i.e., if the irrigation water applied from the beginning of the irrigation season matched to the *IWT* for that period. Otherwise, *IWT* was recalculated for the following months.

Both $IN_{historical}$ and IN_d were calculated as the difference of ET_c and P_{eff}. The main difference between both variables is that $IN_{historical}$ was calculated using historical agroclimatic data and IN_d using the weather forecasting. P_{eff}, the amount of rainfall actually stored in the soil, was calculated using a fixed percentage of P (Smith, 1992). In this case, it was considered a value of the 80% of P. The crop irrigation needs were calculated to refill the daily ET_c, obtained by the methodology proposed by FAO (Doorenbos and Pruit, 1977):

$$ET_c = ET_0 \cdot k_c \cdot k_r \tag{3.1}$$

where ET_0 (mm) was calculated from the weather forecast (see Section 3.2.1.2), k_c is the crop coefficient (in this work the values proposed by (Orgaz and Fereres, 2001) were used, Table 3.1) and k_r is a parameter related to the tree canopy. k_r is equal to 1 for crops with more than 60% of soil cover and ranges from 0 to1 otherwise. In that case, k_r is obtained by using Equation (3.2), proposed by (Fereres et al., 1981).

Table 3.1. Olive crop coefficient (k_c) in Córdoba (Spain)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0.65	0.65	0.65	0.60	0.55	0.55	0.50	0.50	0.55	0.55	0.60	0.65

$$\begin{aligned} k_r &= 2 \cdot S_c/100 && \text{for } S_c \leq 60\% \\ k_r &= 1 && \text{for } S_c > 60\% \end{aligned} \tag{3.2}$$

where S_c (%) is the percentage of the soil covered by the canopy at midday and it is calculated as a function of the average canopy diameter, D (m), and plant density (N(tree/ha)):

$$S_c = \frac{\pi \cdot D^2 \cdot N}{400} \tag{3.3}$$

A soil water balance was used to establish the occurrence of irrigation events. This happened when soil water content was less than 25% of the field capacity value (FC). This is called soil water content threshold (*SWCT*) in this work. The daily soil water content (SWC_d) provides information about the amount of water that the crop can extract from its root zone (Equation (3.4)). Daily, REUTIVAR simulated the soil water balance until that date by using historical data. Then, a soil water content prediction for the following week was conducted considering the weather forecast.

$$SWC_d = SWC_{d-1} + P_{eff,d} + IN_d - ET_{c,adj,d} - R_d - D_d \qquad (3.4)$$

where d is the irrigation day, SWC_{d-1} is the soil water content in the day d-1 (mm), IN_d is the applied irrigation depth (mm), $ET_{c,adj}$ is the crop adjusted evapotranspiration to take into account the crop difficulty to extract water when the soil water content diminishes (mm), R_d is the runoff (mm), and D_d is the deep percolation (mm). Both R_d and D_d are deemed null in this work, since REUTIVAR is designed for a drip irrigation system. To compute the *SWC*, information about soil type and rooting depth were also required.

However, the amount of water that the crop can extract from the soil is not uniformly distributed along the soil drying period and changes depending on the soil moisture. Thus, when the soil is wet, the resistance to water extraction is low, and the crop water uptake can satisfy the atmospheric water demand, i.e., water uptake equals ET_c. In contrast, when the water uptake does not reach ET_c, this term must be adjusted, as shown in Equation (3.5) (Allen, 1998).

$$ET_{c,adj} = ET_c \cdot \frac{TAW - D_r}{TAW - RAW} \qquad (3.5)$$

where *TAW* is the total available water (mm) calculated from Equation (3.6), D_r is the root zone depletion (mm), calculated as the difference between *TAW* and SWC_{d-1}, and *RAW* is the readily available soil water in the root zone (Equation (3.7)).

$$TAW = 1000 \cdot (\theta_{FC} - \theta_{PWP}) \cdot Z_r \tag{3.6}$$

where θ_{FC} is the water content at field capacity (m^3/m^3), θ_{PWP} is the water content at permanent wilting point (m^3/m^3), and Z_r is the rooting depth (m), which was considered as 1 m for the olive case.

$$RAW = p \cdot TAW \tag{3.7}$$

where p is the fraction of *TAW* in which the crop can extract water without suffering water stress, and its value is also obtained from Allen (Allen, 1998). In the olive case, p is considered 0.75 (Orgaz and Fereres, 2001).

In addition, the model considered the days of the week the user chose to undertake irrigation to establish the irrigation volume. To do this, *REUTIVAR* calculated the irrigation needs for the whole week using the weather forecast. In case of internet connection or data source failure, the daily average values were considered temporally. Once connectivity was recovered, the model distributed the irrigation recommendations amongst the selected days by assigning to each of those days its correspondent volume plus the one of the following days, until the next day of irrigation (Equation (3.8)).

$$\begin{aligned} IN_d &= \sum_{d=1}^{n-1} IN_d \cdot k_{strategy} && \text{for } IN_d < \left({}^{IWT}/_{dm}\right) \cdot id \\ IN_d &= \left({}^{IWT}/_{dm}\right) \cdot id && \text{for } IN_d > \left({}^{IWT}/_{dm}\right) \cdot id \end{aligned} \tag{3.8}$$

where *n* is the next irrigation day chosen by the user, $k_{strategy}$ is the applied coefficient depending on the irrigation scheduling options, *dm* is the number of days of the month, and *id* is the number of days from the current day to the next irrigation event.

Three irrigation scheduling options were included in the model: full irrigation (FI), sustained deficit irrigation (SDI), and regulated deficit irrigation (RDI). These strategies are currently the most widespread options, as shown in Padilla-Díaz et al. (2016) for olive orchard. These strategies are explained in detail below.

- FI: in this strategy, the irrigation events are scheduled to cover the total irrigation olive needs, i.e., to fully refill daily ET_c. Therefore, in this case, $k_{strategy}$ equals 1.
- SDI: a percentage of the total olive crop irrigation needs is applied equally along the irrigation period. This percentage can be selected and modified manually, and it corresponds to the value of $k_{strategy}$ in the previous equation.
- RDI: a percentage of the FI is also applied but with varying the irrigation volume according to the crop phenological phase. This strategy concentrates the water stress on the least critical stage to oil production. Specifically, this period is the pit hardening, which ranges from the ending of the fruit set to the beginning of the fruit growth (Orgaz et al., 2017; Rallo and Cuevas, 2017). In addition, the pit hardening stage matches the summer, when transpiration

efficiency is also minimal. Therefore, $k_{strategy}$ is variable based on these variations.

Finally, the irrigation time (t) was determined according to Equation (3.9).

$$t_d = \frac{IN_d \cdot A \cdot 10^4}{IE \cdot q_e \cdot n_e} \tag{3.9}$$

where t_d is the irrigation time for the day d (h/day), A is the sector area (ha), IE is the irrigation efficiency, which was considered 0.95 for the model, q_e is the emitter flow (L/h), n_e is the emitter number, and 10^4 is the unit conversion factor. There is the possibility of limiting t_d according to the off-peak energy tariff hours.

3.2.1.4 Fertilization Scheduling

The fertilization schedule was established according to an annual plan, which varied depending on the crop uptake and the previous year nutritional status, as shown in Fernández-Escobar (2017) for olive trees. According to this author, the nutritional status of the tree is determined by using foliar diagnosis Fernández-Escobar et al. (2009b). The samples must be taken in July since from that date, the foliar nutrient content is stable. In addition, for that period, the critical nutrient level in leaves for olive are tabulated (Fernández-Escobar, 2018) (Table 3.2). The analysis results were compared with the leaf nutrient levels and, only in case of deficiency, fertilization applications were scheduled.

Table 3.2 Interpretation of nutrient content level of olive leaves taken in July, expressed as dry matter percentage according to Fernández-Escobar (2018).

Element (%)	Deficient	Adequate	Toxic
Nitrogen (N)	1.20	1.30–1.70	>1.70
Phosphorus (P)	0.05	0.10–0.30	-
Potassium (K)	0.40	>0.80	-

If fertilizer application was required, the total fertilizer amount was calculated according to an estimation of the annual nutrient uptake for olive crop (Fernández-Escobar, 2017). The following year, foliar analyses were conducted again to increase or decrease the nutrient dose. A flowchart decision tree of the methodology to establish the annual fertilization plan is shown in Figure 3.2. For nitrogen (N), if leaf nutrient content was lower than 1.3 %, the estimation of N requirements was 0.5 kg/tree. However, total N application could not exceed 100 kg/ha. For phosphorus (P), in case P leaf content was less than 0.08%, then 0.5 kg/tree were needed. Finally, for potassium (K), the estimated application was 1 kg/tree if K leaf content was less than 0.7%. The total fertilizer amount was distributed along the irrigation season depending on the crop grow cycle, following the recommendations of García García (2009) (Table 3.3 Monthly distribution of nutrient applications on fertigation (%)Table 3.3). The nutrient requirements were met by applying N, P_2O_5, and K_2O, which are the main components of commercial fertilizers.

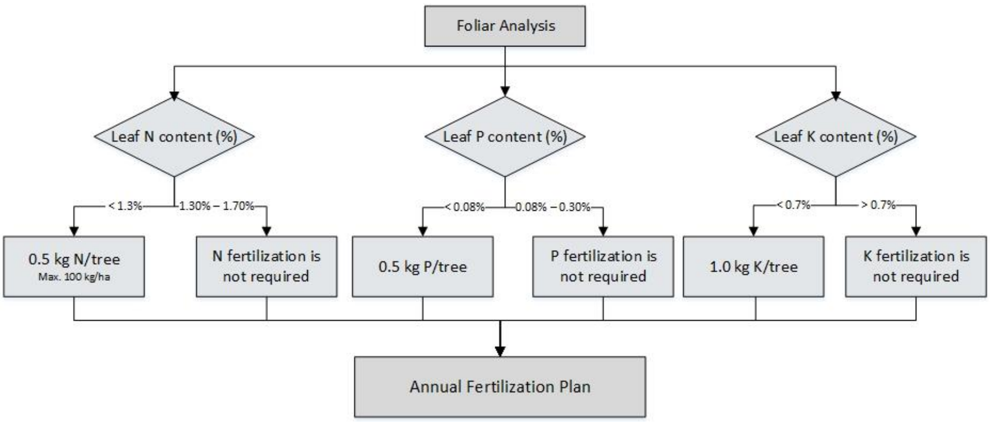


Figure 3.2 Fertilization flow decision tree.

Table 3.3 Monthly distribution of nutrient applications on fertigation (%)

Month	N	P_2O_5	K_2O
April	5	4	4
May	28	25	17
June	28	25	17
July	25	23	31
August	14	23	31

The final nutrient quantity to be applied was calculated as that estimated in the annual plan minus the nutrient content determined from water quality samples. This quantity was adjusted to the irrigation schedule, i.e., the fertilizer application days always coincided with the irrigation days.

Finally, the user can select between fertilizing once a week or in each irrigation event.

3.2.2 Graphical Interface

Finally, the model previously described was integrated in a desktop application to make its use easier. The desktop application was developed by the graphical interface development environment (App Designer) of MATLAB™ version R2018a (Mathworks, 2019). Then, it was compiled using MATLAB Compiler™ with MATLAB Runtime 9.4.

3.2.3 Case Study

The developed model was tested in a commercial olive orchard located in the Tintín Irrigation District (TID), Córdoba (Southern Spain). In this region, the climate is typically Mediterranean, with annual average rainfall of 590 mm, mainly in spring and autumn. The annual average temperature is 16.9 °C and the ET_0 is 3 mm/day. Olive grove is the main crop (*Olea europea* L., cv Hojiblanca and *Olea europea* L., cv Nevadillo azul) spaced at 8 x 8 m and devoted to oil production. The average production of the farm is around 7000 kg/ha. The water applied in TID comes from the village sewage treatment plant. This water is stored in a reservoir where chemical and physical treatments are carried out to obtain the required water quality for reuse. The water is then distributed by subsurface drip irrigation (2.2 L/h pressure compensating drippers spaced at 1 m and installed at a depth of 40 cm). A water allocation of 1500 m^3 /(ha·year) is applied according to the irrigation district manager criteria. Fertilizers are applied by fertigation and also based on the farmer's experience.

3.2.4 Management Scenarios

In order to test the model as well as to highlight its usefulness, five scenarios have been assessed:

1. Actual management scenario (AM). This scenario took into account the fertilization and irrigation scheduling established by the irrigation district manager. It consisted of irrigation applications during 8 hours on Tuesdays, Thursdays, Saturdays, and Sundays for the entire irrigation season. Regarding fertilization, they applied 10 kg/ha of N, 6 kg/ha of P_2O_5, and 12 kg/ha of K_2O.

2. Optimal water and fertilization management scenario (OWAF). This scenario is obtained by applying the REUTIVAR model. It considered the RDI strategy taking into account soil, water, and crop analysis to establish an optimal fertigation scheduling using historical and forecasted climatic data for the actual conditions. The irrigation days were selected according to the TID criteria, but the irrigation events' duration was variable during the irrigation season, according to the most critical crop stages to water stress.

3. Optimal water, fertilization, and electricity cost management scenario (OWAFE). As in the previous scenario, this option considered the RDI strategy to determine the optimal irrigation and fertilization scheduling, but the electricity tariff was included. In this scenario, the optimal

fertigation was scheduled only during off-peak energy tariff hours. Therefore, the irrigation days were similar to previous scenarios. The irrigation event duration was also adjusted to the crop stages. However, in contrast to OWAF, there was also a daily time limit for irrigation. This limit was 8 hours during the weekdays. No limits were established on weekends and in August.

4. Actual management scenario considering a hypothetical olive nutrient deficiency (AM-ND). This scenario was the same as AM, i.e., it considered the fertigation scheduling established by the irrigation district manager, but it also simulated a hypothetical olive N, P, and K deficiency. This scenario intended to evaluate the efficiency and adequacy of the TID fertilization application strategy in case of nutrient deficiencies.

5. Optimal water, fertilization, and electricity cost management scenario considering hypothetical olive nutrient deficiency (OWAFE-ND). As in the previous scenario, this option considered a hypothetical N, P, and K deficiency to determine the optimal irrigation and fertilization scheduling in that case but considering the management of the OWAFE scenario.

3.3 Results and Discussion

3.3.1 Analysis of Soil and Nutrients in the Study Area

In the study farm, the texture and soil nutrient content, water quality, and tree nutritional status were analyzed to run the model. Regarding the soil, tests at different sites in the farm were carried out to assess soil texture, electrical conductivity, pH, and nutrient content. The soil samples were taken considering changes in the morphology, color, and slope to cover as much soil diversity as possible, as recommended by Parra (2017). Four places were selected for this purpose: two of them were located under the tree (U) and the remaining two were located between trees (B). At each place, two samples were taken at different depths, according to the type of crop. For the olive tree case, the samples were taken between 0 and 15 centimeters (P1) and between 15 and 30 centimeters (P2). In terms of assessing the nutritional status of the tree, foliar diagnosis was carried out (Fernández-Escobar et al., 2009b), two samples of 100 leaves from 50 trees each were analyzed in July 2018 and 2019. Finally, water quality analyses were carried out monthly. The water samples were taken in the pipe between the reservoir and the pumping station. Thus, the nutrient content of the water in the model was updated fortnightly using these results.

Several analyses were carried out during the 2018 and 2019 irrigation seasons in the olive orchard farm located in TID. Table 3.4, Table 3.5 and Table 3.6 show the soil, foliar, and water quality analysis results, respectively.

Table 3.4 Soil analyses undertaken in September 2018 in the case study farm.

Name sample	Depth (cm)	Texture			P (mg/kg)	K (mg/kg)
		Clay (%)	Silt (%)	Sand (%)		
U1P1	0–15	37.8	26.8	35.4	14.1	563
U1P2	15–30	38.1	28.0	33.9	7.7	454
U2P1	0–15	34.1	23.5	42.4	9.9	454
U2P2	15–30	37.4	20.0	42.6	5.8	317
B1P1	0–15	37.2	28.2	34.6	23.6	872
B1P2	15–30	34.6	28.9	36.5	25.7	794
B2P1	0–15	32.4	23.7	43.9	22.8	978
B2P2	15–30	36.3	21.3	42.4	27.0	598

The farm soil was defined as clay loam. From the moisture retention curves, the FC value was determined as 0.28 cm^3/cm^3 and the permanent wilting point (PWP) as 0.14 cm^3/cm^3. Finally, as for the macronutrient amount, the phosphorus (P) amount between trees was higher than under the tree. Nevertheless, the P amount contained in all the locations suggests that a P fertilization response was unlikely, especially for olive orchard. This is because P extractions are low, and this nutrient is easily reusable for olive trees. In addition, high P content could cause zinc (Zn) blockages, originating Zn deficiency in the tree. Likewise, considering the potassium (K) analysis, all the samples showed high levels of K and, consequently, the expected fertilizer response was unlikely. The nitrogen (N) levels in soil were not analyzed due to the high short-term mobility of this element in the soil.

Table 3.5 Olive foliar analyses conducted in July 2018 and 2019 in the studied areas (values expressed as dry matter percentage).

Element (%)	'Hojiblanca'		'Nevadillo azul'	
	2018	2019	2018	2019
N	2.02	1.80	1.35	1.81
P	0.11	0.11	0.13	0.14
K	0.92	0.82	0.88	0.84

As shown in Table 3.5, the amount of P and K in olive leaf were within the recommended range in the 2018 irrigation season and the values were adequate in the following year. The P leaf level remained steady for the two seasons. The K leaf content was slightly lower in the 2019 irrigation season, although it stayed within the correct range. However, for the N level, except in 'Nevadillo azul' variety in the 2018 irrigation season, all the leaf samples showed mildly high nitrogen content. According to (Molina-Soria and Fernández-Escobar, 2012), a nitrogen leaf content higher than 1.7% causes impacts on flower and a decrease in oil quality. Other authors also agree with the damages that an excess of nitrogen can produce in olive, such as a decrease in the olive frost tolerance, a delay in the fruit ripening, leading to a reduction in fat yield, and also soil pollution produced by nitrogen leaching (Fernández-Escobar et al., 2014, 2010, 2009a).

