Universidad de Jaén
Escuela de Doctorado

TESIS DOCTORAL

●

USO DE LA RESERVA DE AGUA DEL SUELO EN LAS ESTRATEGIAS DE RIEGO EN EL OLIVAR DE JAÉN

USE OF SOIL WATER RESERVE IN IRRIGATION STRATEGIES IN THE OLIVE GROVE OF JAEN.

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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 Jaén para este fin. Dos de los siete capítulos de esta tesis se corresponden con dos artículos científicos publicados en revistas incluidas en el primer cuartil según las últimas relaciones del “Journal Citation Reports, JCR, (Clarivate Analytics)” y “Scimago Journal & Country Rank, SJR, (SCImago)”, 2022:

– Molina-Moral, J.C., Moriana-Elvira, A., y Pérez-Latorre F.J. *The Sustainability of Irrigation Strategies in Traditional Olive Orchards. Agronomy*, 2022; 12(1):64. 1-15 pp. DOI: [https://doi.org/10.3390/agronomy12010064]. Switzerland. eISSN: 2073-4395. Índice de impacto (JCR): 3.949 (2021). 1er cuartil (Q1) en las áreas de Agronomía y Ciencia de los Cultivos, ranking Q1 en categoría “Agronomy” 18/90, y en categoría “Plant Sciences” 55/238, H-index: 50, Índice SJR: 0.654, Índice JCI: 21/144.

– Molina-Moral, J.C., Moriana-Elvira, A., y Pérez-Latorre F.J. *Estimation of the water reserve in the soil using GIS and its application in irrigated olive groves in Jaen, (Spain)*. Agronomy, 2022; 12(9):2188. 1-24 pp. DOI: [https://doi.org/10.3390/agronomy12092188]. Switzerland. eISSN: 2073-4395. Índice de impacto: 3.949 (2021). 1er cuartil (Q1) en las áreas de Agronomía y Ciencia de los Cultivos, ranking Q1 en categoría “Agronomy” 18/90, y en categoría “Plant Sciences” 55/238, H-index: 65, Índice SJR: 0.654, Índice JCI: 18/124.

TITULO: Uso de la reserva del agua del suelo en las estrategias de riego en el olivar de Jaén.

DOCTORANDO: Juan Carlos Molina Moral

INFORME RAZONADO DEL DIRECTOR DE LA TESIS

El agua es un recurso escaso pero esencial y fundamental para el funcionamiento de los ecosistemas y el sostenimiento de la biodiversidad. Si el riego es el principal consumidor de agua en los países de clima mediterráneo, es primordial maximizar su eficiencia. En el caso del sector agrario, particularmente el sector olivarero provincial ha realizado un grandísimo esfuerzo para maximizarla a través de las transformaciones secano-regadío y de las modernizaciones de las instalaciones existentes. A diferencia de otros cultivos una gran parte de estas instalaciones presentan limitaciones desde el punto de vista de su gestión debido a la asignación de dosis de riego deficitarias para un normal desarrollo del cultivo. De otro lado, un riego eficiente es un riego que permite mantener en el suelo un equilibrio hídrico adecuado en la relación planta-suelo-agua, tratando de evitar la aparición de situaciones de estrés innecesarias y garantizando el correcto desarrollo fisiológico del cultivo como su productividad y rentabilidad. Por lo tanto, en la gestión del agua de riego no solamente hay que tener en cuenta criterios de sostenibilidad en la gestión de los recursos hídricos, sino que también deben considerarse aspectos tales como la garantía de suministro alimentario, la conservación medioambiental del entorno, la rentabilidad de los agricultores y la supervivencia del sistema agrícola. El motivo por tanto del presente trabajo es profundizar en la mejora de la eficiencia hídrica del cultivo de olivar, seña de identidad y motor socioeconómico de la provincia de Jaén.

La Tesis Doctoral se divide en dos grandes apartados claramente diferenciados, los cuáles abordan diferentes problemas relacionados con la mejora de la gestión de los sistemas de riego en los olivares tradicionales y la mejora de su eficiencia hídrica, describiendo las metodologías adoptadas y aportando soluciones y herramientas que facilitan su manejo óptimo. La Tesis se ha elaborado como compendio de artículos científicos, que han dado lugar a dos publicaciones en una revista científica con alto índice de impacto, (Q1):

- Molina-Moral, J.C., Moriana-Elvira, A., and Pérez-Latorre F.J., 2022. *The Sustainability of Irrigation Strategies in Traditional Olive Orchards*.

Agronomy, 12(1), 64. 1-15 pp. DOI: [https://doi.org/10.3390/agronomy12010064].

En este trabajo se desarrolla un modelo para discernir la sectorización más adecuada en función de distintas estrategias de riego, la definición de diferentes calendarios de riego y la aplicación de distintas dosis de riegos deficitarios. Para facilitar la toma de decisiones, el modelo integra información climática, datos de suelo, datos del cultivo, configuración hidráulica del sistema de riego y disponibilidad de agua desarrollándose un programa de cálculo para la obtención del balance de agua en cada situación que permiten aplicar decisiones de ingeniería del riego (sectorizaciones) y de mejora y optimización de la eficiencia hídrica (dosis y frecuencias).

- Molina-Moral, J.C., Moriana-Elvira, A., and Pérez-Latorre F.J., 2022. *Estimation of the water reserve in the soil using GIS and its application in irrigated olive groves in Jaen, (Spain)*. Agronomy, 12(9), 2188. 1-24 pp. DOI: [https://doi.org/10.3390/agronomy12092188].

En este trabajo se analizan las variaciones espacio-temporales del balance hídrico y la reserva de agua en el suelo a nivel de toda la provincia de Jaén por su especial importancia tanto desde el punto de vista de la ingeniería del riego como de su gestión al tratarse de una zona semiárida de limitados recursos que pueden verse afectados de manera negativa a causa del cambio climático empleando metodologías de los sistemas de información geográfica (SIG). Los resultados obtenidos confirman que las programaciones de riego deben realizarse de manera específica y no resulta adecuado la utilización de calendarios de riego fijos. Por otro lado, resulta importante reseñar que la metodología utilizada presenta cualidades de adaptabilidad permitiendo el estudio de otros cultivos, y escalabilidad, posibilitando igualmente el análisis y estudio de otras zonas o ámbitos con un nivel de detalle en función de la precisión requerida.

En su conjunto, la investigación realizada representa un claro avance al estado del conocimiento actual en esta temática. Además, la investigación desarrollada puede tener repercusiones en el sector del riego, cada vez más interesado e involucrado en la mejora de la eficiencia en el uso del agua con un doble objetivo; reducir la intensidad del uso del agua y mejorar la productividad de la misma. Estos factores condicionantes permiten mejorar la eficiencia en su manejo, gestión y asignación permitiendo la obtención de un mayor valor socioeconómico, menor contaminación y el aseguramiento de la viabilidad y desarrollo del cultivo en situaciones de escasez y limitación de recursos.

Por todo ello, los trabajos recogidos en la presente Tesis han sido realizados bajo mi dirección y considero que presentan contenido científico suficiente, por lo que autorizo a su presentación y defensa para optar al grado de Doctor por la Universidad de Jaén.

Jaén, a 29 de Septiembre de 2022.

Firma del director

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A título póstumo dedico este trabajo a mis padres y seres queridos siempre presentes en mi corazón y que me han inculcado todo lo que soy como persona, mis principios, valores, carácter, empeño, perseverancia, coraje y aceptación para afrontar la vida y entregar a los demás lo mejor que tengo.

Resumen

La agricultura de regadío es el principal consumidor de agua en el mundo, empleando más del 70% de los recursos hídricos disponibles. En la cuenca del Guadalquivir la demanda bruta del regadío requiere el 46,22% de las aportaciones totales a la cuenca debidas a la climatología. En el pasado año 2021 este hecho significó un total de 3.202,03 hm3/año. Desde el punto de vista del uso del agua esto significa el 86,24% de la demanda consuntiva total. En esta cuenca encontramos en el caso particular del olivar que es el cultivo que mayor cantidad de agua demanda, (no por sus necesidades sino a causa de su extensión). Sus requerimientos hídricos son de 514,22 hm3/año y suponen el 20,5% del total del riego agrícola y se encuentra en el 45,2% de la superficie total de riego de la cuenca por lo que es el cultivo más representativo de la misma. Por otro lado, hemos de tener en cuenta que los cultivos, (entre ellos especialmente el olivar), son sensibles y especialmente vulnerables a los períodos de sequía y fenómenos extremos cuyas proyecciones climáticas vaticinan un aumento tanto de su duración como de su intensidad.

En esta situación una de las principales prácticas para mejorar la garantía de suministro de agua de riego al olivar consiste en la reducción del consumo de agua mediante la aplicación de estrategias de riego deficitarias en base a criterios agronómicos y técnicos junto con la implantación de sistemas de riego localizado, que en el caso particular de la provincia de Jaén constituyen más del 90% del total de las instalaciones.

En la presente Tesis Doctoral se pretende contribuir a la mejora de la eficiencia hídrica y al uso eficiente del agua del riego en el olivar, (tomando como referencia la provincia de Jaén), mediante el diseño, gestión y programación de la estrategia óptima en estos sistemas de riego utilizando para ello metodologías SIG con datos públicos de libre acceso.

Este trabajo se estructura en 7 capítulos, todos ellos enfocados a las particularidades del sistema de riego localizado en el olivar. En el *Capítulo 1* se expone el contexto actual en el cual se enmarca esta Tesis y se justifica la necesidad de la misma. En el *Capítulo 2* se describen los objetivos perseguidos, así como la estructura del resto del documento.

El *Capítulo 3* presenta el análisis de las fuentes de información disponibles para establecer el diagnóstico y punto de partida respecto del cultivo de olivar particularmente en la provincia de Jaén.

En el *Capítulo 4* se estudian diferentes escenarios climáticos y sus limitaciones en la programación y el establecimiento de calendarios de riego con la aplicación de distintas estrategias. Para ello se han considerado la información agroclimática, características y tipos de suelos, caracterización del cultivo, necesidades hídricas y estados fenológicos más susceptibles a su desarrollo, características del sistema de riego localizado, dotaciones, con el estudio de distintas estrategias, calendarios y programación, mostrando que la estrategia de riego más comúnmente utilizada en la provincia basada en la sectorización en tres sectores no es la más adecuada, y obteniendo una mejora en la eficiencia hídrica y una reducción de los períodos de estrés que afectan al cultivo mediante la definición y establecimiento de uno o dos sectores con la aplicación de programaciones diarias o riego deficitario controlado o regulado.

En el *Capítulo 5* se analizan a nivel provincial el balance hídrico y la reserva de agua en el suelo, obteniéndose como resultados la determinación de la evolución y variaciones espaciales y temporales de las necesidades hídricas del cultivo y la disponibilidad de agua para el mismo, cuyo conocimiento tiene una importancia esencial en zonas de recursos hídricos limitados como la nuestra. Para ello se han utilizado técnicas de sistemas de información geográfica (SIG) que posibilitan su adaptabilidad para el estudio de otros cultivos y otras zonas y que además permiten su escalabilidad en función del grado de

detalle y precisión que pretenda obtenerse abarcando el estudio desde amplias regiones, comarcas, comunidades de regantes, hasta el nivel de explotación o parcela. Los resultados obtenidos confirman que para la obtención de calendarios de riego más eficientes éstos deben adaptarse específicamente a su variabilidad agronómica y fisiográfica tanto espacial como temporalmente por lo que deben evitarse la utilización de calendarios de riego fijos.