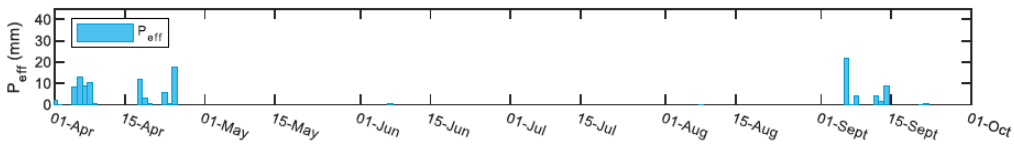
Table 3.6 Water nutrient analysis undertaken in the case study farm during the 2019 irrigation season

Date	$N\text{-}NH_4^+$ (mg/L)	$N\text{-}NO_3^-$ (mg/L)	$P\text{-}PO_4^-$ (mg/L)	K^+ (mg/L)
21 August 2018	1.0	1.5	1.7	-
25 September 2018	1.5	1.3	1.2	-
23 May 2019	10.7	1.8	0.5	-
13 June 2019	13.0	1.9	0.4	-
29 June 2019	12.2	1.7	0.2	32
9 August 2019	2.3	2	0.2	-
9 September 2019	3.3	1	0.2	-

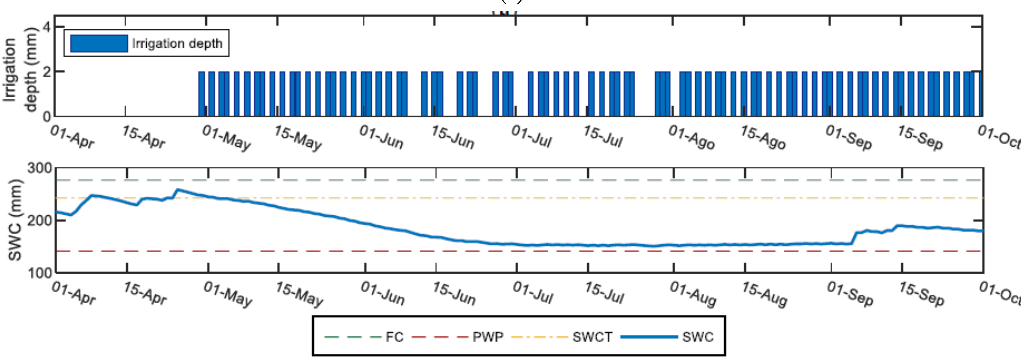
As shown in Table 3.6, the nitrogen content varied along the 2019 irrigation season, especially the ammoniacal nitrogen ($N\text{-}NH_4^+$). The highest nitrogen concentrations occurred in May, June, and July, when nitrogen needs increase. Additionally, in May and June, the irrigation needs for olive are also larger. Therefore, when a RDI strategy is considered, the total nitrogen application must be higher. The nitrogen fluctuation highlighted the importance of a regular water quality control since the N fertilizer amount to be applied could be over or underestimated. Regarding phosphates, the amount contained in water was higher in 2018 than in 2019. During the 2019 irrigation season, the variations were not significant. However, the concentration difference between years also emphasized the relevance of water quality controls. Finally, about potassium concentration, it was only possible to take one sample because of technical problems. The K^+ concentration in that sample was considerably high, which indicated substantial nutrient application throughout the irrigation season. The K^+ concentration was assumed constant for the whole irrigation season.

3.3.2 Analysis of Management Scenarios

The model was applied for 2019 irrigation season data and the five proposed scenarios. Figure 3.3 shows the AM, OWAF, OWAFE, AM-ND, and OWAFE-ND irrigation schedules along the 2019 irrigation season. For AM and AM-ND, the irrigation schedule distribution was the same and, for that reason, both are represented in a single figure (Figure 3.3 (b)). It also occurred for OWAFE and OWAFE-ND scenarios, which are represented in Figure 3.3 (d).



(a)



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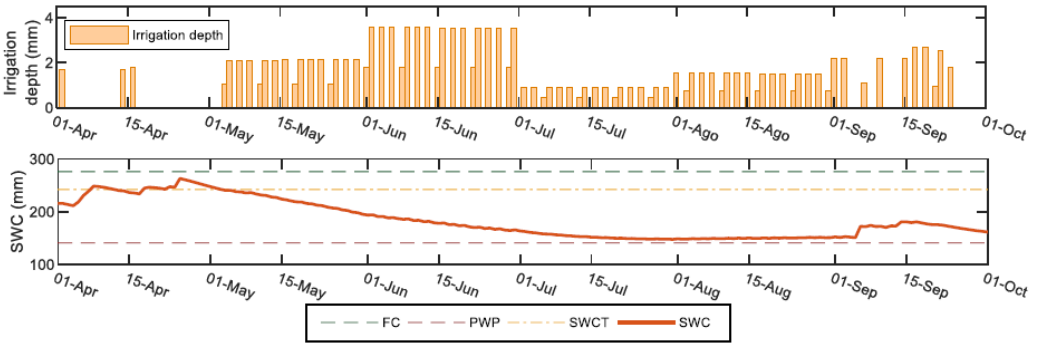

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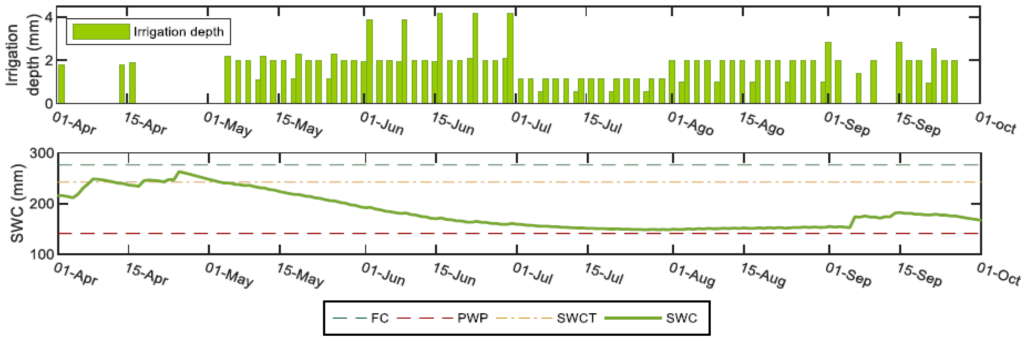


(d)

Figure 3.3 (a) Seasonal distribution of daily effective precipitation for the 2019 irrigation season. **(b)** Seasonal distribution of daily soil water content and irrigation scheduling in the actual management (AM) and actual management scenario considering a hypothetical olive nutrient deficiency (AM-ND) scenarios. **(c)** Seasonal distribution of daily soil water content and irrigation scheduling in the optimal water and fertilization management (OWAF) scenario. **(d)** Seasonal distribution of soil water content and irrigation scheduling in the optimal water, fertilization, and electricity cost management (OWAFE) and the optimal water, fertilization, and electricity cost management scenario considering hypothetical olive nutrient deficiency (OWAFE-ND) scenarios.

The total P_{eff} from April to September was 123 mm Figure 3.3 (a) and the average ET_0 during the irrigation season about 4.5 mm·day^{-1}, which can be considered as a regular year. The total water applied in the AM scenario was 1623 m^3/ha for the 2019 irrigation season. It did not adjust the total water applied to the water allocation according to the irrigation district manager criteria (1500 m^3/ha). This could affect the profitability of the studied irrigation district since the water use in that region is limited by the water authority, causing financial penalties in case of exceeding the established limit. However, OWAF, OWAFE, and OWAFE-ND adjusted the total water applied to this water allocation limit. In particular, OWAF applied a total of 1492 m^3/ha, and OWAFE and OWAFE-ND, a total of 1497 m^3/ha. The three of them concentrated the irrigation events in May, June, and September, when olive is more sensitive to water stress (García et al., 2013; Rallo and Cuevas, 2017). However, for the OWAF scenario, the water application distribution could be steadier since time restrictions were not considered. In contrast, OWAFE and OWAFE-ND took into account the electricity tariff existing in TID. In these scenarios, the optimal fertigation was scheduled only during off-peak hours, when power and energy are cheaper. For the TID electricity tariff, the off-peak hours included from 12 am to 8 am every day, as well as 24 hours for Saturdays, Sundays, and bank holidays. This effect reduced the water application in the most water-demanding months according to the RDI strategy. Thus, the volume of water applied in May and June was lower in OWAF than in the OWAFE and OWAFE-ND scenarios.

In terms of soil water content, in all the scenarios, the water content never fell below the PWP. This could be because the soil is extremely dry and the resistance to water extraction is considerably higher when water content in soil is lower than the RAW. It was also noticed that, despite applying the scheduled irrigation in all the cases, the soil water content decreased from May to the first precipitation event in September. However, this decrease was slightly lower in OWAFE and OWAFE-ND and noticeably lower in OWAF, since more water was applied in June. This allowed the soil not to be depleted abruptly and for a shorter period of time. Despite this, in these three scenarios, the soil water content diminished considerably. This is because of the limit of water allocation, noticeably lower than the olive orchard irrigation needs. Therefore, the soil water content only increased after the first precipitation events.

Regarding fertilization needs in both OWAF and OWAFE scenarios, fertilizer application was not required according to REUTIVAR, as recommended in Fernández-Escobar (2017). This is because the nutrient leaf levels of the olive orchard were in the correct range, i.e., there was no nutrient deficiency. In the AM scenario, although fertilizers were not needed either, some were applied. Then, olive nutrient deficiency was forced for the AM-ND and OWFE-ND scenarios to evaluate how REUTIVAR would operate in that hypothetical situation. Table 3.7 shows the nutrient amount applied for all the scenarios.

Table 3.7 N, P, and K applications through water and fertilizers for AM, AM-ND, OWAF, OWAFE, and OWAFE-ND scenarios.

Scenario	**AM/AM-ND**			**OWAF**			**OWAFE**			**OWAFE-ND**		
Nutrient	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**
Applied with water (kg/ha)	15.8	0.5	52.0	18.3	0.5	48.0	15.5	0.4	48.0	15.5	0.4	48.0
Applied with fertilizer (kg/ha)	9.9	2.7	10.2	0	0	0	0	0	0	59.9	73.7	108.0
TOTAL	25.6	3.2	62.2	18.3	0.5	48.0	15.5	0.4	48.0	75.0	74.1	156.0

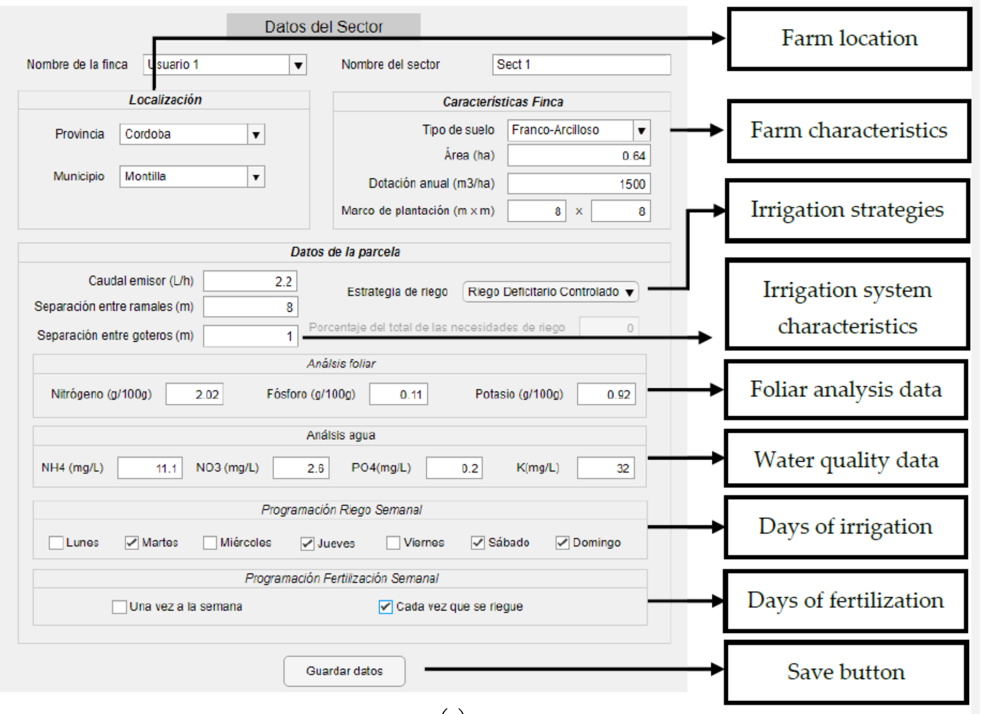
The use of reclaimed water as a water source for irrigation involves the nutrient application within the water, as shown in Table 3.7. For this reason, regular water quality controls are essential for the proper irrigation system performance. In both OWAF and OWAFE scenarios, considering the average production of the farm, the nitrogen removal by harvest and pruning was compensated with the applied nitrogen within water irrigation in addition to the rainwater nitrogen and the organic matter mineralization (García-Novelo, 2006). More nitrogen was applied in the OWAF scenario compared to the OWAFE scenario because in June, when more water was applied in OWAF, the nitrogen content in the water was also higher. As for phosphorus, olive trees show low P extractions by harvest, and they can also reuse it. For that reason, olive orchards in that region do not usually present P deficiency problems and they do not frequently respond to P applications. Therefore, the P application within the water was enough to cover olive needs. Finally, the potassium element showed the highest concentration within the irrigation water. However, the extraction of this element is significantly high in olive trees. Hence, potassium deficiency is the major nutritional problem in olive orchard in Andalusia, playing a key role in the olive tree nutrition. Nevertheless, the K amount applied in the irrigation water covered all potassium removals for harvest. Thus, the fertilizer application was not required, which led to a reduction in the total annual farm cost and a decrease in pollution keeping the olive oil production.

In the hypothetical high nutrient deficiency situation, i.e., the AM-ND and OWAFE-ND scenarios, considering the farm area and the tree spacing, the total nutrient needs according to Fernández-Escobar (2017) recommendations, were: 78 kg/ha of N, 78 kg/ha of P, and 156 kg/ha of K. Based on these recommendations, in the AM-ND scenario, a fertilizer deficiency was determined. In both AM and AM-ND fertilization, decisions were not based on the tree nutritional status, which can cause fatal damages to the farm, its production, and profitability. On the other hand, in the OWAFE-ND scenario, the nutrient needs were covered, which would lead to an increase in farm yield. Under this scenario, the use of reclaimed water as irrigation water would entail savings of 21%, 1%, and 31% of the N, P, and K needs, respectively.

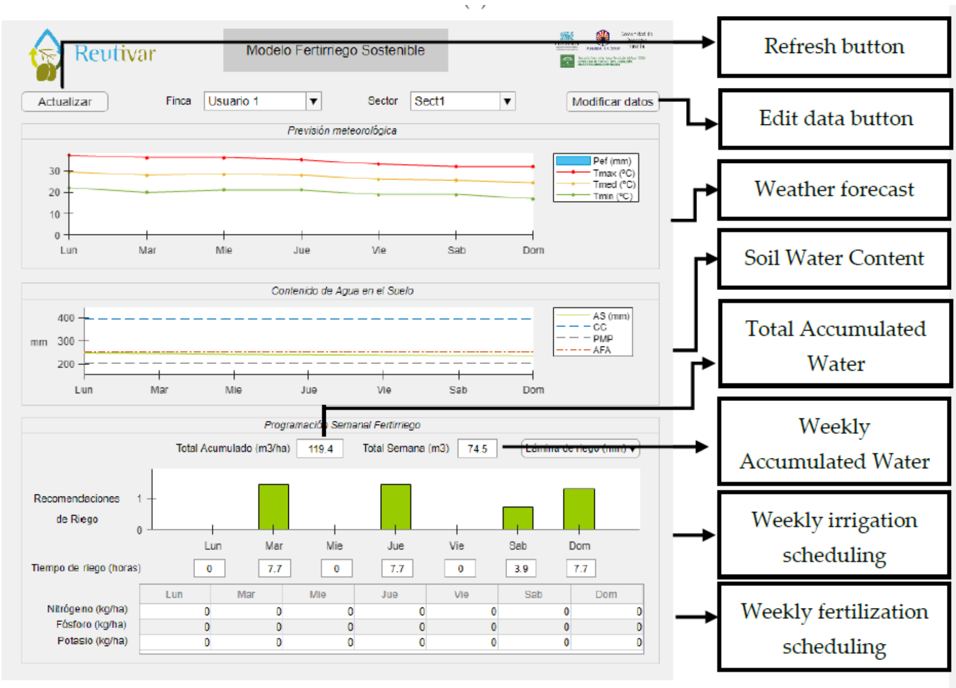
In summary, the use of the fertigation recommendations (OWAF and OWAFE scenarios) provided by the REUTIVAR model entailed a better water distribution along the irrigation season compared to conventional practices (AM) in which water is applied without considering the most critical olive phenological stages. As for nutrient applications, an excess of nutrients was applied in the AM compared to OWAF and OWAFE scenarios, in which the nutrient content of reclaimed water is considered. Furthermore, in the hypothetical case of nutrient deficiency, since the conventional practice is not based on nutrient tree status, not enough fertilizers were applied in the AM-ND scenario. In contrast, if the model recommendation would be followed, all the nutrient requirements would be covered.

3.3.3 Graphical Interface

Finally, the developed model was integrated in a user-friendly graphical interface to make the daily fertigation scheduling management easier (Figure 3.4)



(a)



(b)

Figure 3.4 Graphical interface of the REUTIVAR model for fertigation schedule recommendations from 3 October 2019 to 9 October 2019. (a) Required data to run the precision fertigation model, (b) Irrigation and figure recommendations of the model.

In the screen (a) of the graphical interface (Figure 3.4 (a)), the user must introduce the required data to run the model: farm location, type of soil, water allocation, irrigation system characteristics, irrigation strategy, foliar analysis results, and water quality results. In this screen, the user can select between different irrigation strategy options: RDI, SDI, and FI. They can also select the days of the week they wish to irrigate and if they wish to fertilize whenever irrigation is applied or weekly. Then, all this information is stored in an internal database through the save button. The fertigation schedule for the following week is provided in the screen (b) (Figure 3.4 (b)). Firstly, in this screen, a precipitation and temperature forecast for the following week is provided. Then, a simulation of the soil water content for that week is shown. At the bottom of the screen, irrigation and fertilization scheduling recommendations are provided. The irrigation scheduling is given in volume (mm) and in time units (hours), which is more functional. In addition, information about total water applied from the beginning of the irrigation season and water expected to be applied for that week are also shown. Finally, in this screen, two buttons can also be observed: the refresh button and the edit data button. The refresh button allows to manually update the real-time information of screen (b). By pushing the edit button, screen (a) reappears and the user can modify any of the data previously introduced.

3.4 Conclusions

A precision fertigation model using reclaimed water, REUTIVAR, was developed. REUTIVAR was validated in the 2019 irrigation season in a commercial olive orchard. To do this, five scenarios were simulated. This validation proved that REUTIVAR adjusts the established water allocation along the irrigation season, preventing additional costs to the farm. However, it also showed that this water allocation was much lower than the olive orchard irrigation needs. The scenario simulations also indicated that with the current farm characteristics, the RDI strategy could be applied, even if electricity tariff limitations were considered. This could involve important improvements in both quality and quantity of final oil production. This validation also proved that, thanks to the nutrients which the water carry, additional fertilization was not required. This implies large benefits in the environment but also in the total financial costs of the farm. On the other hand, if the hypothetical nutrient situation is assumed, the current fertigation management of the farm would not cover the nutrient needs either. This shows the importance of the nutritional crop status diagnosis to establish the fertilization decisions.

This work confirms that irrigation with reclaimed water should be managed in a more sustainable way since famers tend to overfertilize. However, following REUTIVAR's recommendations, it is possible to save fertilizer costs with positive effects on the environment and farmer's incomes. In addition, although the model was validated for olive orchard, REUTIVAR could be adapted to other crops, offering a useful tool to manage reclaimed water in an efficient and sustainable way.

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4 Open source application for optimum irrigation and fertilization using reclaimed water in olive orchards

This chapter has been published entirely in the journal "Computer and Electronics in Agriculture", Alcaide Zaragoza C., González Perea R., Fernández García I., Camacho Poyato E. and Rodríguez Díaz J.A. (2020)

Abstract. Olive orchard plays a key role in the economy of Andalusia (Southern Spain). It is also the most representative and extensive crop in that region. In fact, for that reason, it is the crop to which more water is allocated in the Guadalquivir River Basin. Additionally, its fertilization is based on the farmers experience which leads to inaccuracy and unnecessary fertilizers application. This over-fertilization, which is often of Nitrogen, causes significant impacts on soils, water and atmosphere, which threats the biosystem sustainability. At this juncture, olive orchard irrigation using reclaimed water arises as an alternative of the traditional water sources. Nevertheless, its management is more complicated since the water is already a nutrient carrier. In this work, a mobile application for Android devices has been developed. The application aims to provide farmers and technicians of a user-friendly tool which facilitates the fertigation management using reclaimed water for olive orchard irrigation. The mobile application has been used in a commercial farm, reducing the application of additional fertilizers. This leads to both environmental benefits and financial cost reductions.

Keywords: reclaimed water; fertigation scheduling; precision irrigation; app; information and communication technologies (ICTs)

4.1 Introduction

Irrigated agriculture is the main consumer of freshwater resources worldwide, accounting for more than 70% of the total water consumption (FAO, 2017). This makes the agricultural sector highly dependent on water resources and particularly vulnerable to water scarcity. Additionally, in this context, if climate change and the growing demand for water of the other economic sectors and population are considered, the agricultural sector could be seriously jeopardized in the future. This is especially critical in arid and semi-arid countries where irrigated agriculture is one of their economic bases. This is the situation of Andalusia, located in Southern Spain, whose economy depends to a large extend on agriculture. Olive orchard is the most representative and extensive crop of this region accounting for more than one and a half million hectares of the 10 million hectares worldwide. Of the aforementioned hectares in Andalusia, more than five hundred thousand are irrigated. This makes olive the crop to which more water is allocated in the Guadalquivir River Basin, demanding nearly 866 hm^3/year of water. Besides, olive fertilization is often inadequate and based on farmer experience, which usually leads to over-fertilization, particularly of Nitrogen. It produces substantial negative impacts on soil, water and atmosphere, which threats the environment and endangers many species. In this context, irrigation agriculture must take strategies to ensure food production using water and fertilizers as sustainable as possible.

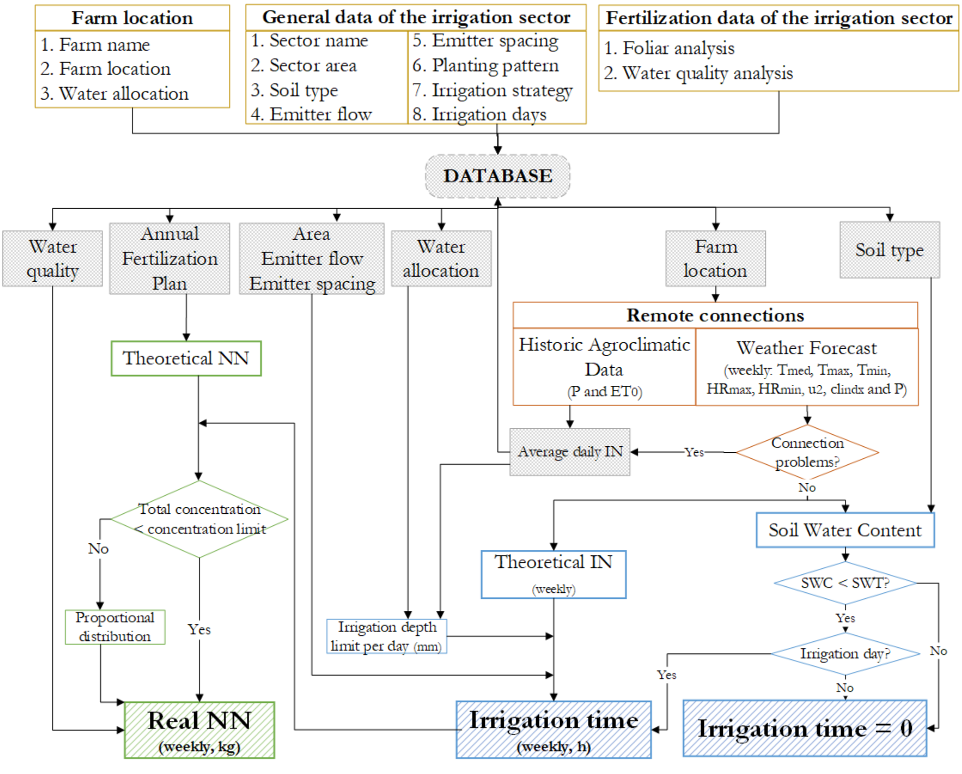
The use of reclaimed water could be a potential alternative to the problem arisen. Treated wastewater is used water from domestic, municipal, industrial or commercial activities that has been processed in a wastewater treatment plant to remove contaminants. However, to make it suitable for reuse, an additional treatment is required. This treatment will depend on the required water quality which is related to the final water use. Then, this water is called reclaimed or recycled water and it can be used for irrigating or enhancing water bodies (e.g. groundwater recharge or wetlands creation) among other uses. In case of woody crops, for example, the additional treatment consists of filtration, UV light application, disinfection and maintenance. The use of reclaimed water can be a solution to the water scarcity problem while improving the environment. It is estimated that 1,100 million m^3/year of reclaimed water are used in agriculture in the EU. The impacts of using reclaimed water for irrigation have been studied by different authors. Some of these authors have focused their studies on citrus trees and horticultural crops. They maintain that, after long-term research, the use of reclaimed water to irrigate them was not only successful but also beneficial for both the environment and the farm profitability since significant fertilizer savings were achieved (Maestre-Valero et al., 2019). In addition, they proved that using reclaimed water for irrigation was absolutely safe for human health. Others have studied the impacts of reclaimed water on olive orchard irrigation. They investigated the impacts on soil pollution, tree development, oil quality and fertilizers application (Ayoub et al., 2016; Bourazanis et al., 2016; Erel et al., 2019). They all agreed that irrigating using reclaimed water did not produce any negative impacts as long as the water was properly controlled and managed. In addition, Erel et al. (2019) affirmed that the reclaimed water used in his study carried enough nutrient to cover olive nutrient requirements and hence fertilizers applications were not required. All these works provided interesting information about irrigation with reclaimed water and proved that it could reduce the intensive use of fertilizers and its economic costs. They also emphasized the importance of regular controls to carry out a proper management since this type of water already contains a large amount of nutrients which are, furthermore, variable along the year. However, none of them provide an easy to use methodology for farmers to use reclaimed water as irrigation water source. This causes that the use of reclaimed water for irrigation is imprecise for farmers who keep behaving as always.

Materializing methodologies and making them user-friendly is essential to bring the acquired knowledge to the agricultural sector. The use of the new advances in the Information and Communication Technologies (ICTs) in combination with the open data sources are the key to achieve this. Its use allows to obtain, process and record large data volume as well as to compute complex models easily. Some methodologies, based on ICTs, to support irrigation and fertilization management decisions of farmers and irrigation district managers have been developed previously. For instance, some authors developed *Irrifresa App*, a mobile and desktop application to aid farmers in irrigation scheduling decisions (González Perea et al., 2017). This application applied the precision irrigation principles in strawberry crop, considering the type of soil and the hydraulic characteristics of the system among other parameters, which contributed to important water savings. Other authors created *cFertigUAL*, a mobile application for fertigation management (Pérez-Castro et al., 2017). The *cFertigUAL* objective was to calculate the optimal fertilizer quantity considering the crop type and the irrigation system conditions. However, it was developed only for greenhouse vegetables. There are other authors who have focused their researches on finding the most economic fertilizer (Bueno-Delgado et al., 2016; Pagán et al., 2015). Both works considered the quality of the irrigation water, but the optimal nutrient solution was also required to run the model. This information is usually unknown by farmers, which complicates the application use. Finally, the Institute for Agricultural and Fisheries Research and Training (IFAPA) developed a website application which aimed to recommend fertigation scheduling for olive orchard. This recommendation was based on monthly average agroclimatic records and, therefore, it did not change depending on real-time data. The results, additionally, are provided monthly and as irrigation depth, which sometimes is not the most practical option in the day to day irrigation management.

In this work, an ICTs based tool, called *REUTIVAR-App*, was developed to schedule irrigation and fertilization for olive orchard at farm level based on precision fertigation principles and using reclaimed water. *REUTIVAR-App* is a mobile application which determines in real-time the fertigation scheduling for olive orchard. It aims to provide famers and technicians with a user-friendly app to applied reclaimed water to irrigate in the most sustainable and productive way. Its key principles are applying nutrients only when the crop needs them and to concentrate water application on the most critical olive stage to water stress. *REUTIVAR-App* was implemented in a commercial farm of olive orchard located in Southern Spain.

4.2 Methodology and App description

REUTIVAR-App calculates in real-time the irrigation time and fertilizer amount required to cover olive tree needs using reclaimed water during the irrigation season. *REUTIVAR-App* is composed of six interconnected modules: 1) input data, 2) database, 3) remote connections, 4) irrigation scheduling, 5) fertilization scheduling and 6) results and visualization (Figure 4.1). A detailed description of each module is provided in the following sections. *REUTIVAR-App* has been built under MVVM pattern (Model-View-ViewModel) to provide more flexibility to manage various types of data sources. The mobile application was developed for Android devices. All of this information is further explained in the following sections.

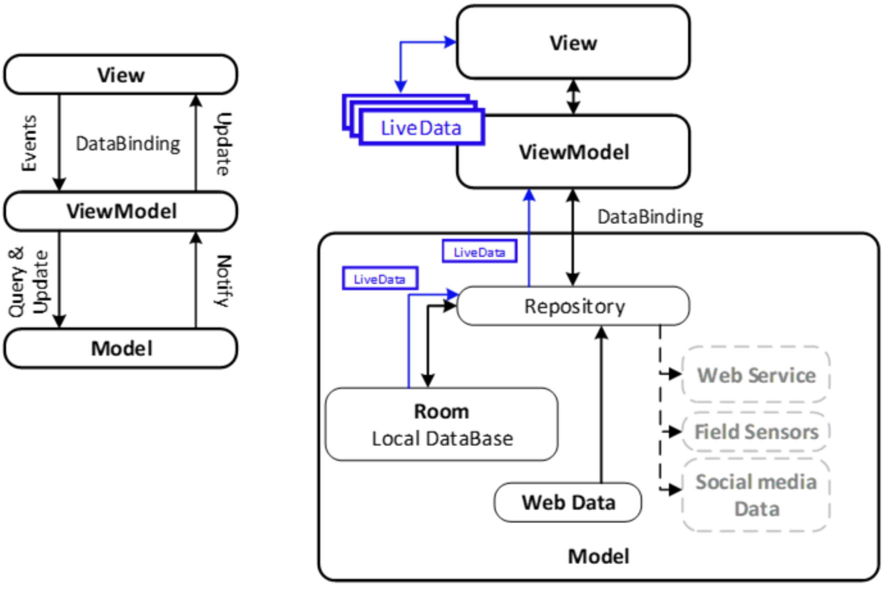


*NN = Nutrient Needs; IN = Irrigation Needs; SWT = Soil Water Threshold; SWC = Soil Water Content

Figure 4.1 *REUTIVAR-App* flow chart

4.2.1 App Architecture Pattern

An architecture pattern in which the underlying data, its presentation and manipulation are clearly differenced is essential for the development of maintenance and high-quality interactive software in any app. In this context, the Model View Controller (MVC) -based on architectural design patterns are the most widely used (Buschmann et al., 2007). The classical MVC pattern was developed to differentiate the business logic from the presentation layer. This design pattern defined three main layers: *Model,* which represents the knowledge of the model by a set of rules; *View,* which provides a visual representation of the Model and *Controller,* which manipulates the View layer and translates the interaction of the user to the Model layer. However, current models are fed by many information sources such as field sensors, web services, social media and so on being MVC pattern too rigid for managing various kinds of data sources. Thus, *REUTIVAR-App* has been built under an evolution of the MVC pattern known as MVVM pattern which aims to increase decoupling between the user interface and the middle layer represented by the ViewModel (Figure 4.2 (a)). The communication between these two layers is done exclusively through two-way data-binding notifications. *REUTIVAR-App* has been originally developed with a local database which stores information from different webservices in real time as well as other kind of data defined by the user. With the aim to improve the scalability, robustness and persistence of the app, two additional components were added to the architecture of *REUTIVAR-App* (Figure 4.2 (b)): *Repository* and *LiveData*. *Repository* is an additional abstraction layer becoming the single source of truth for all app data. Repository can manage other future data sources (dash line) without any alteration in the rest of the app. On the other hand, *LiveData* allows to update all data of the app automatically and in real time, in other words, when some data of any information source changes at any time such as temperature or weather forecasting, the whole app is automatically updated based on that change.



(a) (b)

Figure 4.2 MVC pattern (a) design pattern of *REUTIVAR-App* (b)

4.2.2 Software development

The mobile application was developed in Android Studio, the Google's official integrated development environment (IDE) for Android OS (Operating System) application. It was developed for minimum API level 21 which made it available for more than 90% of current Android devices (mobiles and tablets). The database has been built under SQLite which provides a relational database management system (SQL Consortium, 2000).

4.2.2.1 *Input data module*

The first module includes the input variables required by *REUTIVAR-App*. This data is stored in the database, as explained in section 4.2.2.2. This data includes: 1) general farm information which consists of farm name, farm location and water allocation (Figure 4.3 (a)), 2) general data of the irrigation sector such as sector name, sector area, soil type, irrigation system characteristics, irrigation strategy and the irrigation days (Figure 4.3 (b)) and 3) fertilization data of the irrigation sector which includes the data from the foliar analyses and from water quality analyses (Figure 4.3 (c)).

This module is filled in by the user every time a new fertigation scheduling is carried out. In the general farm information screen (Figure 4.3 (a)) the user must introduce the farm name. Then, from a drop-down list with all the available cities and villages, the user can select the nearest one to its farm location. Finally, they must add the farm water allocation. As for the general data of the irrigation sector (Figure 4.3(b)), the user must introduce the sector name, the sector area, the emitter flow and the emitter spacing. For the soil type, the user can select one of the main type of soils which are presented in a drop-down list (clay, sandy, loam, etc.) or they can introduce their soil data. In terms of the irrigation strategy, they can select between full irrigation, regulated deficit irrigation or sustained deficit irrigation. Finally, the user must select the day of the week they want to irrigate. Figure 4.3 (c) shows the fertilization data of the irrigation sector screen. In that screen the user can introduce the nutrient content of the soil as well as pH and electrical conductivity (EC) of the soil, but this is optional, just in order to increase the precision of the results. They must introduce the nitrogen, phosphorus and potassium content levels of the olive leaves. Finally, they must specify the NO_3^-, NH_4^+, PO_4^{-2} and K^+ values of the water sample.

4.2.2.2 Database module

The database included in *REUTIVAR-App* was managed in SQLite. The major difference compared to other SQL databases is that SQLite does not have a separated server process. SQLite database has multiple tables, indices, triggers and views but all of them contained in a single disk file which makes it considerable lighter (SQL Consortium, 2000). The database is a relational database which consists of eleven tables and it is automatically created the first time the user accesses to the App. Table 4.1 shows the information stored in each table.