En el *Capítulo 6* se enumeran y reseñan las principales conclusiones obtenidas y se identifican las posibles líneas futuras de investigación. Finalmente, en el *Capítulo 7* se describe la difusión de los trabajos realizados.

La mejora de la eficiencia en el uso del agua en los sistemas de riego localizado de olivar permite su mejora en la gestión y suponen un objetivo fundamental a alcanzar en situaciones de escasa disponibilidad de recursos hídricos. En el caso particular de los estudios realizados, la aplicación y utilización de técnicas y metodologías de fácil acceso posibilitan poner a disposición estas tecnologías tanto para ingenieros y gestores de comunidades de regantes como para agricultores.

Abstract/Summary

Irrigated agriculture is the main consumer of water in the world, using more than 70% of the available water resources. In the Guadalquivir basin, the gross demand for irrigation requires 46.22% of the total contributions to the basin due to climatology. In the past year 2021 this fact meant a total of 3,202.03 hm3/year. From the point of view of water use this means 86.24% of the total consumptive demand. In this basin, olive groves are the crop that demands the greatest amount of water (not because of their needs but because of the extent of its distribution). Its water requirements are 514.22 hm3/year and represent 20.5% of total agricultural irrigation and it is found in 45.2% of the total irrigated area of the basin making it the most representative crop in the basin. On the other hand, we must bear in mind that crops (especially olive groves) are sensitive and especially vulnerable to periods of drought and extreme phenomena whose climatic projections predict an increase in both duration and intensity.

In this situation, one of the main practices to improve the guarantee of irrigation water supply to the olive grove is the reduction of water consumption through the application of deficit irrigation strategies based on agronomic and technical criteria together with the implementation of localized irrigation systems, which in the particular case of the province of Jaen constitute more than 90% of the total installations.

This Doctoral Thesis aims to contribute to the improvement of water efficiency and the efficient use of irrigation water in the olive grove, (taking the province of Jaen as a zone reference), through the design, management and programming of the optimal strategy in these irrigation systems using GIS methodologies with open access public data.

This work is structured in 7 chapters, all of them focused on the particularities of the localized irrigation system in the olive grove. *Chapter 1* presents the current context in which this Thesis is framed and justifies the need for it. *Chapter 2* describes the objectives pursued, as well as the structure of the rest of the document.

Chapter 3 presents the analysis of the sources of information available to establish the diagnosis and starting point with respect to olive cultivation, particularly in the province of Jaen.

Chapter 4 studies different climatic scenarios and their limitations in the programming and establishment of irrigation schedules with the application of different strategies. For this purpose, agroclimatic information, soil characteristics and types, crop characterization, water requirements and phenological stages more susceptible to its development, characteristics of the localized irrigation system, endowments, with the study of different strategies, calendars and scheduling have been considered, showing that the irrigation strategy most commonly used in the province based on sectorization in three sectors is not the most appropriate, and obtaining an improvement in water efficiency and a reduction of stress periods affecting the crop by defining and establishing one or two sectors with the application of daily schedules or controlled or regulated deficit irrigation.

Chapter 5 analyzes the water balance and the water reserve in the soil at the provincial level, obtaining as results the determination of the evolution and spatial and temporal variations of the crop water needs and the availability of water for it, the knowledge of which is of essential importance in areas with limited water resources such as ours. For this purpose, geographic information systems (GIS) techniques have been used, which allow its adaptability for the study of other crops and other areas and also allow its scalability depending on the degree of detail to be obtained, covering the study from wide regions, counties, irrigation communities, up to the farm or plot level. The results obtained confirm that in order to obtain more efficient irrigation schedules, these must be specifically adapted to their agronomic and physiographic variability, both

spatially and temporally, so that the use of fixed irrigation schedules should be avoided.

Chapter 6 lists and summarizes the main conclusions obtained and identifies possible future lines of research. Finally, *Chapter 7* describes the dissemination of the work carried out.

The improvement of water use efficiency in localized irrigation systems in olive groves allows for improved management and represents a fundamental objective to be achieved in situations of scarce availability of water resources. In the particular case of the studies carried out, the application and use of easily accessible techniques and methodologies make it possible to make these technologies available to engineers and managers of irrigation communities as well as to farmers.

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Lista de Abreviaturas, Terminología y Símbolos
List of Abbreviations, Terminology and Symbols

AEA:	Anuarios de Estadística Agraria,*(Agricultural Statistics Yearbooks)*
AWAR:	Agua aplicada con precipitaciones medias, *(Applied water at average rainfall)*
AWI:	Intervalo de Humedad Disponible, *(Available Moisture/Water Interval)*
AWAR:	Agua aplicada con precipitaciones medias, *(Applied water at Average Rainfall)*
AWMR:	Agua aplicada con máximas precipitaciones, *(Applied water at Maximum Rainfall)*
AWmR:	Agua aplicada con mínimas precipitaciones, *(Applied water at minimum Rainfall)*
CAP	Consejería de Agricultura y Pesca. *(Regional government of Agriculture and Fisheries)*
CES:	Consejo Económico y Social de la Diputación de Jaén, *(Economic and Social Council of the Provincial Government of Jaen)*
CHG:	Confederación Hidrográfica de la cuenca del Río Guadalquivir, *(Guadalquivir River Hydrographic Confederation)*

CHGA: Confederación Hidrográfica de la cuenca del Río Guadiana, *(Guadiana River Hydrographic Confederation)*

CHGB: Confederación Hidrográfica de la cuenca del Río Guadalete-Barbate, *(Guadalete-Barbate River Hydrographic Confederation)*

CHMA: Confederación Hidrográfica de las cuencas mediterráneas andaluzas, *(Andalusian Basins Hydrographic Confederation)*

CHS: Confederación Hidrográfica de la Cuenca del Río Segura, *(Segura River Hydrographic Confederation)*

CHTOP: Confederación Hidrográfica de la Cuenca del Río Tinto-Odiel-Piedras, *(Tinto-Odiel-Piedras River Hydrographic Confederation)*

CSIC: Consejo Superior de Investigaciones Científicas, *(Superior Council of Scientific Research)*

EMC/EMA: Estaciones meteorológicas convencionales/automáticas, *(Conventional/automatic weather stations)*

FAO: Organización de las Naciones Unidas para la Alimentación y la Agricultura, *(Food and Agriculture Organization of the United Nations)*

FC: Capacidad de Campo, *(Field Capacity)*

ICRA: Inventario y Caracterización de los Regadíos de Andalucía, *(Inventory and Characterization of Andalusian Irrigated Lands)*

IDW: Método de interpolación de la distancia inversa ponderada *(Inverse Weighted Distance Interpolation Method)*

IEA: Instituto de Estadística de Andalucía, *(Statistical Institute of Andalusia)*

IFAPA: Instituto de Investigación y Formación Agraria y Pesquera, *(Institute for Agricultural and Fisheries Research and Training)*

INE: Instituto Nacional de Estadística, *(National Statistical Institute)*

IRNAS: Instituto de Recursos Naturales y Agrobiología de Sevilla, *(Institute of Natural Resources and Agrobiology of Seville)*

K_c: Coeficiente del Cultivo, *(Crop Coefficient)*

K_{cb}: Coeficiente Basal del Cultivo o de Transpiración, *(Basal Crop or Transpiration coefficient)*

K_e: Coeficiente de Evaporación, *(Evaporative Coefficient)*

K_s: Coeficiente de estrés, *(Stress Coefficient)*

LO: Ley Orgánica, *(Organic Law)*

MAGRAMA: Ministerio de Agricultura, *(Ministry of Agriculture)*

NDVI: Indice de Vegetación de Diferencia Normalizada, *(Normalized Difference Vegetation Index)*

PDOA: Plan Director del Olivar, *(Master Plan for the Olive grove)*

Pe: Precipitación efectiva, *(Effective/Usable Precipitation)*

PEN: Plan Estadístico Nacional, *(National Statistical Plan)*

PFA: Producción Final Agraria, *(Final Agricultural Production, FAP)*

PHG:	Plan Hidrológico del Guadalquivir, *(Guadalquivir Hydrological Plan)*
PNR:	Plan Nacional de Regadíos, *(National Irrigation Plan)*
PWP:	Punto de Marchitamiento Permantente, *(Permanent Wilting Point)*
QGIS:	Sistema de Información Geográfica de software libre y código abierto, *(Geographic Information System of free and open source software)*
RD:	Riego Deficitario, *(Deficit Irrigation, DI)*
RDR	Riego Deficitario Regulado, (*Regulated Deficit Irrigation, RDI)*
RDS	Riego Deficitario Sostenido, (*Sustained Deficit Irrigation, SDI*)
REDIAM:	Red de Información Ambiental de Andalucía, *(Environmental Information Network of Andalusia)*
RIA:	Red de Estaciones Agroclimáticas/Agrometeorológicas de Andalucía, *(Andalusian Agroclimatic/Agrometeorological Information Network)*
S1-IDD:	Estrategia 1-Riego todos los días del mes, *(Strategy 1—Irrigation every day of the month)*
S2-ID20:	Estrategia 2-Riego 20 días al mes, *(Strategy 2—Irrigation 20 days of the month)*
S3-RDI:	Estrategia 3-Riego deficitario regulado, *(Strategy 3—Regulated deficit irrigation)*
SAT:	Punto de Saturación, *(Saturation point)*

SAU:	Superficie Agraria Útil, *(Useful Agricultural Area)*
SDBm-SEISnet:	Base de datos del suelo del Sistema Español de Información de Suelos, *(Soil database of the Spanish Soil Information System)*
SER:	Sistema de Explotación de Recursos Hídricos, *(Water Resources Exploitation System)*
SIG/GIS:	Sistemas de Información Geográfica, *(Geographic Information Systems)*
SIGPAC:	Sistema de Información Geográfica de Parcelas Agrícolas, *(Geographic Information System for Agricultural Parcels)*
SIOSE:	Sistema de Información sobre Ocupación del Suelo de España, *(Information System on Land Occupation in Spain)*
SIPNA:	Sistema de Informacion Information sobre el Patrimonio Natural de Andalucía, *(System on the Natural Heritage of Andalusia)*
SNHT:	Test de homogeneidad estándar normal ó Test de Alexandersson, *(Standard Normal Homogeneity Test or Alexandersson´s Test)*
SWRC:	Capacidad de Retención de Agua del suelo, *(Soil Water Retention Capacity)*
TERRA-MODIS:	Imágenes originales del satélite TERRA captadas por el sensor MODIS, *(Original TERRA satellite images captured by de MODIS sensor, Moderate Resolution Imaging Spectroradiometer)*

TrAR:	Tiempo de riego con precipitaciones medias *(Time of irrigation at Average Rainfall)*
TrMR:	Tiempo de riego con máximas precipitaciones, *(Time of irrigation at Maximum Rainfall)*.
TrmR:	Tiempo de riego con mínimas precipitaciones, *(Time of irrigation at minimum Rainfall)*
UA:	Unidades de agregación de recintos de riego, *(Aggregation units of irrigation enclosures)*
UN WATER:	Organización de las Naciones Unidas para el Agua y el Saneamiento, *(United Nations Water Supply and Sanitation Organization)*
USD:	símbolo de moneda de dólar estadounidense, *(U.S. dollar currency symbol)*
WR:	Reserva de Agua del Suelo, *(Water Reserve)*
WRAR:	Reserva de agua con precipitaciones medias, *(Water Reserve at Average Rainfall)*
WRMR:	Reserva de agua con máximas precipitaciones, *(Water Reserve at maximum rainfall)*
WRmR:	Reserva de agua con mínimas precipitaciones, *(Water Reserve at minimum Rainfall)*
ZHR:	Zonas homogéneas de riego, *(Homogeneous irrigation zones)*
ΔW:	Balance de Agua, *(Water Balance)*

1. Introducción

1.1. Antecedentes

El agua es un recurso escaso y limitado, sujeto a la variabilidad climática estacional, y uno de los recursos naturales más importantes para el desarrollo económico.