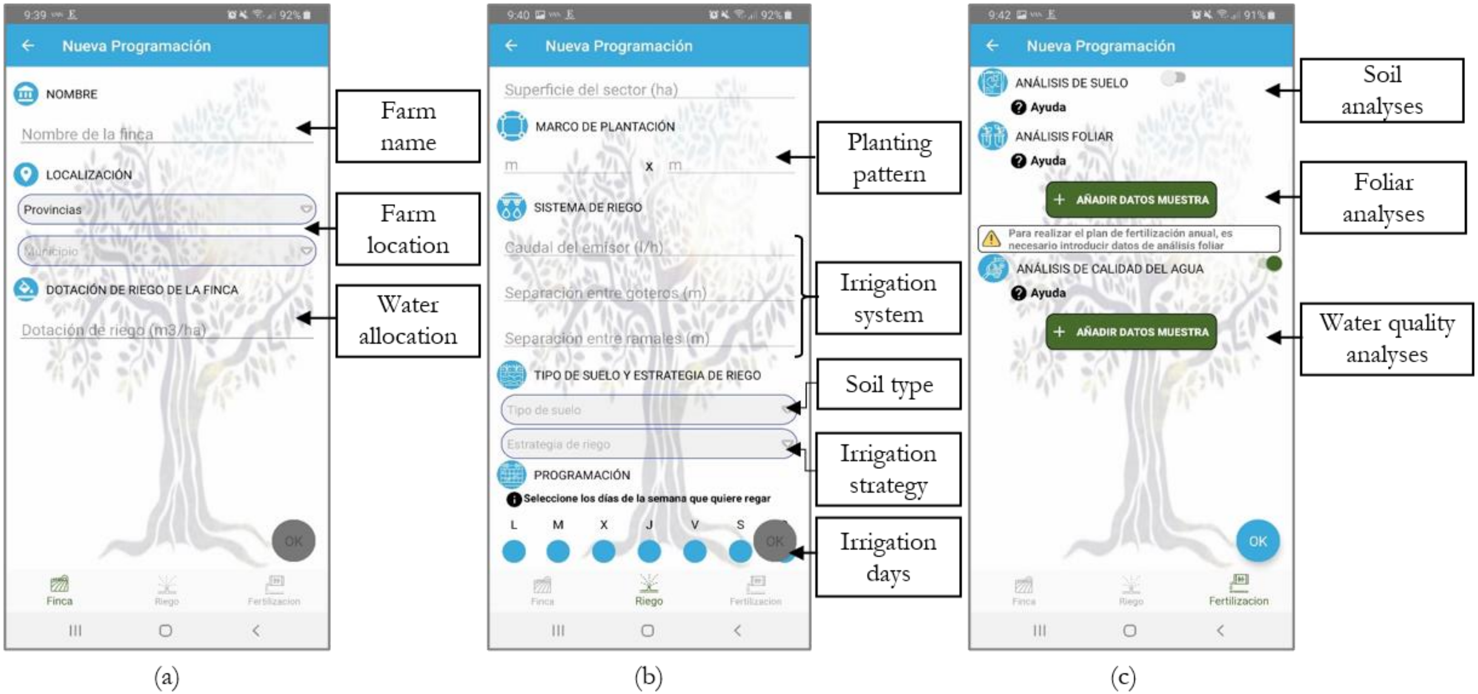


Figure 4.3 Graphical interface of mobile application to introduce the input data: general farm information **(a)**, irrigation sector information **(b)** and fertilization data **(c)**.

Table 4.1. Stored information in the database.

Table name	**Stored information**
Tusers	Username and password for each user.
Tfarms	Farm name, farm location and water allocation.
Tsectors	Sector name, soil type, sector area, planting pattern, irrigation system characteristics, irrigation strategy.
Twaterquality	Sample name, NO_3^-, NH_4^+, PO_4^{-2} and K^+ values of the water sample.
Tfoliaranalysis	Sample name, N, P and K values of the foliar analysis.
Tsoilanalysis	Sample name, P and K values, pH and EC of the sample.
Thistoricalweather	Daily average values of ET_0 and P for each weather station.
TaverageIN	Monthly average value of irrigation needs for each farm location.
Ttheoirrigation	Records of the daily irrigation schedule recommendations.
Ttheofertilization	Records of the daily values of N, P and K recommendations.
Trealfertigation	Records of the real irrigation and fertilization events.

REUTIVAR-App allows the user to display and manage the database from the mobile application. First, a summary of the different farms stored in the database is displayed (Figure 4.4 (a)). In that screen, basic information of each farm is presented. Then, when one of the farms is tapped, a summary of all sectors belong to that farm is shown (Figure 4.4 (b)). When one of the irrigation sectors is selected, a detailed description of the irrigation sector is shown (Figure 4.4 (c)). Finally, *REUTIVAR-App* includes copying and modifying options (Figure 4.4 (d)). These options allow both to create new farms, sectors and/or fertigation scheduling from other farms or sectors previously created sharing one or more characteristics and to delete any of them.

Figure 4.4 (a) shows all the farms previously created by the user. In this screen, the city and village, water allocation and the number of irrigation sectors of each farm are displayed. In Figure 4.4 (b) information about the irrigation sector area, emitter flow and soil type of each irrigation sector is presented. Then, in Figure 4.4 (c) all the irrigation sector data is shown. Particularly, in this screen the user can observe the farm and sector names, the area, type of soil, plating pattern, emitter flow, emitter spacing, irrigation strategy and irrigation days. Finally, Figure 4.4 (d) shows a summary which includes farm location, water allocation, area, flow emitter, soil type and irrigation strategy of each sector. The user can copy this information to create a new irrigation sector or modify the existing data.

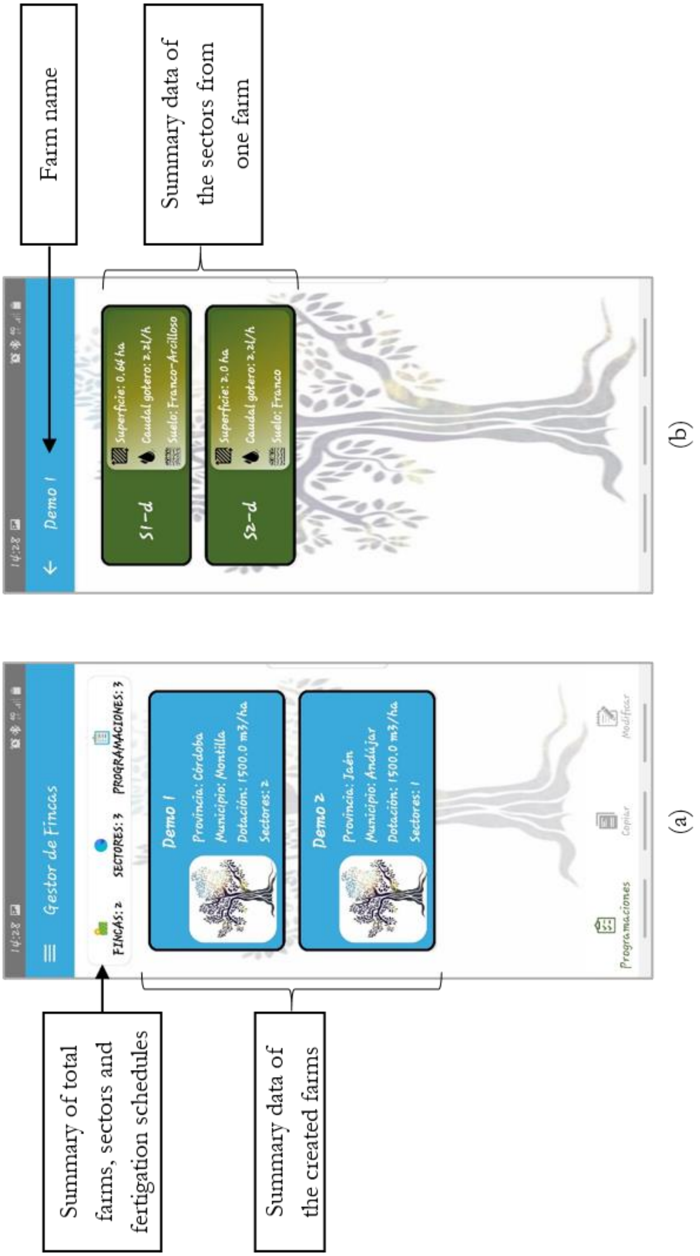

Farm name
Summary data of the sectors from one farm
Demo 1
S1-d
Superficie: 0.64 ha
Caudal gotero: 2.2l/h
Suelo: Franco-Arcilloso
S2-d
Superficie: 2.0 ha
Caudal gotero: 2.2l/h
Suelo: Franco
(b)
Summary of total farms, sectors and fertigation schedules
Summary data of the created farms
Gestor de Fincas
FINCAS: 2
SECTORES: 3
PROGRAMACIONES: 3
Demo 1
Provincia: Córdoba
Municipio: Montilla
Dotación: 1500.0 m3/ha
Sectores: 2
Demo 2
Provincia: Jaén
Municipio: Andújar
Dotación: 1500.0 m3/ha
Sectores: 1
Programaciones
Copiar
Modificar
(a)

Figure 4.4 Graphical interface of *REUTIVAR-App* database manager: **(a)** summary information of all the farms of the data base; **(b)** summary information of all the irrigation sectors of one of the farms; **(c)** detailed description of an irrigation sector and **(d)** copying or modification options of each of the sectors stored in the database.

4.2.2.3 Remote connections module

This module includes the remote connections conducted by *REUTIVAR-App*. It considers two submodules: historical agroclimatic information and weather forecast. Both submodules are based on the farm location. When the user introduces the farm location, *REUTIVAR-App* automatically determines the nearest agroclimatic station from the available stations in the Agroclimatic Station Network of the Regional Government of Andalusia and it is stored in the database. To do this, the geographical coordinates of both the farm location and all the agroclimatic stations are compared and the Euclidean distance between them is calculated. Then, the agroclimatic station whose distance is the lowest is assigned to the farm. From this agroclimatic station and for its entire available time series, daily precipitation (P) and reference evapotranspiration (ET_0) values are downloaded. This is achieved by *web scraping* techniques, i.e., *REUTIVAR-App* extracts data automatically from the website. Then, the irrigation needs are computed as the difference between crop evapotranspiration (ET_c) and effective precipitation (P_{eff}) (Allen, 1998). P_{eff}, the amount of rainfall actually stored in the soil, is calculated using a fixed percentage of P (Smith, 1992) (the 80% of P was considered in this work). The daily average values of P and ET_0 and the monthly average irrigation needs (IN_m) are calculated and stored in the database.

Regarding weather forecast, each day, the daily weather prediction for one week forward for each farm is obtained. This weather forecast is also available for the user in *REUTIVAR-App* (Figure 4.5). Two methodologies are used to obtain it since two different data sources are considered. On the one hand, some of the required parameters are obtained using AEMET OpenData, i.e. the API REST (Application Programming Interface REpresentational State Transfer) of the Spanish State Meteorological Agency (Agencia Estatal de Meteorología (AEMET), 2015). Using AEMET OpenData, *REUTIVAR-App* obtains mean temperature (ºC), maximum temperature (ºC), minimum temperature (ºC), maximum relative humidity (%), minimum relative humidity (%), wind speed (km/h) and cloudiness index (%). From these parameters and using the FAO Penman-Monteith equation (Allen, 1998), the value of ET_0 is calculated. On the other hand, using *web scraping* techniques, forecasted precipitation is obtained from *eltiempo.es* (Pelmorex Corp, 2017). From this data, ET_c and P_{eff} for the following week are calculated according to the methodology explained in the next section. Both weather forecasting and historical data are used to schedule the irrigation events.

Figure 4.5 shows in the first part of the screen the farm name, the location of the farm, from which is obtained the weather forecast, and the rainfall millimeters and maximum and minimum temperatures expected for the current date. Below, rainfall and temperatures for one-week forward are displayed.

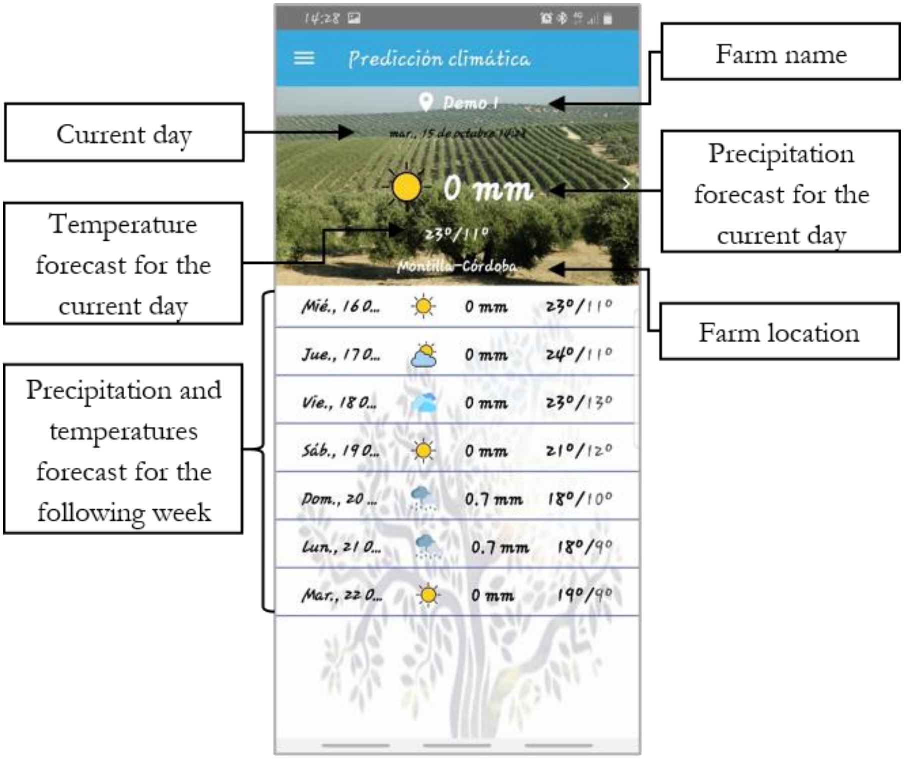


Figure 4.5 Graphical interface of the weather forecast for one week forward for the selected farm.

4.2.2.4 Irrigation scheduling module

This module includes the computation of both IN_m and the daily theoretical irrigation requirements for the following week (IN_d). Both variables are determined as the difference between ET_c and P_{eff} (Allen, 1998). However, IN_m is obtained from daily average values from historical records and IN_d is determined from weekly weather forecasts. In case connection problems with weather stations take place, IN_d is also calculated using historical daily average records temporally. IN_m and IN_d

are calculated to refill the daily ET_c which is obtained by the methodology proposed by FAO (Doorenbos and Pruit, 1977):

$$ET_c = ET_0 \cdot k_c \cdot k_r \tag{4.1}$$

where ET_0 (mm) is calculated from historical records or the weather forecast; k_c is the crop coefficient. In this work, the k_c values were those proposed by (Orgaz and Fereres, 2001) for adult olive trees located in Córdoba. However, the app was designed as flexible as possible, as mentioned in section 4.2.1., and, therefore, it is prepared to include k_c values of any other tree ages or regions. Finally, k_r, a parameter related to the tree canopy, which equals 1 for crop with more than 60% of soil cover and ranges from 0 to 1 for lower soil cover percentages. In that case, k_r is obtained by the methodology proposed by (Fereres et al., 1981). More information about the methodology used can be found in Alcaide Zaragoza et al. (2019).

In case a water allocation is assigned to the farm, IN_d has to be corrected to match the water allocation. Thus, monthly water thresholds for irrigation (*IWT*) are established ensuring water availability at the most critical crop stage. *IWT* are determined considering IN_m, the irrigation strategy and the total water allocation according to the production of reclaimed water in the treatment plant and the water allocation by the water agency. Fortnightly, the model checks if the water initially calculated has been applied. When this is the case, recalculations are not necessary. Otherwise, *IWT* are recalculated for the following months. In case the user does not follow the provided recommendation, they can manually introduce the real fertigation data, as mentioned in section 4.2.2.6

A soil water balance is considered to determine the occurrence of irrigation events, which take place when the soil water content is lower than 25% of the field capacity value (*FC*). The daily soil water content (SW_d) provides information about the amount of water that the crop can extract from its root zone (Equation (4.2). Daily, *REUTIVAR-App* simulates the soil water balance until the current date by using historical data. Then, a soil water content prediction for the following week is conducted considering the weather forecast.

$$SW_d = SW_{d-1} + P_{eff,d} + IN_d - ET_{c,adj,d} - R_d - D_d \tag{4.2}$$

where SW_{d-1} is the soil water content in the day d-1 (mm); $ET_{c,adj}$ the crop adjusted evapotranspiration (mm), which is calculated according to (Allen, 1998); R_d the runoff (mm) and D_d the deep percolation (mm). Both, R_d and D_d are considered null in this work, since *REUTIVAR-App* is designed for drip irrigation systems. To compute SW_d, data about soil type and rooting depth were also required.

Three irrigation scheduling options are included in *REUTIVAR-App*: full irrigation (FI), sustained deficit irrigation (SDI) and regulated deficit irrigation (RDI). These strategies are currently the most widespread for olive orchard (Padilla-Díaz et al., 2016). FI strategy schedules the irrigation event to cover the total irrigation olive needs, i.e., to fully refill daily ET_c. Therefore, in this case $k_{strategy}$, which takes into account the selected strategy, equals 1 in Equation (4.3). In SDI, a percentage of the total olive irrigation needs is applied equally along the irrigation period. This percentage can be selected and modified manually, and it corresponds to the value of $k_{strategy}$. In RDI, a percentage of the FI is also applied but varying the irrigation volume according to the crop phenological phase. Thus, this strategy concentrates the water stress on the least critical stage to oil production which is the pit hardening. The irrigation depths are selected according to Rallo and Cuevas (2017). Therefore, $k_{strategy}$ is variable according to these irrigation volume variations.

REUTIVAR-App also considers the days of the week the user chooses to undertake irrigation to establish the irrigation event volume. To do this, as mentioned before, IN_d is calculated using weather forecast. Then, *REUTIVAR-App* distributes the irrigation recommendations between the selected days for irrigation by assigning to each of those days its correspondent volume plus the volume of the subsequent days until the following day of irrigation (Equation (4.3)). However, this value must not be higher than that established by *IWT*.

$$\begin{aligned} IN_d &= \sum_{d=1}^{n-1} IN_d \cdot k_{strategy} \qquad for\ IN_d < \left({}^{IWT}\!/_{dm}\right) \cdot id \\ IN_d &= \sum_{d=1}^{n-1} IN_d \cdot k_{strategy} \qquad for\ IN_d > \left({}^{IWT}\!/_{dm}\right) \cdot id \end{aligned} \tag{4.3}$$

where n is the next irrigation day chosen by user; d the day of week; dm the number of month days and id the number of days from the current day to the following irrigation event.

Finally, the irrigation time per day d (h/day), t_d, was determined according to Equation (4.4):

$$t_d = \frac{IN_d \cdot A \cdot 10^4}{IE \cdot q_e \cdot n_e} \tag{4.4}$$

where A is the sector area (ha); IE is the irrigation efficiency, which was considered 0.95; q_e was the emitter flow (l/h); n_e the emitter number and 10^4 the unit conversion factor. In addition, *REUTIVAR-App* automatically restricts t_d according to the off-peak energy tariff hours, i.e., when energy and power are cheaper. Thus, during the weekdays, the maximum t_d is eight hours and during the weekends and bank holidays, the maximum t_d is twenty-four hours.

4.2.2.5 Fertilization scheduling module

The fertilization schedule for the case of olive orchard is based on the establishment of an annual plan which varies depending on the previous year nutritional status and the crop uptake (Fernández-Escobar, 2017). Foliar diagnosis is used to determine the nutritional status of the tree (Fernández-Escobar et al., 2009b). *REUTIVAR-App* compares the nutrient leaf levels with the deficiency threshold and, only in case of deficiency, fertilization applications are scheduled. Otherwise, fertilizer applications are not required. When fertilizer application is required, the total fertilizer amount is calculated according to the estimated annual olive nutrient uptake (Fernández-Escobar, 2017). For Nitrogen (N), if leaf nutrient content is lower than 1.3 %, the estimation of N requirements is 0.5 kg/tree. However, total N application cannot exceed 100 kg/ha. For

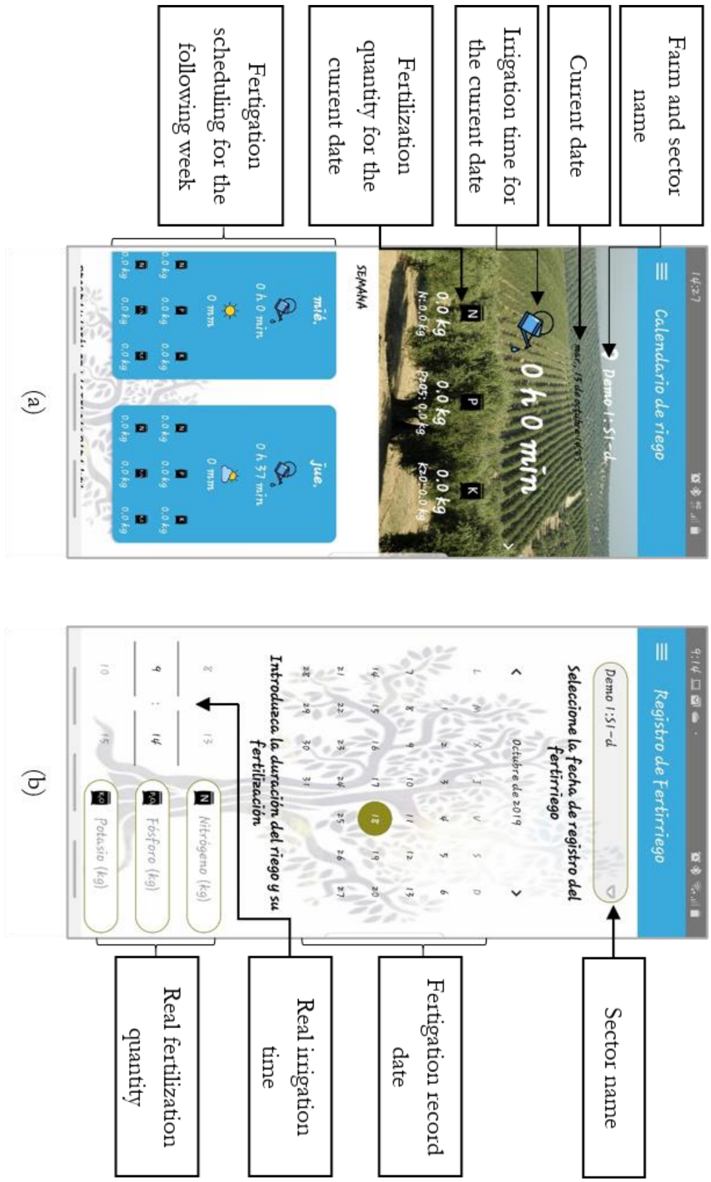
Phosphorus (P), in case P leaf content is less than 0.08%, then 0.5 kg/tree are needed. Finally, for Potassium (K), the estimated application is 1 kg/tree if K leaf content is less than 0.7%.

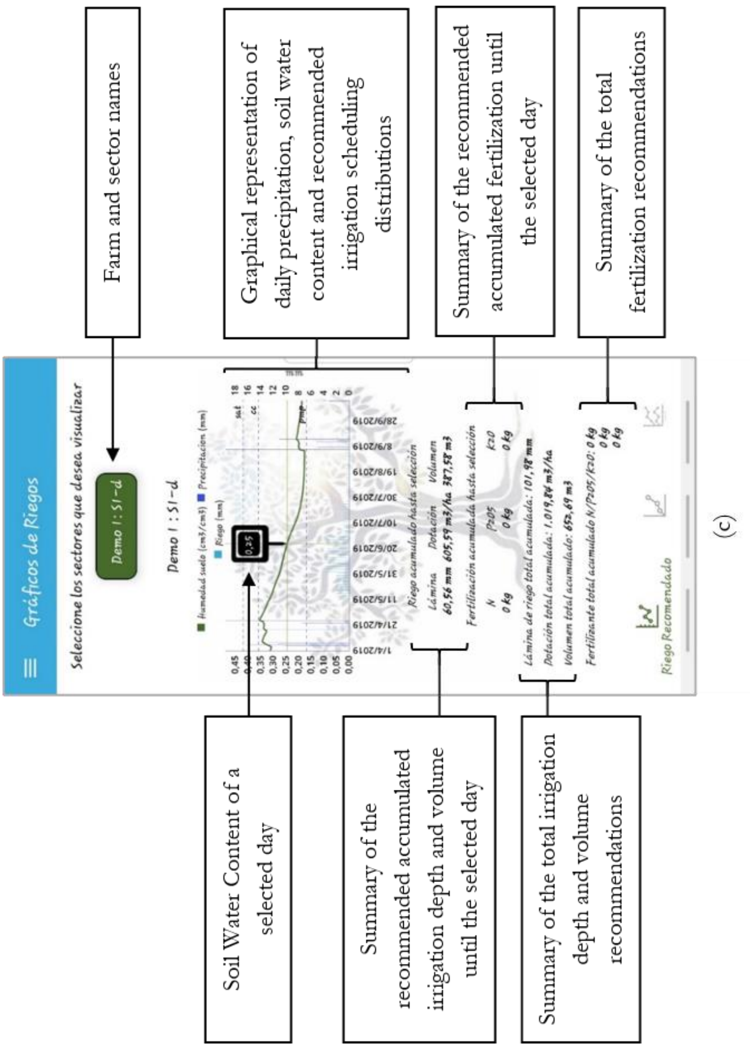
The real nutritional needs (NN) to be applied are adapted according to the water quality analyses, i.e., real NN is obtained by the difference between the crop nutritional requirements minus the water nutrient content. These analyses need to be carried out regularly. Their results can be introduced in *REUTIVAR-App* and the fertilization amount varies according to them. The fertilization management is adjusted according to the irrigation schedule, i.e., the fertilizer application days always coincided with the irrigation days and the fertilizer quantity was restricted to avoid fertilizer interactions and irrigation system obstructions.

4.2.2.6 Visualization module

Finally, from the lateral menu of the app, the user can access to different visualization options. The main screen displays information about the irrigation time and fertilization amount for the current day and the six following days for all the different sectors (Figure 4.6 (a)). The fertilization amount is provided as quantity of nitrogen, phosphorus and potassium but also as N, P_2O_5 and K_2O which is easier to use by the farmer. The user can also check the weather forecast for the same days as previously mentioned (Figure 4.5). Additionally, in case the user does not follow the provided recommendation, they can manually add real fertigation data from the farm (Figure 4.6 (b)). In this screen, firstly the user must select the irrigation sector, the date when the fertigation event happened, the irrigation time and the N, P and K quantity applied. A soil water balance using this data is then performed. In addition, the user can consult the rainfall, recommended irrigation scheduling and the soil water content distribution along the entire irrigation season as well as the total water and fertilizer applied in the graphical interface section (Figure 4.6 (c)). *REUTIVAR-App* also offers the possibility to compare the proposed recommendations to the real irrigation management as shown in Figure 4.6 (d).

Figure 4.6 (c) shows the daily evolution of irrigation events, rainfall and soil water content along the irrigation season according to the scheduling provided by *REUTIVAR-App*. In this screen, the user can tap on the soil water content, irrigation event or rainfall event of any day to know its value. Additionally, at the bottom of the bar chart, a brief summary is provided. This summary contains the irrigation depth (mm), water allocation (m^3/ha), volume (m^3) and fertilization quantity (kg) applied until the selected day by user. The summary also includes the total irrigation depth, the total water allocation, the total volume and the total fertilizers applied from the beginning until the current date. Figure 4.6 (d) shows the comparison of the previous strategy with the real farm management. That screen offers the same information than the previous one, but in this case, it also includes the information regarding the actual fertigation application scheduled by the user.


Farm and sector name
Current date
Irrigation time for the current date
Fertilization quantity for the current date
Fertigation scheduling for the following week
Calendario de riego
Demo 1:S1-d
0 h 0 min
SEMANA
mié.
jue.
(a)
Sector name
Fertigation record date
Real irrigation time
Real fertilization quantity
Registro de Fertirriego
Seleccione la fecha de registro del fertirriego
Octubre de 2019
Introduzca la duración del riego y su fertilización
Nitrógeno (kg)
Fósforo (kg)
Potasio (kg)
(b)


Farm and sector names
Graphical representation of daily precipitation, soil water content and recommended irrigation scheduling distributions
Summary of the recommended accumulated fertilization until the selected day
Summary of the total fertilization recommendations
Soil Water Content of a selected day
Summary of the recommended accumulated irrigation depth and volume until the selected day
Summary of the total irrigation depth and volume recommendations
Gráficos de Riegos
Seleccione los sectores que desea visualizar
Demo 1 : S1-d
Riego Recomendado

(c)

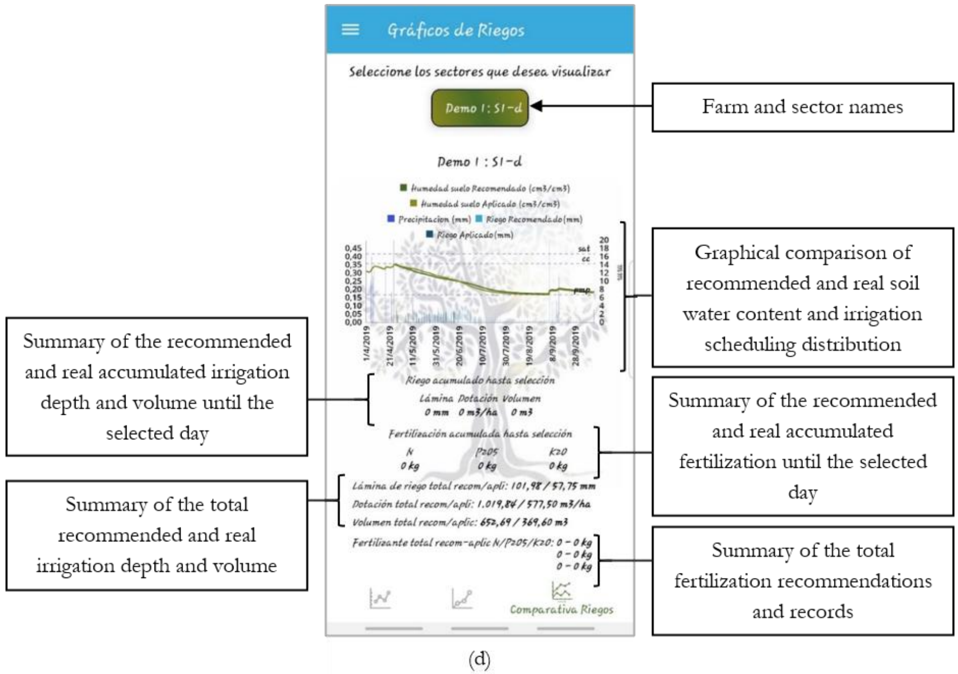


Figure 4.6 Graphical interface of *REUTIVAR-App*: **(a)** Main screen of one irrigation sector and **(b)** screen to introduce real fertigation records. **(c)** Distribution of precipitation, irrigation depth and soil water content in *REUTIVAR-App* recommendation case and **(d)** Comparison of the distribution of precipitation, irrigation depth and soil water content between the *REUTIVAR-App* recommendation case and the actual farm management case.

4.3 Implementation of ***REUTIVAR-App*** in olive orchard farm

REUTIVAR-App was applied as a fertigation programming tool to generate customized and optimal irrigation and fertilization scheduling for the commercial olive orchard farms of the *Tintín Irrigation District* (*TID*), located in Montilla (Córdoba, southern Spain) during 2019 irrigation season. The climate in this region is typically Mediterranean. Average annual rainfall is around 600 mm and the annual ET_0 averages 1,080 mm. The water applied to the farms comes from the village sewage treatment plant. This water is previously stored in a reservoir where chemical and physical treatments are carried out to achieve the required water quality for reuse. Then, water is distributed by subsurface drip irrigation, with drippers of 2.2 L/h flow rate, pressure compensating, spaced at 1 m and installed at a depth of 40 cm. The water allocation, established by the irrigation district manager criteria, is 1,500 m^3 /(ha·year). The irrigation schedule is determined at irrigation district scale at the beginning of the irrigation season and the water allocation is distributed equally along it. Particularly, irrigation events are applied every Tuesday, Thursday, Saturday, Sunday for eight hours. Fertilization is also centralized and applied in May and June.

A one-hectare olive orchard farm of *Olea europea* L., cv Hojiblanca and *Olea europea* L., cv Nevadillo azul adult tree from *TID* was selected as study farm. The trees are spaced at 8 x 8 m and the average production is around 7,000 kg/ha. To carry out the test, the strategy recommended by *REUTIVAR-App* and the actual management of the case study farm (TID irrigation strategy) were compared using the mobile phone application (Figure 4.7). Table 4.2 shows the nutrient application both through water and fertilizer for *TID* and *REUTIVAR-App* strategies.

Table 4.2 N, P and K applications through water and fertilizers for *TID* and *REUTIVAR-App* strategies for 2019 irrigation season

Strategy	***TID***			***REUTIVAR-App***		
Nutrient	**N**	**P**	**K**	**N**	**P**	**K**
Applied trough water (kg/ha)	15.8	0.5	52.0	16.3	0.5	48.0
Applied trough fertilizer (kg/ha)	9.9	2.7	10.2	0	0	0
TOTAL	**25.6**	**3.2**	**62.2**	**16.3**	**0.5**	**48.0**

REUTIVAR-App recommended a different irrigation scheduling strategy compared to the study farm. This strategy is based on the RDI principles, which focuses the irrigation events in the most critical olive orchard stages to water stress, particularly during May, June and September (Figure 4.7). Additionally, the irrigation schedule was adjusted to electricity tariff existing in *TID*, i.e., irrigation events were only schedule during the off-peak electricity tariff hours. This allows to apply more water in these periods without an increase in the total farm cost. In contrast, the farm distributed irrigation events equally along the irrigation season (Figure 4.7). This could cause a lack of water in critical development stages for the final production which would involve both a yield decrease and a worse olive oil quality (Rallo and Cuevas, 2017). In the strategy recommended by *REUTIVAR-App*, the total water used during 2019 was 1,500 m^3/ha, which matched the water allocation according to the irrigation district manager criteria. For the *TID* strategy, however, the total water applied was 1,623 m^3/ha. This can compromise the profitability of the farm, since it can cause financial penalties in case of exceeding the water allocation limit. As for soil water content, this variable decreased slower in the *REUTIVAR-App* strategy than in the actual farm irrigation scheduling. This was caused by the higher water application in June in the *REUTIVAR-App* strategy. However, for both strategies, soil water content decreased up to values close to PWP because the water allocation for olive orchard was significantly lower than the irrigation needs. On the other hand, regarding nutrient needs, fertilizer application was not required for that irrigation season. This was because of the result of the foliar analysis and the water quality analysis. The nutrients applied through reclaimed water combined with the high leaf nutrient content (Table 4.2) involved no additional fertilization. However, according to TID strategy, in addition to the nutrients applied through water, the farmer applied fertilizers when they were not needed as shown in Table 4.2. In fact, the foliar analysis results, conducted in July 2018, showed that the dry matter percentage of N, P and K was 2.02, 0.11 and 0.92 respectively. This implies that the amount of P and K in olive leaves was already in the proper range and, according to (Molina-Soria and Fernández-Escobar, 2012), the N leaf amount was in the toxic range. A N overfertilization in olive could involve considerable development problems, a yield decrease as well as environmental harms (Fernández-Escobar et al., 2009a; Molina-Soria and Fernández-Escobar, 2012). Therefore, the unnecessary fertilization of the case study farm could involve important damages to the environment as well as significant economic losses without any production improvement.