Según la FAO, (2017), más del 70 % de todas las extracciones de agua dulce del mundo se utilizan para el riego agrícola. En la agricultura el agua es un factor clave de la producción final y el empleo, (Baso et al., 2010), de tal manera que el desarrollo de la agricultura de regadío se encuentra limitada por la escasez de agua. Si se tienen en cuenta los pronósticos del cambio climático que predicen alteraciones en los patrones de precipitación y temperatura y mayor probabilidad de ocurrencia de eventos extremos (Beniston et al, 2007), podemos conjeturar un aumento de la presión sobre los recursos hídricos disponibles.

En el entorno del continente europeo España se sitúa en el primer puesto en cuanto a superficie de riego y a nivel mundial se encuentra en la décimo sexta posición, (Aquastat, 2022). A nivel nacional, en el pasado siglo XX se pasó de tener poco más de un millón de hectáreas transformadas en riego a los casi 3,5 millones de hectáreas existentes en la actualidad. Esta cifra supone el 18,3% de la superficie total de cultivo y el 13% de la SAU (Superficie Agraria Útil), produciendo del 55% al 60% de la PFA (Producción Final Agraria), (PNE, 2018). Además, aproximadamente la mitad de la población activa agraria depende del regadío (Berbel J., 2007).

En el caso de los cultivos de la cuenca del Guadalquivir, el uso del agua debe ser particularmente cuidadoso, puesto que la evolución de la media móvil de precipitación durante el período 1980-2018 ha disminuido en torno a un -8.13% (respecto de la serie

1940-2018) pasando de 603 a 548 mm/año. Esta situación ha supuesto un desequilibrio entre las aportaciones y las demandas que ha dado lugar a la aparición de un déficit hídrico de 646.71 hm3 en 2007, 320.11 hm3 en 2015, y 218.81 hm3 en 2021 (PHG, 2022).

Con este escenario, si bien la gestión óptima de los sistemas de riego es muy compleja ya que intervienen distintos factores relacionados con la distribución del agua, sistema de riego en la explotación y agronomía, (Rodriguez et al, 2020), una de las principales estrategias será mejorar la eficiencia en el uso del agua lo que permitirá aumentar su productividad, y que conlleva aspectos tanto de índole hidráulica como energética. Históricamente, los esfuerzos para mejorar la eficiencia en el uso del agua y la energía han sido llevados a cabo por separado, siendo la eficiencia en el uso del agua un concepto de múltiples facetas, (UN Water, 2014). Para ahondar en este aspecto y aumentar la eficiencia hídrica, teniendo en consideración el límite de dotación anual establecido por el organismo de cuenca en 1.500m3/ha (CHG, 2016), se estudian estrategias de riego deficitario en las que el empleo de la capacidad de reserva de agua del suelo es un parámetro fundamental para poder ajustar los calendarios y programaciones de riego.

1.2. Representatividad e importancia del olivar.

Según Vilar et al, (2018), en la actualidad existen unos 11,5 millones de hectáreas cultivadas de olivar a nivel mundial, que representan aproximadamente el 1% de la superficie agrícola mundial, de las cuáles el 22 % son de regadío (Morales-Sillero et al, 2013).

El olivar es el cultivo con más superficie regada en España y el que más ha aumentado dicha superficie en los últimos años. Concretamente en la provincia de Jaén el olivar ocupa el 43 % de las tierras de cultivo lo que representa la tercera parte del total del olivar andaluz y la quinta parte de toda la superficie de olivar en España. La superficie de olivar de regadío asciende a 230.056 ha (39% a nivel provincial), por lo que podemos afirmar que es el principal consumidor de agua en la provincia, (AEA, 2021).

La aplicación de agua en los momentos críticos de desarrollo fenológico del olivo tales como la primavera (floración, cuajado y endurecimiento del hueso) y el otoño (maduración del fruto y formación de aceite) permiten incrementar la producción de manera notable con relación al secano en un 30-60% (Guzmán-Álvarez et al, 2009). Por otro lado, resulta necesario el mantenimiento de un buen estado hídrico del cultivo, (sobre todo durante las fases críticas), con el objeto de evitar condiciones de estrés fisiológico que además de desembocar en una pérdida de productividad pueden afectar a la salud de los árboles, (Chaves, 2006).

La garantía de suministro de agua de riego al olivar es un factor clave para su producción y competitividad (Gómez Ramos et al, 2002) por lo que posibles soluciones serían la mejora las instalaciones de riego, y desde la óptica de la ingeniería del riego estas soluciones se corresponderían con la sectorización óptima de las mismas disminuyendo el número de sectores y la creación de balsas de acumulación en las que se permita almacenar el agua en épocas de mayor disponibilidad.

Finalmente, a nivel socioeconómico, el olivar se constituye como el pilar fundamental y principal motor de la economía de Jaén tanto por el valor económico de sus producciones como en términos de generación de empleo (CES, 2011).

1.3. Tipologías de riego de olivar en la provincia.

El origen del olivar en la provincia de Jaén y específicamente del olivar de riego no está bien documentado, siendo su presencia no muy abundante hasta mediados del siglo XVIII. Sin embargo, a finales del XIX ya ocupaba un tercio de las tierras cultivadas.

A lo largo del pasado siglo XX el olivar ha pasado por dos marcadas épocas de fuerte e importante crecimiento y desarrollo; la primera de ellas tuvo lugar durante los años 50-60 a consecuencia de la iniciativa pública, (Zambrana, 1987), y la segunda durante las décadas 80-90 fundamentalmente por la iniciativa privada, (Paniza y Sánchez, 2015; Sánchez y Ortega, 2016)

La caracterización del olivar a nivel provincial viene realizándose fundamentalmente por instituciones y organismos con orientación o carácter agronómico que establecen una determinada tipología para evaluar sus costes, productividad, y por tanto su rentabilidad, (Parras et al, 2020; Colombo y Ruz, 2019; Sanz et al, 2014; y CES, 2011). Las variables utilizadas para su clasificación distinguen básicamente entre las siguientes características: uso del agua (secano o regadío), densidad de plantación (tradicional o intensivo), y pendiente media (mecanizable o no mecanizable) (IFAPA, 2015), y han sido respaldadas a nivel legislativo, (LO, 2011; PDOA, 2015).

Aproximadamente el 82% de la superficie de olivar en Jaén está categorizado como olivar tradicional, de la cual el 36% se encuentra en regadío.

La densidad media de plantación en la provincia de Jaén es de 117 árboles/ha lo que supone un marco de plantación ligeramente superior a 10 x 10 metros. Aproximadamente el 64% del total del olivar provincial presenta esta disposición, (CAP, 2018). Atendiendo a esta particularidad en el presente trabajo se ha adoptado un marco de plantación de 10 x10 metros que arroja una densidad de 100 olivos por hectárea.

1.4. Tipología del sistema de riego.

La tipología del sistema de riego más comúnmente utilizada en la zona se corresponde con una instalación de riego localizado consistente básicamente en una elevación desde captación o sondeo a balsa de regulación y posterior rebombeo a finca, con la instalación de una red de tuberías primarias, secundarias, terciarias y portagoteros que acaban en dos goteros autocompensantes por árbol con un caudal instantáneo de 8 litros/hora lo que arroja un caudal total por olivo de 16 litros/hora. Esta instalación es la más común de los sistemas de riego en olivar de la provincia de Jaén en al menos un 90 % de las instalaciones, (Peragón et al, 2016).

1.5. Riego deficitario.

Una de las soluciones para disminuir las dosis totales de agua aplicadas a un cultivo es el denominado riego deficitario, (RD), en el que se aplican menores cantidades totales de agua que las que teóricamente podría utilizar el cultivo para afrontar sus necesidades hídricas y la evapotranspiración. Cuando esta estrategia se realiza bajo parámetros reconocidos se denomina riego deficitario sostenido o regulado, RDS ó RDR, (Alcaide et al, 2020), de tal manera que los recortes de agua se realizan teniendo en cuenta la sensibilidad estacional del cultivo al estrés hídrico, lo que conlleva aplicar este recorte en las épocas de menor sensibilidad al déficit. Por tanto, antes de plantear cualquier estrategia de RD es imprescindible tener en cuenta el ciclo anual del cultivo, además de conocer su sensibilidad estacional al déficit hídrico basándonos en los procesos que puedan acaecer en cada momento, (Pastor et al., 2005; Corell et al, 2022).

La selección de una estrategia de riego debe tener en cuenta principalmente dos factores: el momento en que se producirá este periodo de estrés y la cantidad de agua aplicada (Gómez et al., 2011). En el caso del olivar los períodos comprendidos durante el endurecimiento del hueso (principios de julio) y el comienzo de la maduración (mediados de septiembre) son aquellos en los que la sensibilidad del cultivo al déficit hídrico es menor y por lo tanto el olivo es más resistente a la sequía (Goldhamer, 1999; Corell et al, 2016). Se ha comprobado que durante la fase de endurecimiento del hueso la aparición de situaciones de estrés hídrico de tipo moderado favorece la acumulación y formación de aceite, (Corell et al, 2022). Otros trabajos han establecido que tanto en la fase de crecimiento vegetativo y fundamentalmente de crecimiento del endocarpio (junio) como durante la fase de acumulación de aceite (mediados de septiembre a finales de noviembre) posibles situaciones de estrés hídrico pueden afectar al rendimiento anual o incluso al de la cosecha siguiente, (Hueso et al, 2019).

En esta situación, para una buena administración del agua disponible para la planta mediante la aplicación de riegos deficitarios es necesario conocer la reserva de agua en el suelo, que nos indicará le disponibilidad de la misma en los diferentes periodos de necesidad del cultivo y se traducirá en un importante ahorro en el consumo final de agua, (Gómez et al, 2009).

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1. Introduction

1.1. Background Information.

Water is a scarce and limited resource, subject to seasonal climate variability, and one of the most important natural resources for economic development.

According to FAO, (2017), more than 70% of all freshwater withdrawals worldwide are used for agricultural irrigation. In agriculture water is a key factor of final production and employment, (Baso et al., 2010), so that the development of irrigated agriculture is limited by water scarcity. If we take into account climate change forecasts that predict alterations in precipitation and temperature patterns and a greater probability of occurrence of extreme events (Beniston et al, 2007), we can conjecture an increase in pressure on available water resources.

Within the European continent, Spain ranks first in terms of irrigated surface area and is in the sixteenth position worldwide (Aquastat, 2022). At the national level, in the last 20th century, Spain went from having just over one million hectares transformed into irrigated land to the almost 3.5 million hectares existing today. This figure represents 18.3% of the total cultivated area and 13% of the UAA (Useful Agricultural Area), producing 55% to 60% of the FAP (Final Agricultural Production), (PNE, 2018). In addition, approximately half of the agricultural working population depends on irrigation (Berbel J., 2007).

In the case of crops in the Guadalquivir basin, water use must be particularly careful, since the evolution of the moving average precipitation during the period 1980-2018 has decreased by about -8.13% (with respect to the 1940-2018 series) from 603 to 548 mm/year. This situation has led to an imbalance between inflows and demands that has resulted in the appearance of a water deficit of 646.71 hm3 in 2007, 320.11 hm3 in 2015, and 218.81 hm3 in 2021 (PHG, 2022).

With this scenario, although the optimal management of irrigation systems is very complex since different factors related to water distribution, irrigation system on the farm and agronomy are involved (Rodriguez et al, 2020), one of the main strategies will be to improve the efficiency of water use, which will increase its productivity, and which involves both hydraulic and energy aspects. Historically, efforts to improve water and energy use efficiency have been carried out separately, being water use efficiency a multifaceted concept, (UN Water, 2014). To delve into this aspect and increase water efficiency, taking into consideration the annual endowment limit established by the basin organization at 1,500m3/ha (CHG, 2016), deficit irrigation strategies are studied in which the use of the soil water reserve capacity is a fundamental parameter to be able to adjust irrigation schedules and irrigation times.

1.2. Representativeness and importance of the olive grove.

According to Vilar et al, (2018), there are currently about 11.5 million hectares cultivated with olive groves worldwide, representing approximately 1% of the world's agricultural area, of which 22% are irrigated (Morales-Sillero et al, 2013).

Olive groves are the crop with the largest irrigated area in Spain and the one that has increased the most in recent years. Specifically, in the province of Jaen, olive groves occupy 43% of the cropland, which represents one third of the total Andalusian olive groves and one fifth of the total olive grove area in Spain. The irrigated olive grove area amounts to 230,056 ha (39% at the provincial level), so we can state that it is the main water consumer in the province, (AEA, 2021).

The application of water in the critical moments of phenological development of the olive tree such as spring (flowering, fruit set and stone hardening) and autumn (fruit ripening and oil formation) allows a notable increase in production of 30-60% compared to rainfed production (Guzmán-Álvarez et al, 2009). On the other hand, it is necessary to maintain a good water status of the crop (especially during the critical phases), in order to avoid physiological stress conditions that, in addition to leading to a loss of productivity, can affect the health of the trees (Chaves, 2006).

The guarantee of irrigation water supply to the olive grove is a key factor for its production and competitiveness (Gómez Ramos et al, 2002), so possible solutions would be the improvement of irrigation facilities, and from the point of view of irrigation engineering these solutions would correspond to the optimal sectorization of the same, reducing the number of sectors and the creation of accumulation ponds in which water can be stored in times of greater availability.

Finally, at the socioeconomic level, the olive grove is the fundamental pillar and main driving force of the economy of Jaen, both in terms of the economic value of its production and in terms of employment generation (CES, 2011).

1.3. Olive grove irrigation typologies in the province.

The origin of the olive grove in the province of Jaén and specifically of the irrigated olive grove is not well documented, being its presence not very abundant until the middle of the 18th century. However, at the end of the 19th century it already occupied a third of the cultivated land. Throughout the past twentieth century the olive grove has gone through two marked periods of strong and important growth and development; the first one took place during decades 50-60 as a result of public initiative, (Zambrana, 1987), and the second one during decades 80-90 mainly due to private initiative, (Paniza and Sanchez, 2015; Sanchez and Ortega, 2016).

The characterization of the olive grove at the provincial level has been carried out mainly by institutions and organizations with an agronomic orientation or character that establish a certain typology to evaluate its costs, productivity, and therefore its profitability, (Parras et al, 2020; Colombo and Ruz, 2019; Sanz et al, 2014; and CES, 2011). The variables used for their classification basically distinguish between the following characteristics: water use (rainfed or irrigated), planting density (traditional or intensive), and average slope (mechanizable or non-mechanizable) (IFAPA, 2015), and have been endorsed at the legislative level, (LO, 2011; PDOA, 2015).

Approximately 82% of the olive grove area in Jaen is categorized as traditional olive grove, of which 36% is irrigated.

The average planting density in the province of Jaen is 117 trees/ha which means a planting frame slightly higher than 10 x 10 meters. Approximately 64% of the total provincial olive grove presents this arrangement, (CAP, 2018). In view of this particularity, a planting frame of 10 x 10 meters has been adopted in the present work, which yields a density of 100 olive trees per hectare.

1.4. Irrigation system typology.

The type of irrigation system most commonly used in the area corresponds to a localized irrigation installation consisting basically of an elevation from a catchment or borehole to a regulation pond and subsequent pumping to the farm, with the installation of a network of primary, secondary, tertiary and dripper pipes that end in two self-compensating drippers per tree with an instantaneous flow of 8 liters/hour, resulting in a total flow per olive tree of 16 liters/hour. This installation is the most common of the irrigation systems in olive groves in the province of Jaen in at least 90% of the installations, (Peragon et al, 2016).

1.5. Deficit irrigation.

One of the solutions to reduce the total doses of water applied to a crop is the so-called deficit irrigation (DI), in which lower total amounts of water are applied than those that theoretically could be used by the crop to meet its water needs and evapotranspiration. When this strategy is carried out under recognized parameters it is called sustained or regulated deficit irrigation, SDI or RDI, (Alcaide et al, 2020), in such a way that water cuts are made taking into account the seasonal sensitivity of the crop to water stress, which entails applying this cutback in the periods of less sensitivity to deficit. Therefore, before considering any DI strategy, it is essential to take into account the annual cycle of the crop, in addition to knowing its seasonal sensitivity to water deficit based on the processes that may occur at any given time (Pastor et al., 2005; Corell et al, 2022).

The selection of an irrigation strategy should mainly take into account two factors: the time at which this period of stress will occur and the amount of water applied (Gómez et al., 2011). In the case of olive trees, the periods during stone hardening (early July) and the beginning of ripening (mid-September) are those in which the sensitivity of the crop to water deficit is lower and therefore the olive tree is more resistant to drought (Goldhamer, 1999; Corell et al, 2016). It has been shown that during the stone hardening phase, the occurrence of moderate water stress situations favors the accumulation and formation of olive oil (Corell et al, 2022). Other works have established that both in the vegetative growth phase and essentially endocarp growth (June) and during the oil accumulation phase (mid-September to the end of November) possible water stress situations can affect the annual yield or even the yield of the following crop, (Hueso et al, 2019).

In this situation, for a good management of the water available to the plant through the application of deficit irrigation, it is necessary to know the water reserve in the soil, which will indicate its availability in the different periods of crop need and will result in significant savings in the final water consumption, (Gómez et al, 2009).

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2. Objetivos y estructura de la Tesis.

2.1. Objetivos.

El objetivo general de esta tesis es profundizar en el conocimiento en el diseño, gestión y programación del riego localizado en el olivar de Jaén, para mejorar su eficiencia hídrica mediante el uso de la reserva de agua del suelo y la selección de la estrategia óptima de riego, incluidas las decisiones sobre la ingeniería de riego a implantar, utilizando metodologías y técnicas de los sistemas de información geográfica, (SIG), a partir de datos públicos de libre acceso.

Para lograr este objetivo, los objetivos específicos alcanzados se detallan a continuación:

- Diagnóstico, evolución, situación actual de las explotaciones de olivar en la provincia de Jaén.
- Conocimiento y determinación de los parámetros agroclimáticos de la superficie de olivar de riego de la provincia; meteorología, lluvias, evapotranspiración, tipo y textura de las diferentes clases de suelo.
- Caracterización de las características propias del cultivo; variedad, edad, grado de desarrollo, etapas de desarrollo fenológico, densidad, disposición, volumen de copa y cobertura.
- Conocimiento de la ingeniería de riego de las instalaciones; determinación de las distintas sectorizaciones, estrategias, programaciones o calendarios de riego y aplicación de distintas dosis para satisfacer los requerimientos hídricos del olivar.
- Estudio de la evolución del balance hídrico, la reserva de agua en el suelo y el gasto o consumo de agua teniendo en cuenta las variaciones espaciales y

temporales (a nivel provincial), mediante la aplicación y uso de técnicas SIG.

2.2. Estructura de la tesis.

Para alcanzar estos objetivos, esta tesis se organiza en siete capítulos. El **capítulo 1** y el **capítulo 2** son la introducción y los objetivos perseguidos, respectivamente.

El **capítulo 3** consiste en el análisis de las fuentes de información disponibles que nos ofrecen un punto de partida mediante el diagnóstico y caracterización de los distintos cultivos de olivar presentes en la provincia. Este capítulo ha sido publicado con el título "*Las fuentes de información en Agricultura. Estudio y evolución de la superficie de olivar de riego en Andalucía. Comparación con la provincia de Jaén*", (2020). por Molina-Moral, J.C., y Pérez Latorre, F.J., en Actas del XXXVIII Congreso Nacional de Riegos, Cartagena, (Murcia). Asociación Española de Riegos y Drenajes, (AERYD), Nº A-01-2020. Parte I. [https://www.doi.org/10.31428/10317/8664].

El **capítulo 4** abarca el estudio de diferentes escenarios climáticos y sus limitaciones en la programación para el olivar de la provincia de Jaén permitiendo el establecimiento de los calendarios de riego mediante la aplicación de diferentes estrategias de riego deficitario controlado, (RDC), en función del caudal de agua máximo disponible y los días disponibles para el riego. Este capítulo ha sido publicado con el título "T*he Sustainability of Irrigation Strategies in Traditional Olive Orchards*", (2022), por Molina-Moral, J.C., Moriana-Elvira, A., y Pérez-Latorre, F.J. Agronomy, 12(1):64. 1-15 pp. [https://doi.org/10.3390/agronomy12010064].

El **capítulo 5** analiza el balance hídrico y la reserva de agua en el suelo a nivel de toda la provincia de Jaén, en condiciones áridas y semiáridas para estudiar la conveniencia de la aplicación de estrategias y calendarios de riego fijos o particularizados a la ubicación de la explotación y sus requerimientos hídricos mediante técnicas SIG. Este capítulo ha sido publicado con el título "*Estimation of the water reserve in the soil using GIS and its application in irrigated olive groves in Jaen, (Spain)*", (2022), por Molina-Moral, J.C., Moriana-Elvira, A., y Pérez-Latorre, F.J. Agronomy, 12(9):2188. 1-24 pp, XX. [https://doi.org/10.3390/agronomy12092188].

Finalmente, el **capítulo 6** presenta las conclusiones obtenidas en esta tesis y detalla las posibles líneas de investigación futuras, y el **capítulo 7** describe la difusión de los trabajos.

3. Las fuentes de información en Agricultura de regadío. Estudio y Evolución de la superficie de olivar d riego en Andalucía. Comparación con la provincia de Jaén.

Este capítulo fue publicado completamente en las Actas del XXXVIII Congreso Nacional de Riegos en Cartagena, (AERYD). Parte I. Molina-Moral, J.C., y Pérez-Latorre, F.J., (2020). [https://www.doi.org/10.31428/10317/8664].

Resumen: Conocer y determinar con la mayor precisión posible la superficie de riego de los cultivos, es un punto de partida necesario para posteriores estudios de caracterización de las instalaciones desde la perspectiva de análisis hídrico y energético. Es necesario también tener en cuenta otros aspectos como el origen de las aguas utilizadas, superficie regada, sistema de riego empleado, desniveles existentes, número de estructuras de almacenamiento/regulación, características de las redes de riego, número y potencia de los sistemas de bombeo, etc. Disponer de esta información se hace más interesante ante la posible transformación del modo de cultivo con la adopción de los sistemas intensivos, o en la aplicabilidad de estrategias de riego deficitario en grandes regiones. La consulta de diferentes Organismos Públicos pone de relieve, de forma habitual, que éstos presenten criterios distintos y utilizan metodologías diferentes para determinar la superficie de riego, dificultando la comparación de la información obtenida, de modo que en la mayoría de las ocasiones los resultados no son coincidentes. A esta situación se podría añadir la discrecionalidad con la que se publican dichos datos. Las distintas metodologías de recogida y tratamiento de los datos, así como las fuentes principales de los mismos, son abordadas en el presente trabajo.