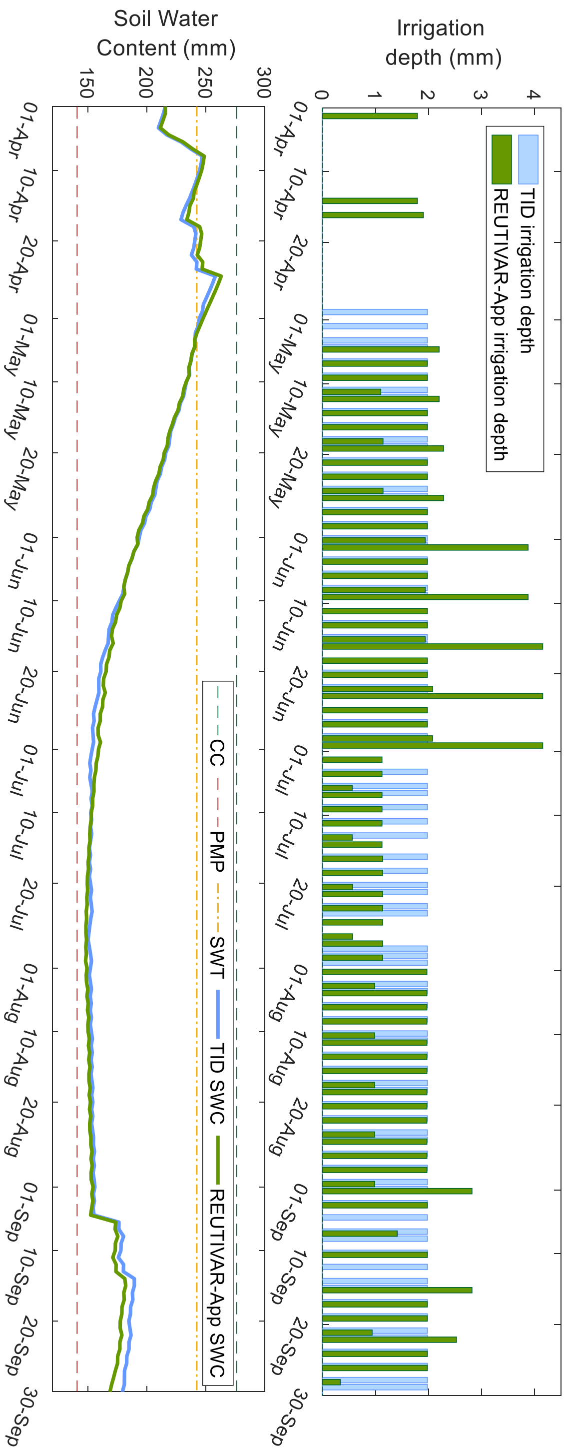


Figure 4.7 Comparison of the seasonal distribution of the irrigation scheduling between *TID* and *REUTIVAR-App* strategies for 2019 irrigation season

4.4 Conclusions

Water resources management is a major concern in arid and semi-arid regions currently. One of these regions is Andalusia, where water authorities support new strategies to reduce pressure in water resources, such as irrigation with reclaimed water. Olive orchard, the most widely grown crop and hence, the crop to which more water is allocated in Andalusia, could benefit substantially from this kind of water source. However, the proper and sustainable use of reclaimed water is still difficult for the farmer, whose decisions continue to be based on traditional knowledge.

Thus, a user-friendly mobile application, *REUTIVAR-App*, for fertigation scheduling using reclaimed water was developed. *REUTIVAR-App* provides a daily real-time irrigation and fertilization schedule recommendations at farm scale. These recommendations are based on the historical agroclimatic records and weather forecast, the precision irrigation guidelines, the water quality and foliar analyses.

REUTIVAR-App was tested in a TID commercial olive orchard farm during 2019 irrigation season. It proved that the mobile application adapted the fertigation scheduling according to the actual weather conditions and adjusted the water allocation along the irrigation season, preventing of additional cost to the farm. *REUTIVAR-App* also showed that thanks to the nutrient applied through water, additional fertilization application was not required, saving 100% of fertilizers applied by the farmer. It entails benefits not only for the farmer, who can reduce their total economic costs, but also for society, since it avoids the unnecessary and intensive use of fertilizers and its associated environmental pollution. Its implementation for supported irrigation and fertilization management was considered a suitable way to improve the efficiency of water and fertilizer use and increase farmers engagement with sustainability concerns.

This work highlights the importance of a user-friendly platform in the agricultural sector to guide farmers and technicians in taking the most profitable and sustainable decisions. In addition, these support tools, could be used to simulate different strategies and compare their results. Although *REUTIVAR-App* was developed specifically for olive orchard, its structure can be adapted to other crops and system conditions.

Finally, to succeed in the implementation of these tools, training courses should be held to encourage farmers to use these Apps and make them aware of the importance of regular leaf and water quality analyses. *REUTIVAR-App* will be available for free from April 2020.

Acknowledgments. This work is part of REUTIVAR (Modelo Sostenible del Olivar Mediante el Uso Aguas Regeneradas) project, co-funded by the Regional Government of Andalusia and the European Union through EARF 2014-2020. We would also like to acknowledge to the Spanish Ministry of Science, Innovation and Universities for funding the Juan de la Cierva-Formacion grant to Rafael González Perea

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5 Spatio-temporal analysis of nitrogen variations in an irrigation distribution network using reclaimed water for irrigating olive trees

This chapter has been published entirely in the journal "Agricultural Water Management", Alcaide Zaragoza C., Fernández García I., Martín García I., Camacho Poyato E. and Rodríguez Díaz J.A. (2021)

Abstract. Fertigation management of olive grove is highly complex, especially when reclaimed water is used for irrigation. Nitrogen (N) is the main nutrient component of olive trees which, traditionally, has led to an excessive use in fertilization programs. This problem can be exacerbated if reclaimed water is used since it already contains N. For this reason, water quality must be considered in the fertilization plan. Both total content and N form arriving to the trees have implications in olive tree nutrient requirements as well as the environment. If reclaimed water particularities and the length of the pipes of water distribution networks are considered, the form and total concentration of N can change over space and time. In this work, both spatial and temporal analysis of the N content and form in a water distribution network using reclaimed water for irrigating olive trees was performed. This study proved that changes in N were evident both over time and across the irrigation water distribution network. Seasonally, N content was reduced during the summer period. Spatially, a clear nitrification occurred from the pumping station to the farms. These

variations demonstrate the importance of a continuous water quality control in order to adjust the fertilization plan according to the N content in water.

Keywords: reclaimed water; fertigation scheduling; precision irrigation; nitrogen changes; water quality; olive tree fertigation

5.1 Introduction

Arid and semi-arid areas, such as Mediterranean countries, are already facing significant pressure on water resources. In the context of climate change, with the resulting increase in extreme weather events, and with the predicted growth in food demand, an exponential rise in that pressure is predicted (Bisselink et al., 2018). The use of non-conventional water sources, such as wastewater, and more specifically reclaimed water (RW), is one of the most sustainable alternatives to cope with water shortages and a key way to approach this problem (Iglesias and Garrote, 2015; Maestre-Valero et al., 2019b). Treated wastewater is water from any combination of domestic, industrial or commercial sources that has been processed in a wastewater treatment plant to remove contaminants (International Organization for Standardization, 2018). However, to make it appropriate for reuse, an additional treatment is necessary. Then, the former wastewater is called reclaimed or recycled water and it can be used for irrigation, enhancing water bodies among other uses (Raschid-sally and Jayakody, 2008). Worldwide, the countries that, according to Sato et al. (2013), reuse treated water the most are the USA (6.4 hm^3/day), Egypt

(1.9 hm^3/day), Syria (1.5 hm^3/day), Spain (1.4 hm^3/day), Israel (0.7 hm^3/day) and Saudi Arabia (0.4 hm^3/day). Uses of RW vary largely, even within the same country, depending on the country's development, climate, main economic activities, etc. In general, it is estimated that, in developed countries and after secondary treatment, the main destination of these waters is agricultural irrigation (33%), followed by the irrigation of green areas (20%) and industrial uses (8%) (Prats-Rico, 2016). In a context where the agricultural sector is responsible for 70% of water abstractions worldwide, the use of treated wastewater for agricultural irrigation constitutes one of the basic strategies to manage imbalances between resource availability and demand. This also contributes to the promotion of the circular economy by recovering nutrients from the RW and applying them to crops, by means of fertigation techniques. Thus, water reuse could potentially reduce the need for supplemental applications of conventional fertilizers. Due to increasing interest, the application of this type of water to irrigate has already been evaluated by different authors. Some of them have focused their studies from a safety and environmental perspective (Chen et al., 2013; Kalavrouziotis et al., 2012; Lopez-Galvez et al., 2014). Others have paid more attention to the nutritional aspects (Maestre-Valero et al., 2019a; Pereira et al., 2011). There are also authors who have studied how RW could influence the development or quality of the crop (Lu et al., 2016). All of them agree with the fact that RW used as an irrigation water resource, if properly managed, does not result in adverse impacts and is safe for human health and the environment. At the same time, it could lead to significant fertilizer savings, since the application of additional fertilizers is reduced, increasing the yield and quality of the crops. Additionally, it may be essential for addressing both the water scarcity problem and irrigated agriculture sustainability enhancement.

Olive trees, the most iconic crop in the Mediterranean basin, have to adapt to the new political and institutional framework, both at national and international level, where a synergy between agricultural and environmental policies and the conservation of natural resources is taking place. In this sense, this crop represents a typical example of irrigation using RW resources and several authors have investigated its potential and effects. For example, Ashrafi et al. (2015) assessed the olive tree response in terms of growth, photosynthesis rates and nutrient content. They concluded that, thanks to the higher nutrient concentrations, plant development was improved. Erel et al. (2019) conducted a long-term study which demonstrated that olive nutrient requirements were covered using RW. They found that the olive trees nitrogen (N), phosphorus (P) and potassium (K) needs were met by irrigating with RW and without the use of additional fertilizer. Thanks to these nutrients, the RW irrigated trees also obtained higher fruit yields. However, they indicated that special attention must be paid to the soil which, over the long term, could suffer negative effects such as an increase in the ratio of sodium absorption. Salinity problems, nevertheless, were not found either in the soil or the olive trees. Pedrero et al. (2020) conducted a review considering different water sources and qualities, analyzing their benefits and limitations for olive tree irrigation. They affirmed that, in Mediterranean countries and over a long period, olive trees irrigated with RW are likely to improve their yield. However, they highlighted that, although N contribution through RW could be essential to achieve this greater production, it may also generate negative impacts on both olive yield and oil quality if given in excess. In addition, even though RW already contains N, Alcaide Zaragoza et al. (2019) confirmed that farmers keep applying significant fertilizer quantities without considering the negative environmental impacts and additional costs.

N is the main nutritional component of any crop and, therefore, of olive trees. For this reason, N has traditionally been the main mineral element used in olive fertilization plans. However, these plans are frequently based on farmer's experience which can lead to inappropriate N applications and, in many cases, over-fertilization (Fernández-Escobar, 2011). This can cause negative effects on crop health, quality and also the environment (Fernández-Escobar et al., 2006). Due to this importance, the N cycle and its implications in olive tree nutrition have been studied in the past. For example, Fernández-Escobar et al. (2012) estimated a N balance for olives, determining that an olive orchard had lower N requirements than historically thought. Traditionally, it was thought that annual N fertilizer applications were required for maintaining high yields. This research proved that depending on different factors (irrigation water quality, rainwater inputs, organic matter, etc.) N applications may not be necessary. The form in which N is applied is another important aspect to consider. Fertilizers can be in organic form, inorganic form (NH_4^+-N or NO_3^--N) or as a combination of both organic and inorganic. Depending on the crop, N is assimilated in one of its soluble forms, i.e., inorganic forms. In the case of the olive tree, it is able to assimilate N in both NH_4^+-N or NO_3^--N. However, differences in olive nutrition and impacts on the environment under the application of different N forms have been found. For instance, Tsabarducas et al. (2017) found differences in growth and photosynthesis rates in olive trees depending on the N form applied. Fernández-Escobar et al. (2004) also detected variations in N leaching depending on the N form used for fertilizing. However, all of them considered that the form of N arriving to the crop was the same as they were applying. In other words, none of them considered the influence of water quality parameters or the irrigation network characteristics on N form changes.

Irrigation district distribution networks usually cover large areas which involve big pipe lengths. Sometimes, particularly in areas devoted to one single crop, fertilizers are applied in the pumping station and distributed along the irrigation district through the water distribution network. Consequently, the travel time from the pump station to the plot hydrant is important, particularly to the furthest farms. This could entail unequal nutrient distribution to users. This effect was confirmed by Jimenez-Bello et al. (2011) at irrigation district level. They found considerable differences depending on the farm location. But they focused their attention on the irrigation network and considered that all the fertilizers injected in the network were received at farm level without changes in the water quality and concentration of nutrients. However, due to the RW particularities, some studies have proved that water quality changes inside the pipes. For example, Yu et al. (2020) studied the variability of the water quality parameters in river water replenished by RW. They found modifications in both the total N content and its inorganic forms (NH_4^+-N or NO_3^--N). Both Wang et al. (2016) and Wang et al. (2020) conducted experiments under controlled conditions in order to investigate the relationship between the RW quality parameters and pipe length. They detected that pipe length had an important effect on the nitrification process. However, there are no studies that have assessed these effects on pressurized irrigation networks under real conditions.

N concentration in RW changes throughout the irrigation season and during the travel time within the irrigation network as a result of oxidation-reduction reactions, plot elevation differences, pipe length, etc. The N form which arrives at the farm influences both crop nutrition and N leaching. In this work, a spatial-temporal analysis of the N form changes in a water distribution network using RW for irrigation was carried out. Its implications in olive production and soil pollution were discussed.

5.2 Materials and Methods

5.2.1 Case Study

The study was carried out in the Tintín Irrigation District (TID), located in Montilla (Córdoba, southern Spain). This region has a typical Mediterranean climate with an average annual rainfall of 590 mm, mostly during spring and autumn while they are almost negligible in summer. The daily mean temperature is 16.9ºC and the mean reference evapotranspiration, ET_0, 3 mm/day. However, ET_0 ranges from 0.5 mm/day during winter to 8 mm/day in summer. The water distributed for irrigation comes from the Montilla wastewater treatment plant (WWTP). Secondary treated wastewater (by extended aeration) and settled is diverted to the reclamation train, initially composed by a settling reservoir. Subsequently, the water is sent by communicating vessels to a larger reservoir for storage, where two ultrasound treatment units are installed for microalgae reduction. Before its distribution, the water, by floating intake, is sent to the filtration process composed of several automatic filter units (130 μm), self-cleaning by opening the ring pack (Figure 5.1). Finally, some disinfectant treatments are applied: potassium permanganate ($KMnO_4$) was applied in both settling and storage reservoirs and peracetic acid ($C_2H_4O_3$) in the irrigation network. Particularly, 500 l of $KMnO_4$ were applied bimonthly and 900 l of $C_2H_4O_3$ were applied at the end of June. Thus, the water quality required for the irrigation of olive trees is achieved according to the Spanish regulation for water reuse (Spain Government, 2007). The TID water distribution network irrigates 150 ha within the

Guadalquivir River basin where mainly olive is the cultivated crop. The average plot size is 1.5 ha. All the fields have the same irrigation system, subsurface drip irrigation with 2.2 $l \cdot h^{-1}$ pressure compensating drippers spaced at 1 m and installed at a depth of 30 cm. The water allocation is 1,500 $m^3 \cdot year^{-1} \cdot ha^{-1}$. The irrigation season usually lasts between five and seven months depending on the rainfall of the year. Irrigation events are scheduled at district level by the irrigation district's manager and all the fields are irrigated simultaneously. The irrigation schedule consisted of applications four times a week for 8 hours during the entire irrigation season. Irrigation was carried out every Tuesday, Thursday, Saturday and Sunday.

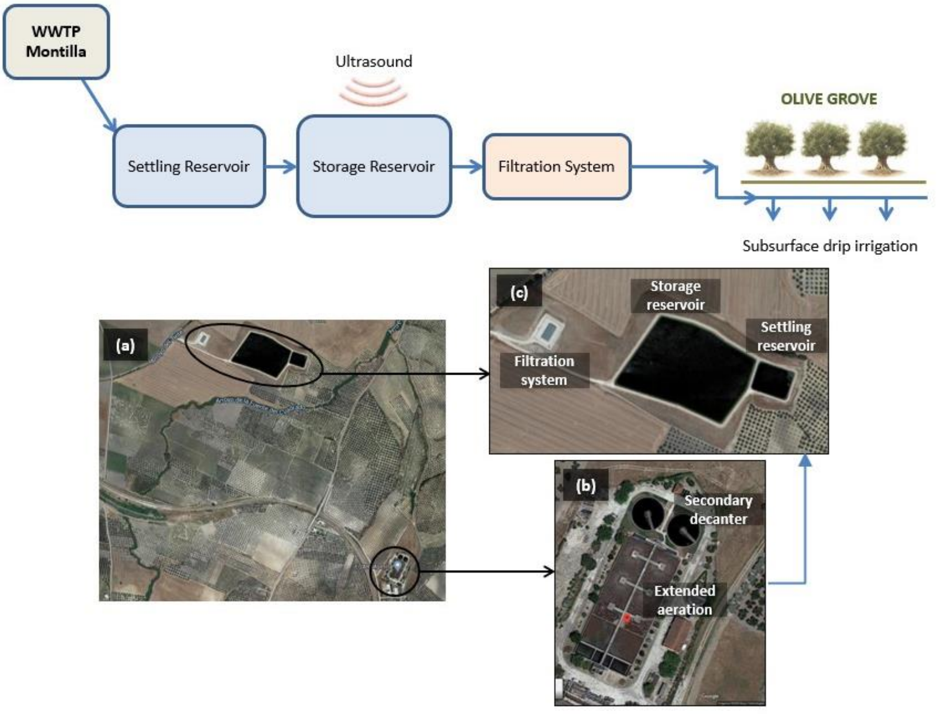

Figure 5.1. (a) Aerial view of the complex Montilla WWTP - reclamation treatment in TID (Montilla, southern Spain)**; (b)** Location of extended aeration and secondary decanter at the WWTP Montilla and **(c)** Aerial view of the reclamation treatment train installed in TID.