Abstract: Know and determine with the major possible precision the crops irrigation surface is a necessary starting point for further research studies of characterization of the facilities from the perspective of water and energetic analysis. It is also necessary to take into account other aspects such as the origin of the used waters, watered irrigation, system of irrigation, differences in levels, number of structures of storage/regulation, characteristics of irrigation networks, number and power of the systems of pumping systems,.. etc. Having this information becomes more interesting in view of the possible transformation of the cultivation mode with the adoption of intensive systems, or in the applicability of deficit irrigation strategies in large regions. The consultation of different Public Organizations shows, in a habitual way, that they present different criteria and use a different methodology to determine the surface of irrigation, making difficult the comparison of the obtained information, so that in most of the occasions the results they are not coincidental. To this situation could be added the discretion with which data are published. The different methodologies of data collection and treatment, as well as the main sources thereof, are exposed in the present work, with the objective of determining the irrigation surface of olive groves at Andalusia, and particulary at Jaen´s province, for further studies from the optics of water and energy efficiency.

3.1. Introducción.

En la actualidad, en España a consecuencia de un profundo cambio estructural y determinados condicionantes ocurridos desde los primeros años del siglo pasado han originado que hoy en día tan solo el 3% de su población figure como agricultora, y a pesar de ello es uno de los países que mayor porcentaje de su territorio utiliza para uso agrícola y el medio rural, representando el 90% del territorio y el 20% de la población, (Robledo R, 2011). Así en el siglo XX se ha pasado de tener poco más de un millón de hectáreas transformadas en riego a las aproximadamente 3.488.000 has existentes en la actualidad. Esta cifra, que supone el 18,3% de la superficie total de cultivo y el 13% de la Superficie Agraria Útil (SAU), produciendo del 55% al 60% de la Producción Final Agraria (PFA), (Plan Nacional de Regadíos, PNR). Además, aproximadamente la mitad de la población activa agraria depende del regadío (Berbel J., 2007).

Hoy día, las estadísticas agrarias, aun siendo realizadas por el Ministerio, están integradas en los Planes Estadísticos Nacionales, (PEN), que tienen una vigencia de 4 años, y que se enmarcan dentro del PEN 2017-2020, y coordinadas con el INE (Instituto Nacional de Estadística) y su homólogo autonómico IEA, (Instituto de Estadística de Andalucía) cristalizando en la publicación de los Anuarios de Estadística Agraria, de carácter anual, desde inicios del siglo pasado, con algunos paréntesis.

A nivel autonómico, la Consejería de Agricultura, Pesca y Desarrollo Rural de la Junta de Andalucía, elaboró y publicó en tres ocasiones; 1997, 2002 y 2008 el ICRA, "Inventario y Caracterización de los Regadíos de Andalucía", que tuvo vigencia durante el período 1996-2008, empleando como fuente de datos además de las previamente citadas, la realización de encuestas y entrevistas directas a las entidades vinculadas con la agricultura de regadío y técnicas cartográficas. Además, ha venido estableciendo la planificación y asignación de recursos al regadío, y concretamente al sector del olivar, (CAP,2011-2014-2019).

Por otra parte, la Directiva 2000/60/CE, de 23 de octubre del Parlamento Europeo y del Consejo, denominada como Directiva Marco del Agua, estableció la realización de Planes Hidrológicos de Cuenca por los organismos de cuenca, denominados como Confederaciones Hidrográficas, que se revisan y actualizan cada seis años, si bién antes de esta disposición europea ya se realizaban en España desde 1998, en virtud de la Ley de Aguas, (Ley 29/1985, de 2 de agosto). Hasta el momento ha habido tres ciclos: 2009-

2015, 2015-2021, (actualmente vigente), y el futuro 2021-2027, (CHG,2009-2015-2019). Esta actuación tuvo como punto de partida el informe final sobre la superficie de los cultivos de regadío y sus necesidades para el riego en la demarcación hidrográfica del Guadalquivir, (CHG, 2005).

Las cuencas y ríos que discurren por Andalucía se enmarcan en seis distritos hidrográficos distintos: tres intracomunitarios (Guadalete-Barbate, Odiel-Piedras, y Cuencas Mediterráneas Andaluzas; y tres intercomunitarios, (Guadalquivir, Segura y Guadiana), fijadas por el Real Decreto 125/2007, de 2 de febrero. En el caso particular de la provincia de Jaén, ésta queda afectada por dos cuencas, la del Guadalquivir y la del Segura. La cuenca hidrográfica del Guadalquivir en la provincia de Jaén ocupa casi la totalidad de la extensión de la misma con 12.892 km2, y la cuenca hidrográfica del Segura cuenta con 594 km2, aproximadamente.

Los organismos de cuenca registran los datos de superficies, tanto de solicitudes como de concesiones, ya sean públicas o privadas, diferenciando las otorgadas, denegadas o en proceso de resolución, en su ámbito territorial.

Finalmente, con carácter discrecional y puntual encontramos algunos trabajos realizados por entidades u organismos públicos o privados, y autores reconocidos que utilizan diferente metodología tanto en la adquisición como en el tratamiento de la información en atención a los objetivos que persiguen, y presentación de sus resultados. Un ejemplo de ello es el observatorio Económico de la provincia, entidad pública perteneciente al ámbito de la Diputación Provincial de Jaén, que abordó un estudio del olivar de riego durante el período 1985-1998, y posteriormente realizó un estudio-dictamen sobre la rentabilidad económica de las explotaciones de olivar en la provincia en 2011, (CES. 2011).

3.2. Objetivos.

El objetivo fundamental del presente Trabajo es determinar la superficie de riego de olivar en Andalucía, y particularmente en la provincia de Jaén, para su posterior estudio desde la óptica de la eficiencia hídrica y energética.

3.3. Materiales y Métodos.

Para la obtención de los datos de partida se han consultado los siguientes organismos y administraciones:

3.3.1 Anuarios de Estadística Agraria, (AEA).

Los anuarios de estadística agraria no recogen aspectos tales como el origen de las aguas o tipología de riego, pero a nivel general si vienen informando de modo anual, de la superficie de riego y secano a nivel provincial. Inicialmente la recogida de datos se realizaba en base a los aforos de campo, prospecciones a entidades representativas y/o encuestas directas. En la actualidad, los datos se recogen de la información administrativa derivada de las declaraciones de los solicitantes de ayudas por superficies, así como el SIGPAC, (Sistema de Información Geográfica de Parcelas Agrícolas). Para ello, tiene en consideración como parcelas de riego como aquellas que son declaradas por los propios agricultores. Los datos son recogidos por el Ministerio de Agricultura (MAGRAMA), y las Delegaciones Provinciales de Agricultura de cada provincia.

A partir de 1999 aplican un cambio de la metodología volviendo a sus inicios y aportando datos sobre el número de árboles diseminados, además de otros relativos al rendimiento.

3.3.2. Organismos de cuenca, (CHG, CHS).

Los organismos de cuenca básicamente realizan el recuento de solicitudes, concesiones y actas de notoriedad, refiriendo sus datos a cuencas y distritos hidrográficos, utilizando criterios que distinguen entre olivar tradicional e intensivo, pero no permiten discernir a nivel municipal o provincial la información ofrecida ni tampoco la superficie de riego de las parcelas que estén pendientes de los trámites de concesión, o bien que tengan concedidos riegos deficitarios o riegos de emergencia.

Para la determinación de que una superficie se encuentre o no en regadío establecen tres procedimientos; en primer lugar la declaración/solicitud de su propietario o titular; en segundo lugar porque se hayan detectado infraestructuras para el riego y/o cultivos o zonas regadas, (utilizando para ello la cartografía existente empleando técnicas de fotointerpretación y teledetección; y finalmente, en tercer lugar, por la inspección que se realice para verificar la situación declarada o detectada, lo cual pone de relieve cierto grado de incertidumbre y de la complejidad de la situación.

3.3.3. Instituto Nacional de Estadística (INE) e Instituto de Estadística de Andalucía (IEA).

Aporta datos a nivel provincial, comarcal y por cuencas hidrográficas, diferenciando el origen del agua de riego utilizada. El INE toma como fuente de datos los suministrados por el Ministerio de Agricultura, principalmente los Censos Agrarios, (el último se realizó en 2009), y las encuestas sobre la estructura de las explotaciones agrícolas, (de carácter anual). El IEA realiza las mismas labores que el INE a nivel autonómico, siguiendo las directrices de los Planes Estadísticos Nacionales.

3.3.4. Inventario y Caracterización de los Regadíos de Andalucía, (ICRA).

El ICRA realizado por la administración autonómica, (Consejería de Agricultura y Pesca de la Junta de Andalucía), supuso un esfuerzo de la administración andaluza por realizar un sistema información territorial del regadío aproximado a la realidad que sirviera de base a su planificación. Se realizaron tres publicaciones; 1997, 2002, y 2008. Posteriormente publicó el informe "Inventario de Regadíos 2008 y su evolución en la última década", (CAP, 2011).

En el primer inventario del ICRA (1997) la unidad mínima de información era la Zona de Riego, (Z.R.), cuya delimitación se basaba en la información disponible (recintos SIGPAC de riego) y su intersección con los límites municipales e hidrológicos tras un trabajo de campo consistente en la elaboración de cuestionarios específicos para los diversos grupos de usuarios: Comunidades de Regantes, regantes singulares, técnicos, funcionarios de diversas Administraciones, Ayuntamientos y Cámaras Agrarias (hoy desaparecidas), y la posterior cartografía de las zonas de riego, completándolas y contrastándolas con diversas fuentes estadísticas. De esta manera se creó una cobertura denominada “Sistemas de Explotación de Recursos Hídricos”, (SER), que no coincidía ni con la delimitada en el Plan Hidrológico de Cuenca, ni con la del organismo de cuenca, (CHG), por lo que hubo que contrastarla y ajustarla. La posible razón de este hecho es que los recintos SIGPAC definidos como regables podían presentar tres orígenes distintos; en primer lugar las propias declaraciones de los agricultores al solicitar éstos las ayudas comunitarias con carácter anual; en segundo lugar por la identificación y fotointerpretación de infraestructuras de riego en las parcelas; y finalmente, en tercer lugar, por las parcelas declaradas como de riego en base al catastro de rústica. En el primer caso, como en el olivar las ayudas no están vinculadas al secano o regadío, la fiabilidad de los datos aportados por los agricultores depende de su propia actitud.

En su última revisión de 2008, se definieron las Unidades de Agregación de Recintos, (U.A.), y las Zonas Homogéneas de Riego, (Z.H.R,). Las primeras estarían constituidas por Comunidades de Regantes o regantes individuales mayores de 200 has, y las segundas serían las restantes, teniendo en cuenta criterios de proximidad geográfica y homogeneidad de los regadíos, desglosando los datos por comarcas agrícolas.

3.3.5. Observatorio económico de la provincia de Jaén, (CES).

La primera publicación relativa al olivar la realizó este organismo en 1998 (Consejo Económico y Social de la Provincia de Jaén, 1997), en base a los datos de los Anuarios de Estadística Agraria en los períodos 1985-86 y 1997-98. Posteriormente, en 2011, realizó una segunda publicación denominada "Dictamen sobre el Análisis de la rentabilidad económica de las explotaciones de olivar en la provincia de Jaén", usando la misma base de información y determinaciones propias, elaborando un desglose por comarcas agrícolas y distintas tipologías o categorías agronómicas de olivar, en base a la publicación "El Olivar Andaluz", (CAP, 2002). No existe otra publicación análoga en las restantes provincias de Andalucía.

3.4. Resultados y Discusión.

3.4.1 Anuarios de Estadística Agraria, (AEA).

Los Anuarios de Estadística Agraria son la fuente de información más completa proporcionándonos datos, generalmente, con periodicidad anual. En la figura 3.1 se ha representado la evolución de la superficie de riego de olivar en Andalucía y en la provincia de Jaén durante el periodo de tiempo 1928-2019. Al analizarla se observa que a grandes rasgos la superficie total de olivar en Andalucía ha ido expandiéndose paulatinamente, así como el aumento de la superficie de riego en este cultivo encontrándose respecto de ésta última tres momentos clave; la década de los 80, la primera década del segundo milenio, y finalmente a partir del año 2014, aunque en la actualidad la tendencia es a disminuir ligeramente.

Respecto de la provincia de Jaén, la primera expansión del olivar de regadío en la provincia tuvo lugar durante el período 1972-1998, mostrando una tendencia ascendente moderada, sin embargo, es durante la década correspondiente al período 1995-2005 cuando la expansión de la superficie de riego muestra una tendencia más acusada. Finalmente, la subida desde 2012 no se debe a una expansión del cultivo, sino que es consecuencia un cambio en la metodología por parte de la Consejería de Agricultura de la Junta de Andalucía al incorporar los datos del ICRA, los recintos SIGPAC y modificar su metodología.

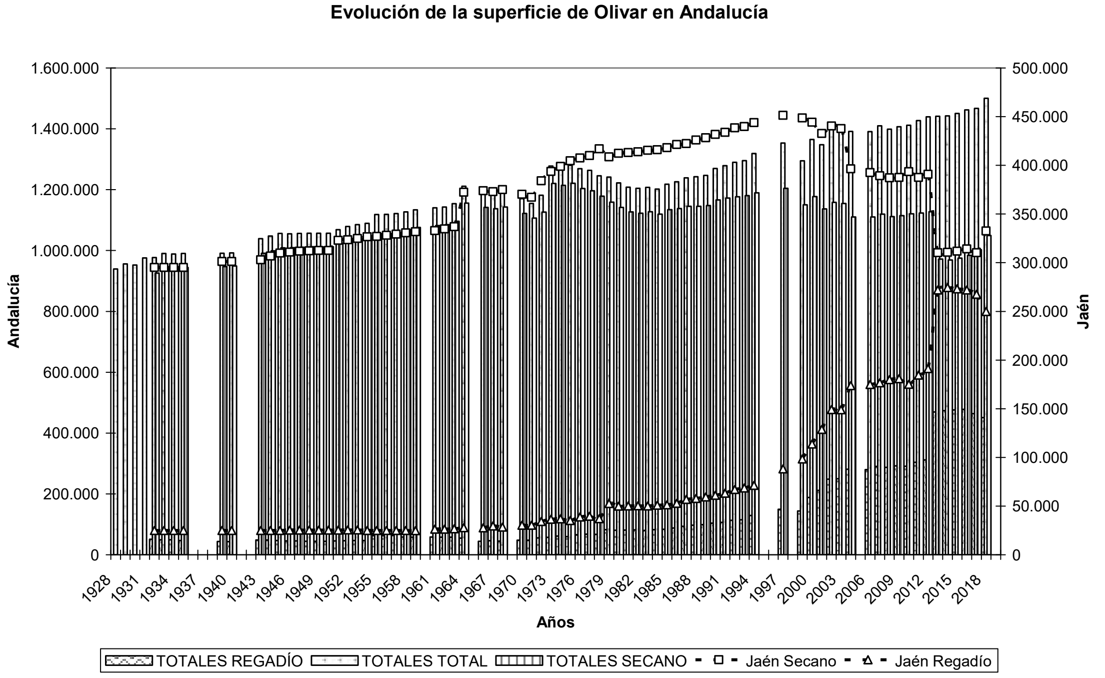

Figura 3.1: Evolución de la superficie de riego de olivar. Fuente: AEA, Anuarios de Estadística Agraria y Delegación Provincial de Jaén, (1904-2019).

En un análisis de mayor detalle se ha tabulado la evolución del olivar en períodos quinquenales durante los últimos cuarenta años, diferenciando los datos de superficie total, secano y regadío (tablas 3.1 y 3.2). De este modo se pueden destacar incrementos muy acusados en el periodo 1995-2000 (de más del 41%) y en el 2009-2012 (de más del 36%).

El continuo crecimiento se ha visto favorecido por el establecimiento de ayudas a la producción, y la ampliación favorable del mercado del aceite de oliva, así como ayudas específicas a la mejora de regadíos. También podemos destacar la relación entre olivar total y el de regadío, manteniéndose en valores próximos al 10 % en el principio de la década de los años 90 del siglo pasado, y actualmente superando el 40%.

Tabla 3.1: Superficies de secano y regadío a nivel autonómico, por periodos de cinco años. Fuente: AEA, Anuarios de Estadística Agraria, (1976-2019).

Superficies medias de olivar en Andalucía.

Periodo	Secano, (has)	Regadío (has)	Total (has)	Sup. Regadío/Total %
1976-1980	1.175.912	72.627	1.248.539	5,82%
1981- 1985	1.126.196	81.937	1.208.133	6,78%
1986- 1990	1.148.618	96.361	1.244.978	7,74%
1991-1995	1.179.799	115.929	1.295.728	8,95%
1996-2000	1.177.311	160.466	1.337.777	11,99%
2001-2005	1.140.051	247.666	1.387.717	17,85%
2006-2010	1.115.484	288.157	1.403.641	20,53%
2011-2015	1.033.373	406.911	1.440.284	28,25%
2016-2019	1.012.294	464.237	1.476.531	31,44%

Tabla 3.2: Superficies de secano y regadío a nivel provincial, por periodos de cinco años. Fuente: AEA, Anuarios de Estadística Agraria, (1976-2019).

Superficies medias de olivar en la provincia de Jaén.

Periodo	Secano, (has)	Regadío (has)	Total (has)	Sup. Regadío/Total %
1976-1980	411.089	43.659	454.748	9,60%
1981- 1985	415.310	50.634	465.944	10,87%

1986- 1990	425.917	57.625	483.542	11,92%
1991-1995	439.012	67.540	506.552	13,33%
1996-2000	448.092	100.178	548.271	18,27%
2001-2005	426.822	150.149	576.971	26,02%
2006-2010	390.051	177.560	567.612	31,28%
2011-2015	342.225	239.097	581.321	41,13%
2016-2019	318.973	263.109	582.082	45,20%

3.4.2. Organismos de cuenca, (CHG, CHS).

Realizan escasas publicaciones, discrecionales, y desglosadas según parámetros hidrológicos, sin divisiones administrativas, con datos aislados y desagregados sin conexión ni continuidad temporal, (tabla 3.3).

Tabla 3.3: Superficies de regadío a nivel autonómico según organismos de cuenca en Andalucía. Fuente: Elaboración propia a partir de Planes Hidrológicos de Cuenca vigentes.

	CHG	**CHCMA**	**CHGA**	**CHGB**	**CHS**	**CHTOP**
1999			20.936			
2004	292.818					
2005					17.718	
2008		25.346				
2009	409.808		27.930			
2015	440.097					82
2019				77		

En cuanto a la superficie de riego en las tablas 3.4 y 3.5 se pueden apreciar los datos correspondientes al año 2017, pudiéndose distinguir olivar tradicional y olivar intensivo y a la superficie regada cuando el olivar se asocia con otro cultivo.

Tabla 3.4: Superficie regada y regable de olivar en Jaén. Fuente: CHG, Organismo de cuenca, 2018. (Datos de 2017).

	SUPERFICIE REGADA (has)	**SUPERFICIE REGADA OLIVAR Y OTROS MÁS (has)**	**SUPERFICIE REGABLE (has)**
Olivar	231.611,64	239.352,79	240.027,94
Olivar intensivo	31.870,16	46.413,46	48.970,83
TOTAL	**263.481,80**	**285.766,25**	**288.998,77**

Tabla 3.5: Tipología de olivar en función del origen del agua en Jaén. Fuente: CHG, organismo de cuenca, 2018. (Datos de 2017).

Olivar tradicional

Nº de concesiones	**Origen del Agua**	**Sup. Regada (has)**	**Sup. Regable (has)**
178	AGUAS SUBTERRÁNEAS	121.664,95	121.967,29
188	AGUAS SUPERFICIALES	103.501,41	103.794,03
7	ESCORRENTÍA	987,61	987,61
21	AGUAS REUTILIZADAS (EDAR)	13.198,82	13.279,01
394		**239.352,79**	**240.027,94**

Olivar intensivo

Nº de concesiones	**Origen del Agua**	**Sup. Regada (has)**	**Sup. Regable (has)**
6	AGUAS SUBTERRÁNEAS	3.886,27	3.886,27

49	AGUAS SUPERFICIALES	42.527,19	45.084,56
0	ESCORRENTÍA	0	0,00
0	AGUAS REUTILIZADAS (EDAR)	0	0,00
55		**46.413,46**	**48.970,83**
449		**285.766,25**	**288.998,77**

Los datos ofrecidos ponen de relieve que la variación final entre la superficie regada y regable es de 25.516,97 has. En cambio, si se considera la superficie de olivar con otros cultivos asociados la diferencia se reduce a 3.232,52 has. Si distinguimos entre superficie regable y regada de olivar con otros cultivos tenemos una diferencia de 675,15 has para el olivar tradicional y 2.557,37 has en olivar intensivo.

Respecto de las concesiones otorgadas observamos que el olivar tradicional supone el 46,74% y el olivar intensivo el 53,26% respecto del total.

En relación al origen del agua tenemos que el empleo de aguas de escorrentía y residuales solo se utiliza en olivar tradicional, en el que por otra parte la utilización de aguas subterráneas y superficiales también se encuentra próxima al 50%. En cambio, el olivar intensivo presenta una mayor utilización de aguas superficiales, con el 92,06%, frente a las aguas subterráneas, que arrojan un valor de 7,94% respecto del total.

Con respecto a la tipología de riego este es mayoritariamente localizado en el momento actual con el 90,92 % de la superficie regada, seguido muy de lejos por el riego de superficie con un 7,17%, y finalmente con un residual uso del riego por aspersión con un 1,91%.

3.4.3. Otras fuentes de información.

Bajo este epígrafe englobamos los datos ofrecidos por el INE, IEA, ICRA y CES, que básicamente adquieren los mismos de las dos principales fuentes de información previamente analizadas. Se ha de señalar que, los datos recogidos en el ICRA se adquieren con otra metodología e incluyen a las parcelas con riegos deficitarios y/o riegos de emergencia. También se han considerado los datos arrojados por otros autores de reconocido prestigio que recogen los datos suministrados por las fuentes oficiales, realizan estimaciones, o utilizan como base la cartografía para inferir la superficie de olivar de riego.

3.4. Síntesis de Resultados.

Al compararse los datos de las distintas fuentes de información disponibles, así como los referidos a trabajos publicados de diferentes autores que reflejan con carácter histórico las diferencias entre los mismos se observa que hasta el año 1995 no empiezan a aparecer diferencias significativas, que se mantienen fluctuando, hasta el año 2011, cuando comienzan a mostrar cierta convergencia. Así por ejemplo en el año 1991, según el organismo de cuenca (CHG), Jaén contaba con 62.000 has de riego de olivar, y en 1996 con 156.000 has (Saura, J., 1998). Este mismo año, el estudio monográfico del olivar realizado por el Observatorio Económico de la Provincia de Jaén expresaba según datos facilitados por la Delegación Provincial de Jaén, de la Consejería de Agricultura y Pesca de la Junta de Andalucía, que la superficie de olivar de regadío en la provincia era de 111.726 has, (CES, 1997).