5.2.2 Sampling collection

Water quality analysis was carried out once a month during the 2019 irrigation season to assess the fluctuations in the N chemical forms throughout the year (temporal scale). They were measured before and after the filtration system (Filtration System Inlet – FSI and Filtration System Outlet – FSO) well as in two TID farms (F2 and F5). Later, the sample point number was extended in order to assess the spatial variability. Then, six strategic points across the irrigation network (F1 to F6) were selected to analyze the water quality they receive and the differences in the chemical forms of N (spatial scale). The farm points were selected according to their distance from the pumping station, elevation and pressure criteria. The characteristics of each sampling point are shown in Table 5.1. Differences between FSI and FSO made it possible to determine if additional fertilizer was being applied on the sampling days as well as the changes of N forms in the farms with respect to the pumping station. TID irrigation network and the selected points are shown in Figure 5.2. In each sample, the total N (N_T) and different N forms were measured: ammoniacal nitrogen (NH_4^+-N), nitric nitrogen (NO_3^--N) and the N Total Kjeldhal (NTK). Organic N (N_{org}-N) was obtained as the difference between NTK and NH_4^+-N. Some other water quality parameters were also selected to be analyzed since they could influence the oxidation-reduction reactions and, therefore, the N form. Some particular bacteria are required for these reactions to take place which are highly susceptible to certain environmental factors, specifically to dissolved oxygen (DO) temperature

(T) and pH, (Brion and Billen, 2000; Shammas, 1986). All of them need to be at optimal values for the reaction to occur. The chlorophyll a (Chl-a) content is another important parameter to analyze. It is related to the microalgae biomass which could affect the N content because of the microalgae consumption of N (Kuenzler et al., 1982). Finally, organic matter content can also affect the N form (Stein and Klotz, 2016) and, for that reason, the Chemical Oxygen Demand (COD) and the Biochemical Oxygen Demand (BOD_5) were measured. These parameters are indirect indicators of the organic matter content in the water. The description and reference methods used for the analysis of the mentioned parameters in water samples are shown in Table 5.2.

Table 5.1. Characteristics of the sampling points

Sample point	Pipe length (m)	Elevation above the pumping station (m)	Pressure (m)
F1	1453	6	56
F2	3436	7	131
F3	3871	94	31
F4	4105	1	24
F5	6626	46	93
F6	6944	71	40

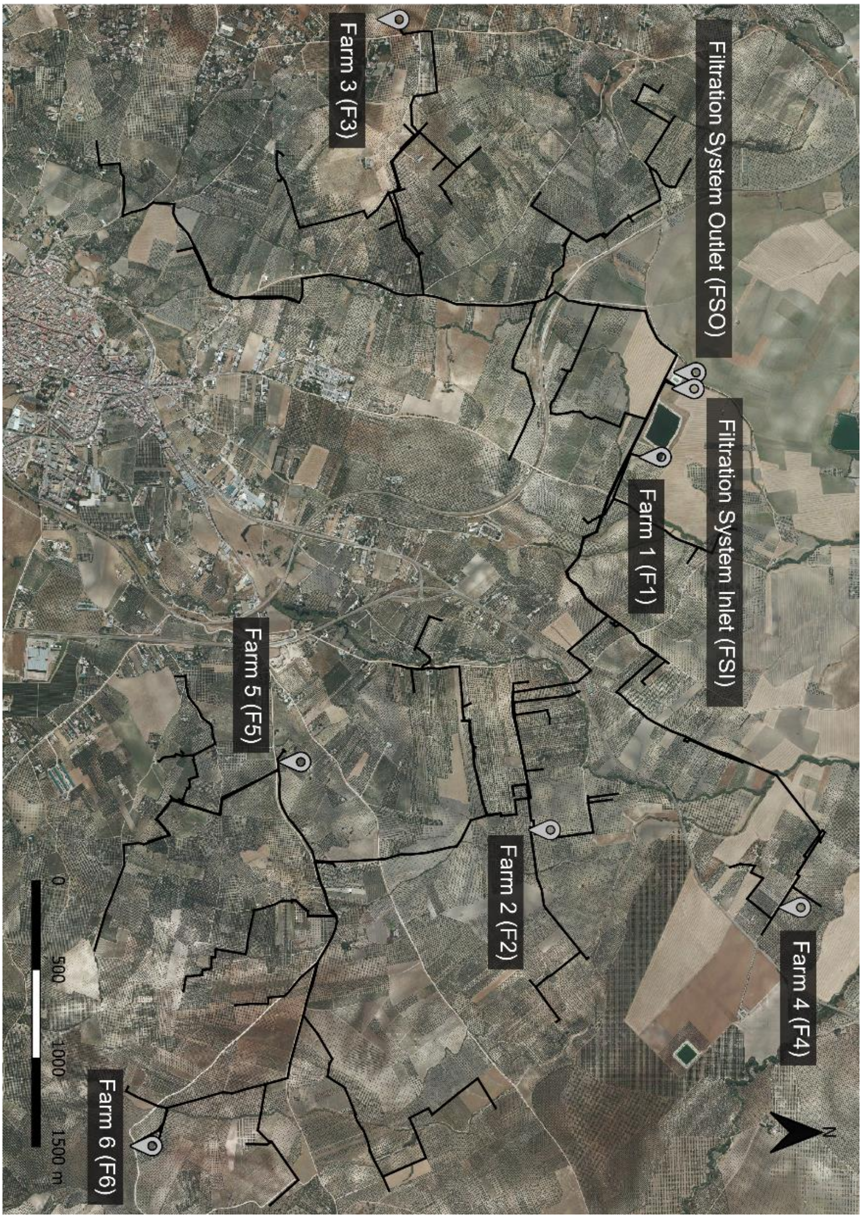

Figure 5.2. Sampling point locations in TID (Montilla)

Table 5.2 Description and reference methods used for the parameters analyzed in the water samples.

Parameter	Description	Reference method
Temperature (T)	Thermometry	S.M.*2550 B
pH	Electrometry	S.M. 4500 H+ B
Dissolved oxygen (DO)	Electrometry	S.M. 4500-O G
Total nitrogen (N_T)	Digestion with potassium peroxydisulphate. Nitrophenol. Spectrophotometry.	APC228/338, methods DR3900 EN ISO 11905-1
Ammoniacal nitrogen (NH_4^+-N)	Spectrophotometry. Salicylate, nitroprusside and indolphenol blue.	APC303, methods DR3900 ISO 7150-1, DIN 38406 E5-1
Nitric nitrogen (NO_3^--N)	Spectophotometry.Dimethylphenol	APC339, methods DR3900 ISO 7890-1-2-1986, DIN 38405 D9-2
Chlorophyll a (Chl-a)	Spectrophotometry. Methanol extraction	(Talling and Driver, 1963)
Chemical Oxygen Demand (COD)	Volumetry	S.M. 5220 C
Biochemical Oxygen Demand (BOD_5)	Incubation	S.M. 5210 B

*S.M.: Standard Methods for the Examination of Water and Wastewater,1989

5.2.3 Data Analysis

Means and standard errors were obtained for each data. A Pearson correlation was performed to assess the relationships of the water quality parameters. Then, one-way repeated measures analysis of variance (RM ANOVA) was carried out for the temporal analysis. This analysis is suitable for data in which the same variables are measured more than once (Davis, 2002). RM ANOVA must fulfill the sphericity condition which was analyzed using the Maulchy test. When the sphericity condition was not confirmed, the Greenhouse-Geisser correction was applied to be able to continue with the RM ANOVA. For spatial analysis, the difference between the N concentration on the farms and the N concentration at FSO was performed for each N form and each period. All the analysis were performed in R programming language using RStudio as the integrated development environment (IDE) for Windows (Van der Loo and De Jonge, 2012).

5.3 Results and discussion

5.3.1 Water quality characterization

Results of the water quality parameters analyzed in the eight sampling points during the 2019 irrigation season in TID are shown in Table 5.3. N_T ranged from 21.8 $mg \cdot l^{-1}$ to 3.3 $mg \cdot l^{-1}$ which implied an important difference between some water samples. This quantity of NT was similar to other RW used for olive tree irrigation (Bourazanis et al., 2016; Petousi et al., 2015; Segal et al., 2011). On average, the NH_4^+– N concentration was higher than NO_3^-– N. As for N in nitrite form, this was not found during the experiment, being the rest of the N_T in organic form. The value of the pH during the whole season was considered as slightly alkaline with an average value of 7.8. DO and Chl-a also changed largely during the experiment. These parameters can affect both the amount of N_T and also its form (Cira et al., 2016; Espinosa Rodríguez et al., 2014). In the case of water temperature, its variation may be caused by the fluctuation in the environment temperature. The results of both COD and BOD_5 met the minimum quality requirements for water reuse established in the EU Regulation (The European Parliament and the Council of the European Union, 2020), which are 125 mg/l O_2 and 25 mg/l O_2, respectively.

Table 5.3. Water quality parameters analyzed in TID during 2019 irrigation season (n = 39)

Parameter	Max	Min	Mean	SD
N_T (mg·l^{-1})	21.8	3.3	10.7	5.0
NH_4^+– N (mg·l^{-1})	13.5	0.0	5.3	4.5
NO_3^- – N (mg·l^{-1})	8.0	0.1	2.5	1.8
N_{org}-N (mg·l^{-1})	7.6	0.0	2.9	1.6
pH	9.0	7.1	7.9	0.5
DO (mg·l^{-1})	12.0	0.9	5.0	2.8
T (ºC)	28.1	19.3	24.7	2.5
Chl-a (µg·l^{-1})	303.4	0.7	64.4	61.3
COD (mg/l O_2)	79.0	22.0	41.7	13.2
BOD_5 (mg/l O_2)	17.0	0.0	6.7	4.0

Table 5.4 shows the Pearson correlation applied to the water quality parameters analyzed. N_T was positive correlated to both NH_4^+-N and NO_3^--N. All the analyzed parameters, except for DO, were significantly correlated to the N content or its form. Although no correlation was observed between either COD or BOD_5 and the total N content, different correlations were found with the different chemical forms. Specifically, both showed a significant positive correlation with N_{org}-N, which is expected since these parameters are indicators of the organic matter in the water. In addition, a significant positive correlation between BOD_5 and NO_3^--N was found as well as a significant negative correlation with NH_4^+-N, which may indicate that BOD_5 could be affecting nitrification. Chl-a is used as an indicator of microalgae biomass (Desortová, 1981) which could explain its negative correlation with N content due to the consumption of this nutrient by microalgae (Kuenzler et al., 1982). Both pH and T were also influential parameters for N_T and NH_4^+-N. This may indicate that nitrification was occurring (Shammas, 1986). Finally, there was not a noticeable correlation between the pipe length and the total content in N. However, a positive significant correlation was found between pipe length and NO_3^--N in contrast with the negative correlation found for NH_4^+-N. This may suggest that a nitrification process was occurring throughout the irrigation network, which matches the information given by Wang et al. (2016).

Table 5.4 Pearson correlation of the water quality parameters in TID during 2019 irrigation season

Parameter	**N_T**	**$NH_4^+ - N$**	**$NO_3^- - N$**	**$N_{org} - N$**	**pH**	**DO**	**T**	**Chl-a**	**COD**	**BDO_5**	**Pipe length**
N_T (mg·l^{-1})	1										
$NH_4^+ - N$ (mg·l^{-1})	0.82***	1									
$NO_3^- - N$ (mg·l^{-1})	0.40*	-0.16	1								
$N_{org} - N$ (mg·l^{-1})	0.37*	0.34*	0.15	1							
pH	0.45**	0.53***	-0.17	0.13	1						
DO (mg·l^{-1})	0.07	0.08	-0.10	-0.12	0.62***	1					
T (ºC)	-0.44**	-0.55***	0.26	-0.04	-0.19	-0.14	1				
Chl-a (µg·l^{-1})	-0.54***	-0.62***	-0.10	-0.25	-0.32	-0.09	0.32*	1			
COD (mg/l O_2)	0.02	-0.29	0.31	0.56***	0.08	0.18	0.17	0.58***	1		
BOD_5 (mg/l O_2)	0.00	-0.36*	0.60***	0.41*	0.05	0.24	0.35*	0.17	0.52***	1	
Pipe length (m)	-0.13	-0.34*	0.47**	0.06	-0.59***	-0.52***	0.27	0.13	0.04	0.12	1

*: significant correlation at $p < 0.05$; **: significant correlation at $p < 0.01$; ***: significant correlation at $p < 0.001$.

5.3.2 Temporal analysis

Figure 5.4 (a) shows the results for the different N forms at the inlet and the outlet of the filtration system. According to this graph no substantial differences between FSI and FSO were detected, except in May. In this month, there was a decrease of N_T after the filtration treatment. This reduction was mainly caused by an organic N drop. In all other cases, neither N_T nor the N forms changed meaningfully. No additional fertilizer was applied during the sampling days and, therefore, the irrigation water quality was only determined by the water source quality. However, changes in N_T and the N forms can be observed over time. During May, June and July, a higher N_T concentration was found. In these months, N was mostly in ammonium form, with a concentration around 30% higher than in the remaining months. NO_3^--N concentration had approximately the same value during all the season excluding October, when it was nearly zero. Finally, for the remaining N, i.e., N_{org}-N, its concentration was not steady throughout the season.

As mentioned before, the Chl-a content is related to the phytoplanktonic biomass. The highest values of Chl-a were obtained in August, September and October which matched the lowest N_T contents (Figure 5.4 (b)). This confirmed that the absorption and utilization of phytoplankton in the storage reservoir was an important reason for N_T reduction throughout the irrigation season. This is consistent with previous results found by Yu et al. (2020). Regarding the Chl-a trend over time, it is important to highlight that phytoplankton growing is promoted by light and temperatures (Geider, 1987). Because of that, a growing content was determined from May to September. However, during July, when temperatures were highest, the Chl-a concentration dropped to values of nearly zero. It is important to highlight that, in order to increase filtration system efficiency, potassium permanganate was applied to the storage reservoir. This treatment was complemented with the ultrasound treatment which, according to numerous scientific studies, has an important anti-algae effect (Jachlewski et al., 2013; Joyce et al., 2010; Wu et al., 2011).

RM ANOVA was calculated for the water quality parameters of the samples collected at the farms. As a result, p-value was less than 0.05 for all the parameters analyzed. In other words, all the water quality variables measured at farm level changed significantly throughout the 2019 irrigation season. Figure 5.3 showed the mean and standard error of the different N form at the analyzed farms. If both Figure 5.3 (a) and Figure 5.4 are compared, it is observed that the N_T remained steady from FSO to the farms. This implies that the total N content was mainly determined by the water quality source. The N_T concentration peaked in June amounting to 19.7 $mg \cdot l^{-1}$ (Figure 5.4 (a)), a 63% higher than in August, when the lowest N_T content was measured (7.1 $mg \cdot l^{-1}$). The average nitrate concentration detected at farm level was around 3.4 $mg \cdot l^{-1}$ except in June with a maximum average concentration of 6.8 $mg \cdot l^{-1}$, and in October with a minimal of 0.6 $mg \cdot l^{-1}$ (Figure 5.4). As for ammonium, its concentration varied largely in the irrigation season. This variation matched with the variation at FSO: highest concentration in May, June and July; medium content in October and nearly zero in August and September. Besides the parameter itself, the proportion of each N form also changed over time. Figure 5.4 shows that during May, June and October the majority of the N was in ammonium form in contrast to July and August when the NO_3^- – N and N_{org}– N proportions were higher. However, June was the only month in which the proportion was similar for the three N forms. These results highlight the importance of a regular control when RW is used for irrigating olive trees. The fertilization plan must be adjusted and modified depending on the water quality.

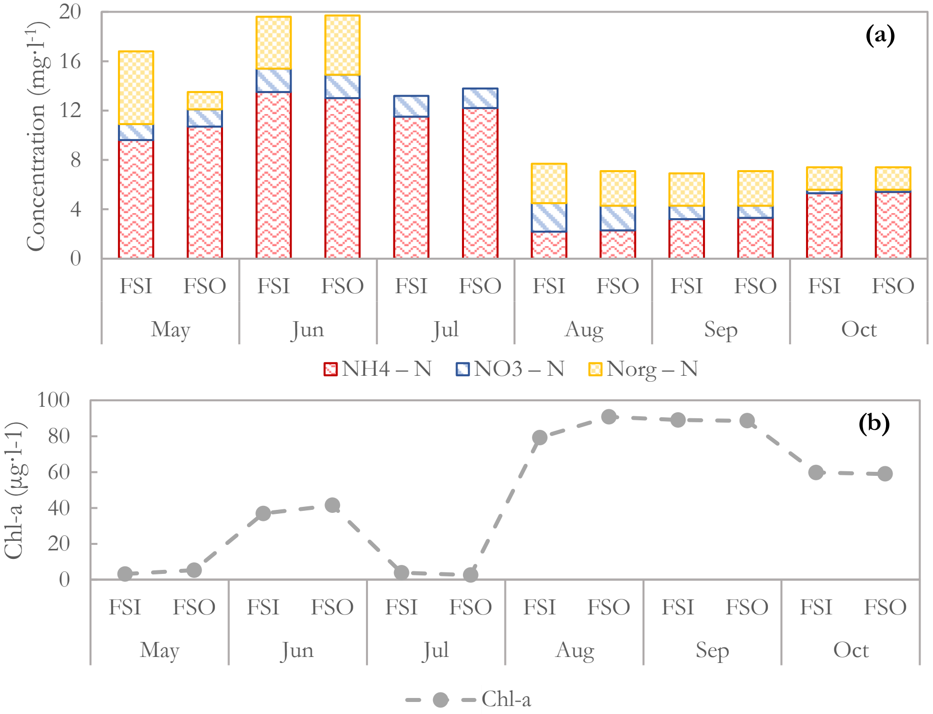

Figure 5.3 . Different N forms **(a)** and Chl-a **(b)** variations before and after filtration system of TID during 2019 irrigation

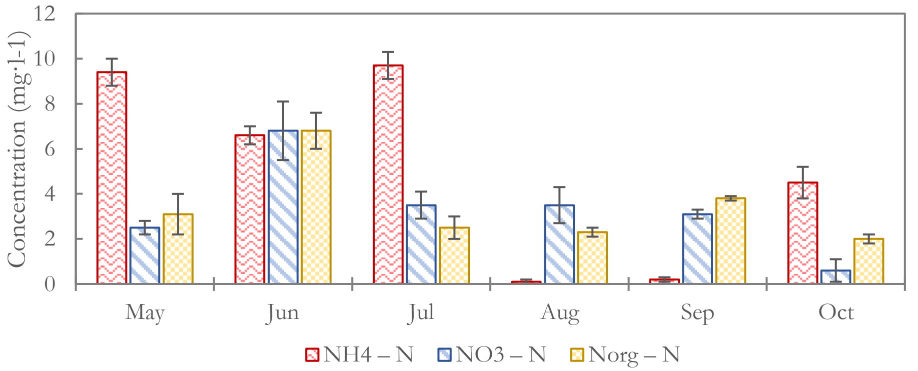

Figure 5.4. Mean and standard error of the N forms in the samples collected at the farms during 2019 irrigation season

5.3.3 Spatial analysis

Total inorganic N (NH_4^+-N and NO_3^--N) arriving at the farms is shown in Table 5.5. Modifications in inorganic N across the TID network were also determined (Figure 5.5 (a)). These modifications were calculated as the difference between concentrations arriving at the farms and concentrations at FSO. Nitrate concentration increased across the irrigation network in contrast to the reduction observed in the ammoniacal forms. These modifications are usually interrelated, which confirms a nitrification process is occurring. Nitrification is a very complex process in which the nitrifying bacteria transform the ammonium ion into nitrate ion (Rittmann and McCarty, 2001). RW generally has an elevated content of these bacteria which are highly susceptible to certain environmental factors, specifically to pH, DO and T (Brion and Billen, 2000; Shammas, 1986). The modifications in these parameters during 2019 are also shown in Figure 5.5 (b), (c) and (d) respectively.