De otro lado, la Consejería de Agricultura y Pesca de la Junta de Andalucía, en la elaboración del "Inventario y Caracterización de los Riegos de Andalucía", ofrece en 1997 valores intermedios respecto de los datos recabados por el Ministerio de Agricultura y el organismo de cuenca, pero a partir de 1998 arroja valores superiores a los ofrecidos por el primero, (estando ausentes los datos del segundo al no realizar un desglose por límites administrativos). De otro lado, los datos ofrecidos por distintos autores reconocidos arrojan valores ligeramente superiores a los de los Anuarios de Estadística Agraria.

Para poner de relieve los resultados obtenidos, se han elaborado las tablas 3.6.a, y 3.6.b, en las que se aborda parte de la información en períodos quinquenales recopilada considerando los casos en los que tenemos distintos valores de datos y aplicando técnicas de estadística descriptiva, debido a que las variables presentan observaciones limitadas.

Tabla 3.6.a: Tasa de variación. Andalucía.

Período	AEA	CHG	ICRA	CAP	CES	Otras fuentes de información
1976-1980	72.627					
1981- 1985	81.937					
1986- 1990	96.361					
1991-1995	115.929 27,39%	91.000				1.094.000 1102,20%
1996-2000	160.466	229.627 43,10%	231.961 44,55%	195.330 21,73%		230.767 43,81%
2001-2005	247.666 7,59%	277.905 20,73%	422.212 83,42%			230.193
2006-2010	288.157 7,46%	409.808 52,83%	297.444 10,92%	268.151		467.638 74,39%
2011-2015	406.911	440.097 8,16%		986.957 142,55%		
2016-2019	464.237					

Tabla 3.6.b: Tasa de variación. Jaén.

Período	AEA	CHG	ICRA	CAP	CES	Otras fuentes de información
1976-1980	43.659					
1981- 1985	50.634				50.844 0,41%	50.844 0,41%
1986- 1990	57.625					56.029
1991-1995	67.540 24,34%	62.000 14,14%			74.577 37,29%	54.321
1996-2000	100.178	156.088 55,81%	157.800 57,52%	191.218 90,88%	105.081 4,89%	143.924 43,67%
2001-2005	150.149 620,17%	20.849	202.237 870,01%			156.057 648,51%
2006-2010	177.560		189.023 6,46%	261.140 47,07%		181.510 2,22%
2011-2015	239.097 66,11%			294.036 104,27%	143.943	270.000 87,57%
2016-2019	263.109	285.766 8,61%				

A partir de los resultados, se puede afirmar que a nivel de Andalucía encontramos más datos durante los períodos del 1991-2015, y a su vez encontramos mayores divergencias.

La mayor tasa de variación tiene lugar durante el período 1991-1995, con el 1102,20%, seguida del período 2006-2010 con el 74,39%. También podemos observar discrepancias significativas entre los datos ofrecidos por los AEA, (Anuarios de Estadística Agraria) y el organismo de cuenca, (CHG). que llegan a alcanzar valores máximos en torno al 3% durante el período 1996-2000. También se pone de relieve que los datos ofrecidos por el ICRA, la Consejería de Agricultura y Pesca y distintos autores suelen ofrecer datos convergentes respecto al organismo de cuenca, pero arrojando discrepancias significativas.

A nivel de la provincia de Jaén obtenemos más datos en un amplio margen, desde 1981 a 2019 entre los datos ofrecidos. La mayor tasa de variación tiene lugar durante el período 2001-2005. llegando hasta el 90,88%. y el período 2011-2015, que llega hasta el 140,25%. Al comparar las distintas fuentes de información los valores del organismo de cuenca también muestran generalmente, con excepciones, valores superiores a los ofrecidos por los AEA. La Consejería de Agricultura y Pesca y el ICRA también ofrecen discrepancias durante los mismos períodos considerados; 1996-2000, y 2006-2010. Al igual que ocurre en el ámbito autonómico, los datos encontrados en otras fuentes de información correspondientes a autores de prestigio también ofrecen generalmente valores superiores al de los AEA, encontrando la máxima discrepancia durante el quinquenio 2001-2005.

El panorama general encontrado pone de manifiesto que existe una gran divergencia y dispersión de los datos.

3.5. Conclusiones y Recomendaciones.

Se desprende del estudio realizado una falta de actualización de los datos recogidos pues en ocasiones la información existente se remite a fechas anteriores, los que nos lleva a determinar que no resultan válidos si queremos tomar decisiones acertadas. De igual forma se puede señalar que los organismos encargados de recabar información utilizan distintas metodologías, que además van modificando, y presentan una falta de uniformidad tanto en el tratamiento como en el desglose y publicación de los mismos, lo que arroja en numerosas ocasiones grandes divergencias que imposibilitan el conocimiento y la determinación con unos criterios básicos y generales de la superficie de riego del cultivo de olivar.

Se comprueba por orden de importancia que la principal fuente de información son los Anuarios de Estadística Agraria, y en segundo lugar la ofrecida por los Organismos de Cuenca, aunque arrojan discrepancias y diferencias significativas.

Se considera por tanto necesario la definición de una mejor y más clara estrategia de recogida de la información, con datos más actualizados, que posibilite determinar aspectos básicos como los usos, superficies, consumidores, precios, demandas, fuentes de agua, etc, siendo interesante así mismo el caracterizar los estudios a niveles más pequeños, por ejemplo, a nivel de municipio. En cualquier caso, con las precauciones precisas podemos afirmar que la superficie de olivar de riego en Andalucía se encuentra en torno a las 450.000 has, de las que más de la mitad se encuentran en la provincia de Jaén 250.000 has, lo que supone el 55,55%, en 2018.

También se hace necesaria una mayor transparencia, periodicidad y publicación de la información recogida, el diseño de una estrategia de complementariedad de las metodologías empleadas, y finalmente la facilitación de su acceso, difusión y publicación libre de estos datos.

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4. The sustainability of irrigation strategies in traditional olive orchads.

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Abstract: Olive trees are one of the few alternative crops available for farmers in arid environments. In many of these regions, surface irrigation is increasing. The aim of this study was to estimate the pattern of water soil reserves through the season considering different climatic scenarios, limitations in irrigation scheduling, and irrigation systems. Modelling was performed with the most common type of soil, and a tree density of 10 x 10 m was used. Three different climatic scenarios were estimated using eighteen agroclimatic stations along the zone (Jaen, Spain). In these climatic scenarios, different irrigation strategies were considered. First, the percentages of maximum flow available (100%, 50%, and 33%) was used. In each of these flows, the days available for irrigation was considered: daily irrigation (IDD), 20 days per month (ID20), and no irrigation during August (RDI). The results suggest that a 33% flow strategy, the most common in the surveyed area, would produce the greatest water stress period in the most sensitive phenological stage. However, 100%, in all scenarios, and 50% (only IDD and RDI) would obtain the best water status. According to the estimated water applied, 50% was the most advisable strategy. However, in a minimum rainfall scenario, water needs could be excessive.

Keywords: climatic change; pit hardening; water stress; water availability.

Abbreviations:

- S1-IDD: Strategy 1—Irrigation every day of the month;
- S2-ID20: Strategy 2—Irrigation 20 days of the month;
- S3-RDI: Strategy 3—Regulated deficit irrigation;
- AWMR: Applied water at maximum rainfall (mm);
- TrMR: Time of irrigation at maximum rainfall (hours);
- WRMR: Water reserve at maximum rainfall (mm);
- AWAR: Applied water at average rainfall (mm);
- TrAR: Time of irrigation at average rainfall (hours);
- WRAR: Water reserve at average rainfall (mm);
- AWmR: Applied water at minimum rainfall (mm);
- TrmR: Time of irrigation at minimum rainfall (hours);
- WRmR: Water reserve at minimum rainfall (mm).

4.1. Introduction.

There are around 11.5 million hectares of olive groves (Olea europaea L., Oleaceae) around the world, which is approximately 1% of the world's agricultural area [1], suggesting that this is the most important fruit crop. From the 1990s, there has been an increase in the coverage of olive orchards globally; most of these new surfaces are irrigated and denser orchards. The impact of new olive orchard irrigation implies an increase in production and changes in farming methods that will have socioeconomic and environmental repercussions and shows that the sector will experience an increase in competitiveness at an international level. Olive growing is present in 58 countries throughout five continents. The largest producer is Europe (55.43%), followed by Africa (30.53%), and then Asia (12.11%), with a very localized production [1-2]. However, traditional olive farms are still the most common production system. Moreover, these traditional, low-density olive orchards are the most important in arid agricultural zones, commonly associated with a low availability of water and poor soils. Spain is the world's leading producer of olive oil and is the country with the largest available surface [2], which results in a great diversity in farming systems. Andalusia, in southern Spain, has 1,500,290 ha of olive orchards, representing 69.96% of rainfed olive groves and 30.04% of irrigated olive groves. Jaén, located in the northeast of the autonomous community of Andalusia, is the Spanish province that dedicates the greatest surface to this species, with 582,427 hectares, of which 249,888 hectares are irrigated [3]. In contrast to other parts of the world, most of the irrigated area in this zone is in low-density traditional olive orchards with common planting frames of 9 to 12 meters (88% of irrigated olive orchards versus 12% of intensive systems) [4].

Water sustainability is associated with two main conditions. On the one hand, the most traditional involves conservation of the quality and quantity of water resources in the long term [5-6]. However, in recent years, economic considerations have also been suggested. The undesirable effects of irrigation on climate change can be reduced by reducing its impacts on the environment, caused by poorly managed irrigation, which leads to drainage problems, excessive salinity, and the unsustainable overexploitation of resources [5]. The sustainability of an agricultural system supposes that people are fixed in rural areas. In this way, sustainable agricultural managements will apply when sufficient farm economic revenues are obtained [7]. Climate change forecasts anticipate an increase in temperature and lower rainfall and greater variability, which may affect the most sensitive physiological phases of crops, such as flowering and ripening [8]. Then, irrigation water needs would increase and traditional rainfed olives orchards, which nowadays have an acceptable yield, could strongly reduce their profits and would be given up. Irrigation of traditional orchards is a very good example. Expected increases in yield could enhance sustainable management in traditional rainfed olive orchards, which is commonly limited because of the low profits. Positive aspects of the transformation from rainfed to irrigated land are perceptions by society of the sustainability of the agricultural systems, as well as increasing the income for farmers.

Olive trees are a traditional rainfed fruit crop, one of the most resistant to water-stress conditions. Fruits and oil features in these conditions are very variable between cultivars [9] and ripening stages [10]. In general, water-stress conditions enhance total phenol levels in oil; however, recently, some authors have suggested a parabolic response [11]. All these suppose greater variations in the final food products in rainfed olives as opposed to those from irrigated orchards. Moreover, rainfed conditions are associated with less productive farms with limited profitability because of the small crown growth and alternate bearing; these farming systems are strongly dependent on rainfall [12]. Production functions suggest a high productivity of irrigation, resulting in a large increase in yield with a small increase in crop evapotranspiration [13]. However, studies in low-density olive orchards have not presented this clear response [14]. Traditional low-density olive orchards are located in zones with a low availability of water resources. Thus, increasing the irrigated surface of an agricultural system may not be a sustainable strategy. In addition to water scarcity, these zones commonly have problems of water availability throughout the season (with a short irrigation season or short window of irrigation). This is an additional problem in irrigation scheduling and the design of irrigation systems. Although olive trees are a drought-resistant species, not all phenological stages are equally resistant, and combinations of the duration and level of water stress are important [15]. The flowering, fruit set, and oil accumulation periods are the most sensitive to water stress conditions [16]. On the other hand, relatively severe levels of water stress during the pit hardening phase did not appear to reduce the final yield [13]. Therefore, reduced irrigation could be considered here; although, at least, the moment when these water stress conditions will transpire should be estimated. On the other hand, traditional olive orchards, even accounting for the potential increase in yield, generally have a narrow capacity for irrigation investment. Thus, irrigation systems are commonly very limited in terms of the pumping capacity and flows of the water applied. These could be an important constraint in the irrigation scheduling of olive orchards.