Table 5.5. Total inorganic N arriving to the farms during 2019 irrigation season

	NH_4^+-N ($mg \cdot l^{-1}$)						**NO_3^--N ($mg \cdot l^{-1}$)**					
	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**
May	-	9.9	-	-	8.8	-	-	2.1	-	-	2.8	-
June	-	6.9	-	-	6.2	-	-	5.5	-	-	8	-
July	11.1	10.2	11	7.9	8.8	8.6	2.6	3.2	2.2	5.2	2.1	4.6
August	0	0	0	0	0	0.3	4.5	4.6	4.7	5	2.4	0.9
September	0.2	0.4	0.4	0.1	0.3	0	2.8	2.9	3	3.8	2.9	3.3
October	5	5.4	-	5.4	2.3	5.1	0.2	0.1	-	0.1	2.6	0.1

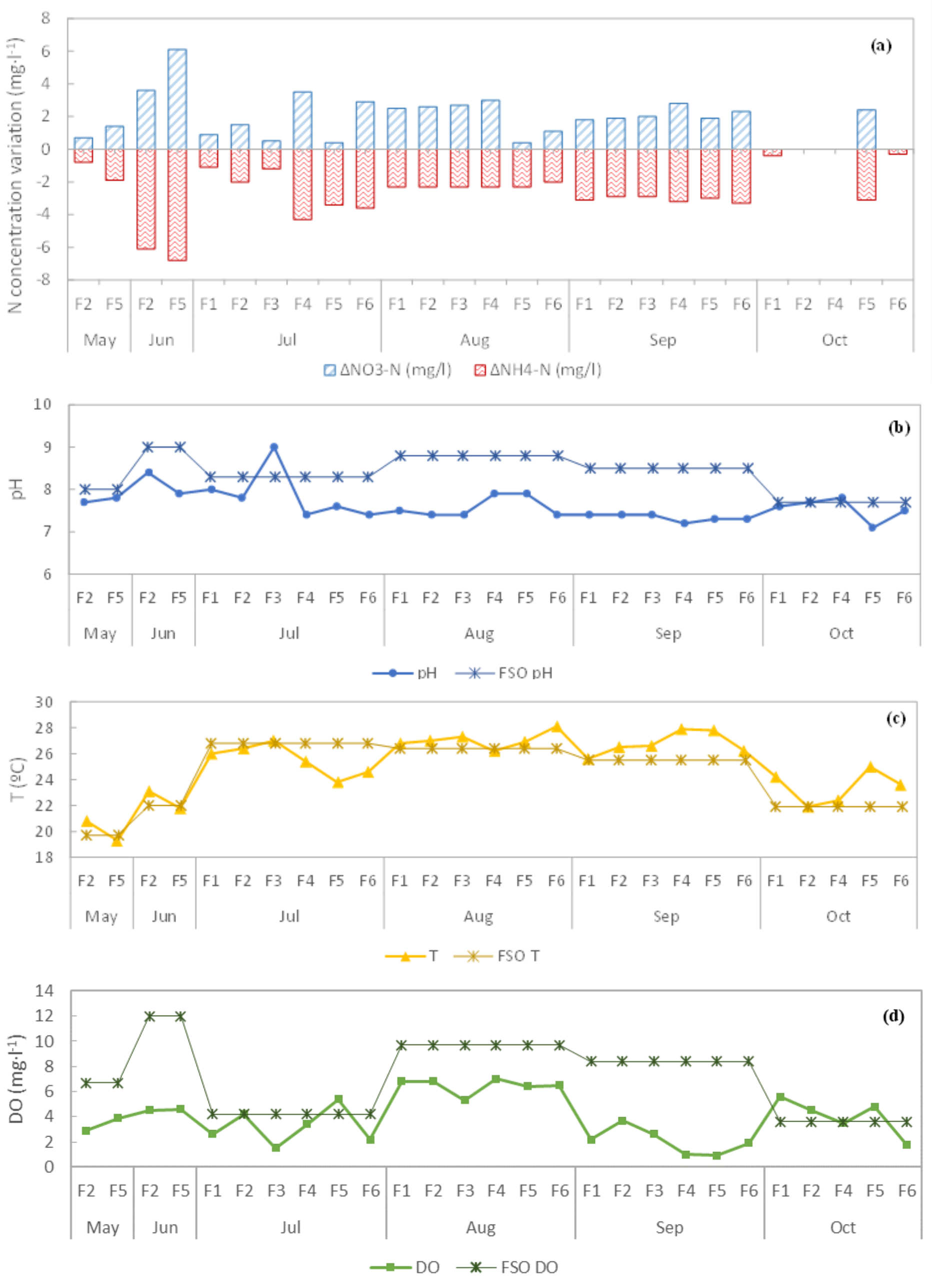

Figure 5.5 Variations across the TID irrigation network in: (a) inorganic N (mg·l-1); (b) pH; (c) T (ºC) and DO (mg·l-1)

In general, Table 5.5 shows that in May, June, July and October the reduced forms (ammonium) were in higher concentration than the oxidized ones (nitrates). Only in August and September is this pattern reversed. Figure 5.5 (a) shows an uneven nitrification throughout the irrigation season. For that reason, the influential parameters were analyzed previously. Regarding pH, Figure 5.5 (b) shows that pH varied from 9 to 7. The optimal value for the nitrification process is 8, while pH values below 6.5 reduce the nitrification rate significantly (Shammas, 1986). Therefore, pH values in TID were suitable for the nitrification process. This reaction consumes alkalinity, since it reduces the HCO_3^- content and increases H_2CO_3, which decreases the pH (Rittmann and McCarty, 2001). This is consistent with the information observed in Figure 5.5 (a) and (b), in which the pH decreased at farms where NH_4^+-N transformation into NO_3^--N occurred. This pH reduction was around 1 as average from FSO. As for T, the nitrification process can occur from 15 to 35ºC, with 30ºC being the optimal temperature (Shammas, 1986). Figure 5.5 (c) shows that during July, August and September water temperatures were higher (around 26.5ºC) compared to May, June or October when temperatures were 22ºC on average. There were no important modifications in T from FSO and the farms. Finally, considering DO concentrations, values below 4 $mg{\cdot}l^{-1}$ indicates a slowdown of nitrification rate until less than 2 $mg{\cdot}l^{-1}$ when this rate drops significantly (Espinosa Rodríguez et al., 2014). Figure 5.5 (d) shows that at FSO, DO concentration were above 4 $mg{\cdot}l^{-1}$ in May, June, August and September, in contrast with July and October when its value was about 4, which can compromise the nitrification process. DO arriving at the farms also decreased when nitrification occurred due to its use during this reaction.

Therefore, during May and June part of the NH_4^+-N turned into NO_3^--N from FSO to the farms (Figure 5.5 (a) and Table 5.5). Information related to the farm distances are shown in Table 5.1. In June this transformation was probably higher because of the higher temperature and DO content than in May. In both cases, nitrification was higher in F5 which was further than F2, which may indicate the influence of distance, and therefore the travel time of the water, in the N form arriving at farms. This matches the results found by Wang et al. (2020) who found a clear relationship between nitrification and pipes length. During August and September, the ammonium transformations to nitrate were more similar between the farms. T, DO and pH were in appropriate ranges in t these months for the nitrifying bacteria. However, these were the months in which N_T was lower and nitrification occurred until the entire NH_4^+-N removal as shown in Table 5.5. Finally, in July and October, the nitrification process was irregular along the farms. In both months, DO concentration at FSO was significantly lower than in other months, around 4 $mg \cdot l^{-1}$, which compromised the oxidation reaction. In October, T was also lower which can also affect this reaction.

5.3.4 Implications of using RW for olive tree irrigation

The N form arriving at the farm affects both the olive grove growth and the environment. This work proved that important changes in both N form and total N content took place in TID during the 2019 irrigation season. Removal of N and nitrification were produced both temporally and spatially. Considering the irrigation schedule of TID and the results of the water quality analyses, the total N applied was estimated at 19.6 $kg \cdot ha^{-1}$ during the irrigation season. According to Fernández-Escobar et al. (2012), who estimated the N extractions and inputs in olive grove, that quantity was enough to cover olive N requirements. This means that, in this particular case, no additional fertilizers would be needed. However, farmers applied additional fertilizers as their fertilization management is based on traditional methods and they do not consider the nutrients carried in water (Alcaide Zaragoza et al., 2019). This results in overfertilization, which causes numerous negative effects: reduction in yield, oil quality and frost tolerance as well as water pollution problems (Fernández-Escobar et al., 2009, 2006). As for N distribution, different authors affirmed that the more distributed the N applications, the higher the N efficiency (Fernández-Escobar et al., 2004). Thanks to the nutrients going through RW, the N application was continuous and distributed over time. However, the total quantity arriving at the farms was not steady. This proved the importance of a periodic water quality control and of a real-time fertilization dose adjustment to that quality. The supply of N through RW must be considered when carrying out additional fertilization programs since, if necessary, they should supplement the N already dissolved in the water. This could be a complex task for farmers on a day-to-day basis. However, thanks to advances in technology nowadays, there are tools or Apps for mobiles that can help farmers to do that in an easy way, such as that developed by Alcaide Zaragoza et al. (2020).

Considering N form, this work also proved that pipe length and abiotic factors could influence the final form arriving at the farms. Fernández-Escobar et al. (2004) affirmed that the olive tree growth was adequate regardless the N form used as long as the applied dose of fertilizer was correct. However, if N form did not change, it could create some problems. For example, excessive application in the ammonium form could acidify the rhizosphere and cause Ca, Mg or K absorption problems (Fernández-Escobar, 2017). Tsabarducas et al. (2017) also found that an excess in ammonium use inhibited the photosynthetic ratio of olive trees. On the other hand, nitrate is easily used by the olive trees when the application dose is low. But, given in excess, it can cause a drop in P, Fe, Mn and Zn concentrations as well as leaching problems. In fact, NO_3^--N is the main form of N leaching which is one of the major concerns facing sustainable agriculture. N leaching is exacerbated by rain events. However, in this work, the highest amount of nitrate reached the farms during the summer months, when rain fall is less likely, which entailed less nitrate leaching risk during the rainy season. In any case, the nitrate concentration did not exceed the harmful quantity to the environment (Spanish Government, 1996). Influence of the farm distance in the arriving N form could be valuable guidance for managers in order to avoid leaching or other nutrient absorption problems. In this particular case, the changes produced in N temporally and spatially prevented the aforementioned problems related to the constant N form. Finally, the nitrification process also entailed modifications in some other water quality parameters which could influence the olive irrigation, particularly, pH. The water pH could influence the emergence of plugging problems in the irrigation system. García Zamorano et al. (2004) established the chemical plugging risk as high when pH was higher than 8. Then, in those farms in which nitrification occurred, the plugging risk was reduced without the need to apply additional products.

5.4 Conclusions

A spatial and temporal analysis of N content and form in reclaimed water used for olive tree irrigation was carried out. This study proved that, due to the characteristics of the RW, changes in N were produced both over time and across the irrigation water distribution network. The temporal changes were strongly linked to the content in Chl-a which was not related to the distribution network but to the storage reservoir. The concentration of algal biomass in the water was one of the regulatory factors of the total content of N arriving at the farms. Spatially, a clear nitrification occurred from the pumping station to the farms. This reaction was determined by the pH, T and DO values of the water in the pumping station. In most cases, part or the totality of the ammonium was converted into nitrate.

This study confirmed that, due to the quantity of N found in the RW, olive tree requirements were covered. The temporal and spatial changes of N form allowed for the avoidance of problems related to the same N form in olives trees. In addition, these changes demonstrate the importance of a continuous water quality control to adjust the fertilization plan to the N content in water. For all that, this work confirms that irrigation with RW is a sustainable alternative for olive grove irrigation.

5.5 References

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6 Conclusions

6.1 General conclusions

- The use of reclaimed water is a very good alternative for olive orchard fertigation in Andalusia, which mitigates the imbalances between the water resources availability and the demand. Fertigation using reclaimed water also allows the promotion of circular economy, since it reuses nutrients and water for its application to the crop.
- The optimal use of reclaimed water for irrigation requires regular analysis of water quality, soil nutrient content and tree nutritional status.
- The complex management of reclaimed water for fertigation requires the development of user-friendly tools for farmers, who do not consider the trees nutritional status or the reclaimed water nutrients, thus providing an optimal application of both water and fertilizer.
- Thanks to the nutrients carried in reclaimed water, savings up to 100% of the additional fertilizer applied to Andalusian olive orchards can be achieved, covering their nutritional needs.
- The total nitrogen content of the reclaimed water and the form in which it reaches the farms, change both spatially and seasonally. This variability highlights the importance of continuous

monitoring of reclaimed water quality to adapt the fertilization plan.

- In the case study, it was found that there is significant nitrification in the water transport from the pumping station to the hydrants, which influences the how nitrogen is received in each farm.
- Temporal changes of total nitrogen content are closely linked to the chlorophyll-a content and, therefore, to the algal biomass in the water storage reservoir.

6.2 Avenues for future research

According to the conclusions drawn from this thesis, some of the avenues for future research are listed below:

- Spatio-temporal variation assessment of the main macro and micronutrients as well as toxic ions concentration in the irrigation distribution network.
- Analysis of the repercussions of plot location on production and the nutritional status of the olive grove, depending on the quality of the water that it receives.
- Medium and long-term analysis of the impacts of irrigation with reclaimed water on agricultural soils.
- Calibration of the Epanet hydraulic model to simulate the distribution of these elements in the irrigation network and their impact on fruit and oil quality.
- Development of a precision fertigation model for the irrigated area considering the spatio-temporal variability.

These future research lines are intended to be carried out in the second part of the project (REUTIVAR 2.0), which has already been granted.

6 Conclusiones

6.1 Conclusiones generals

- La utilización de aguas regeneradas constituye una buena alternativa para el fertirriego del olivar en Andalucía, permitiendo mitigar los desequilibrios entre la disponibilidad de los recursos hídricos y la demanda. El fertirriego con aguas regeneradas también permite el fomento de la economía circular, ya que reutiliza tanto el agua como los nutrientes para su aplicación al cultivo.
- El uso óptimo de las aguas regeneradas para riego requiere de análisis periódicos de la calidad del agua, contenido de nutrientes en el suelo y estado nutricional del árbol.
- La complejidad en la gestión de las aguas regeneradas para el riego hace necesario el desarrollo de herramientas de fácil utilización para los regantes, quienes normalmente no consideran el estado nutricional de los árboles ni los nutrientes del agua regenerada, permitiendo así optimizar la aplicación tanto de agua como de fertilizante.
- Gracias a los nutrientes que aportan las aguas regeneradas, es posible alcanzar en algunos casos un ahorro de hasta el 100% del fertilizante adicional aplicado en el olivar andaluz, cubriendo completamente sus necesidades nutritivas.

- El contenido total de nitrógeno presente en el agua regenerada, así como la forma en la que llega a las fincas de riego, cambian tanto espacial como estacionalmente. Esta variabilidad evidencia la importancia de un control continuo de la calidad del agua regenerada para adaptar el plan de fertilización.
- En el caso de estudio se ha comprobado que existe una importante nitrificación en el transporte del agua desde la estación de bombeo hasta los hidrantes, lo cual influye en la forma en la que se recibe el nitrógeno en cada parcela.
- Los cambios temporales del contenido de nitrógeno total que llega a cada parcela están estrechamente vinculados al contenido de clorofila-a y, por tanto, al contenido de biomasa algal en la balsa de almacenamiento del agua.

6.2 Nuevas líneas de investigación

Tras los resultados obtenidos en esta tesis, se enumeran, a continuación, algunas líneas de investigación futuras:

- Evaluación de la variación espacio-temporal de las concentraciones de los principales macros y micronutrientes, así como los posibles iones tóxicos en la red de distribución de riego.
- Estudio de los impactos de regar con aguas regeneradas en los suelos en cada zona de la comunidad de regantes.
- Calibración del modelo Epanet para la reproducción de la distribución de dichos elementos en la red de riego y su repercusión en la calidad del fruto y el aceite.
- Profundización en las técnicas de fertirriego de precisión de olivar con aguas regeneradas y realización de recomendaciones concretas sobre las aplicaciones de fertilizante necesarias en cada zona de la comunidad de regantes

Todas estas líneas futuras de investigación pretenden llevarse a cabo en la segunda parte del proyecto (REUTIVAR 2.0), la cual ha sido ya concedida.