The aim of this study was to estimate the water soil reserves over the season in a traditional low-density olive orchard, considering several limitations at farm level and possible scenarios in rainfall behavior. It is, therefore, a question of providing technician at the preliminary project or preliminary study level with a methodology that would enable determination of the best irrigation strategy with criteria of efficiency and consideration of the phenology of the crop to establish the application flows and irrigation calendar for irrigating the entire surface at the same time or selection among the most common types of sectorization carried out (due to the impossibility of instantaneous irrigation of the entire surface simultaneously). Therefore, the results will provide a holistic view of the sustainability of irrigation in this agricultural system. Climatic conditions of the province of Jaen (Spain) have been considered, because this is the most important traditional olive growing zone in the world. In order to include the most common limitation for irrigation scheduling, out of the amount of water, considerations about the time of irrigation available throughout the season and organization of the irritation system have also been included.

4.2. Materials and Methods.

4.2.1. Study Area.

The study area included the province of Jaen (Spain), which covers an area of 13,489 km2, in which olives are the most important fruit crop on the agricultural surface (582,427 hectares), of which 249,888 hectares are irrigated (around 43%). This zone is the world's largest producer of olives and oil, with more than 60 million olive trees; the average annual production in the last decade was 2,214,021 tons of olives and 480,025 tons of olive oil [3-17], which means that this crop is the main socioeconomic engine in the province. The irrigation period in the province of Jaen is from March to September.

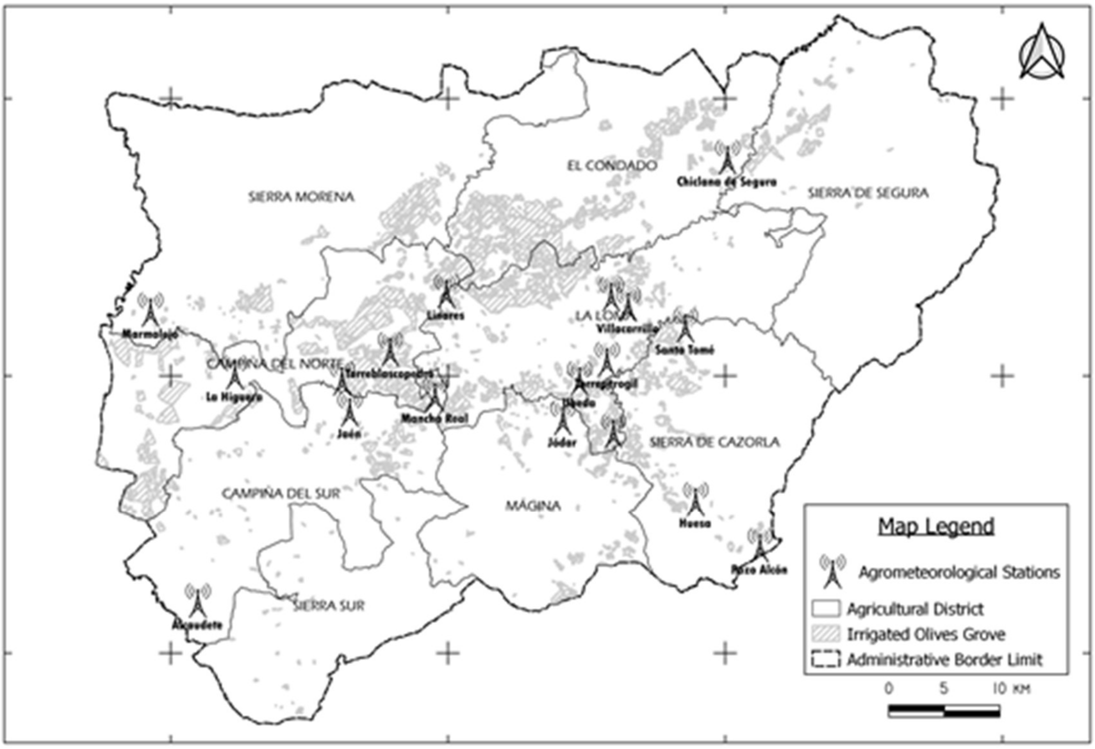

Figure 4.1. Study area with indication of irrigated olive groves and location of agroclimatic stations.

4.2.2. Characteristics of the irrigation installation.

Several different systems are present in contemporary olive zones. From the 1990s, the density of olive orchards has been increasing, and sections of the traditional, dry, and low-density systems have been substituted for irrigated super-high-density orchards [18]. However, low-density olive orchards are still the most important in traditional surface olive groves, with planting frames of 9 to 12 meters and densities between 80 and 120 plants/ha [19-20]. The autonomous legal government have established that the average plantation density in the province of Jaen is 117 plants/ha [21]. Most commonly (around 62.82%), olive plantations in this zone have an average planting frame greater than 10x10 meters. Some of these traditional orchards have changed from non-irrigated to irrigated conditions. The most common irrigation system uses two drips per tree, allowing a flow of 16 L h-1 per plant [22-23]. On the other hand, water availability is very limiting and there are often serious restrictions in the amount and times of irrigation [24]. To maximize the irrigated surface area, the maximum daily irrigation is divided by between 2 and 3 [25]. Regarding the type of sectorization used, the researchers in [26] they carried out a survey in the irrigation communities of the province, showing that more than 90% of the facilities had divisions in three sectors. Then, the amount of available water has been divided between one, two, or three sections in order to irrigate the whole orchard to different degrees (hereafter, 100%, 50%, or 33%, respectively).

The typical agricultural plots comprise mature olive groves (≥30 years old) of the cultivar known locally as "*Picual*" (Olea europaea L. var. Rostrata Clem), with strong resilience and open bearing, a high and fruitful productive capacity, with one to four trunks per tree, good floral induction and little alternate bearing, self-fertile, and medium flowering. The standard cultivation practice is in traditional tillage systems which allows mechanization depending on the slope and orography of the land, and in which soil management operations can be carried out, such as the distribution of fertilizer and application of phytosanitary products, and the elimination of pruning and weeding, with the aim of making the maximum amount of water available for the desired crop. The common distance between trees is 10*10 m, which results in a density of 100 olive trees per hectare, with a drip irrigation system which basically consists of elevation from a water catchment to a water tank and subsequent pumping it back to the olive farm, with the installation of a network of primary, secondary, and tertiary drip pipes that end in two self-compensating drippers per tree, supplying 8 liters/hour of instantaneous water flow (0.44 l/s/ha). With the irrigation system proposed as a case study, irrigation scheduling was limited based on the maximum number of hours available for irrigation (i.e., 20 hours per day). Thus, the maximum flow to be applied depended on the realization of sectorization into one, two, or three sectors, allowing the use of the available water 100%, 50%, or 33% of the time, respectively (Figure 4.3). This means limiting the irrigation capacity of the olive orchards to 3.2 mm day-1 (100%), 1.6 mm day-1 (50%), or 1.1 mm day-1 (33%). For each of these strategies, the available reserves in the soil were characterized on a monthly basis. In the irrigation schedules, it was considered that at the beginning of the agricultural year (October), a reserve of 10 mm (an amount very close to the reality under natural conditions in the area studied) was used. The application efficiency of the irrigation system used, corresponding to a localized drip irrigation system, was considered to be 95%.

4.2.3. Climatic Variables.

4.2.3.1. Precipitation.

The averages of all the stations presented very similar annual rainfall patterns, with a wet period between September and May, maximums in November and March, and a very dry period during late spring and early summer. The extreme precipitation values and their trends have also been obtained, in which we can observe that, generally, the range between extreme precipitation values was greater in wet years than in dry years; Figure 4.2 shows the variability of the data throughout the average years (a) and the maximum and minimum values found.

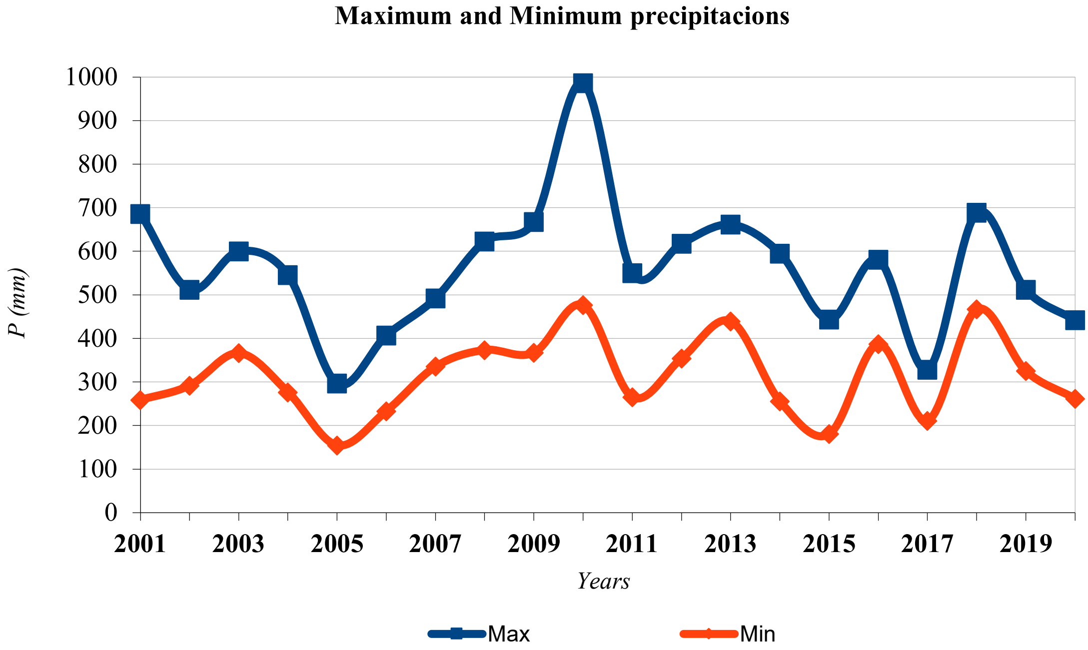

Figure 4.2. Maximum and minimum precipitation.

Figure 4.2 shows that most years' maximum rainfall was below 600 mm, whereas for minimum rainfall, most years were below 300 mm, although this shows a trend of significantly increasing from 2016 onwards. Data for these 18 agroclimatic station were used for obtaining the scenarios of maximum, average, and minimum rainfall.

4.2.3.2. Evapotranspiration.

Regarding the reference evapotranspiration (ETo), there was interannual variation in the values collected, with a greater range during the spring–summer months and less during the autumn–winter period.

In the case study, because it concerned a single crop and was calculated with meteorological data for each of the agroclimatic seasons, normal values were adopted.

This hypothesis was confirmed by determining the probability distribution of the monthly evapotranspiration values, which had a lower standard deviation in the results (Figure 4.3). Average ETo data were used in the estimation of water soil reserve.

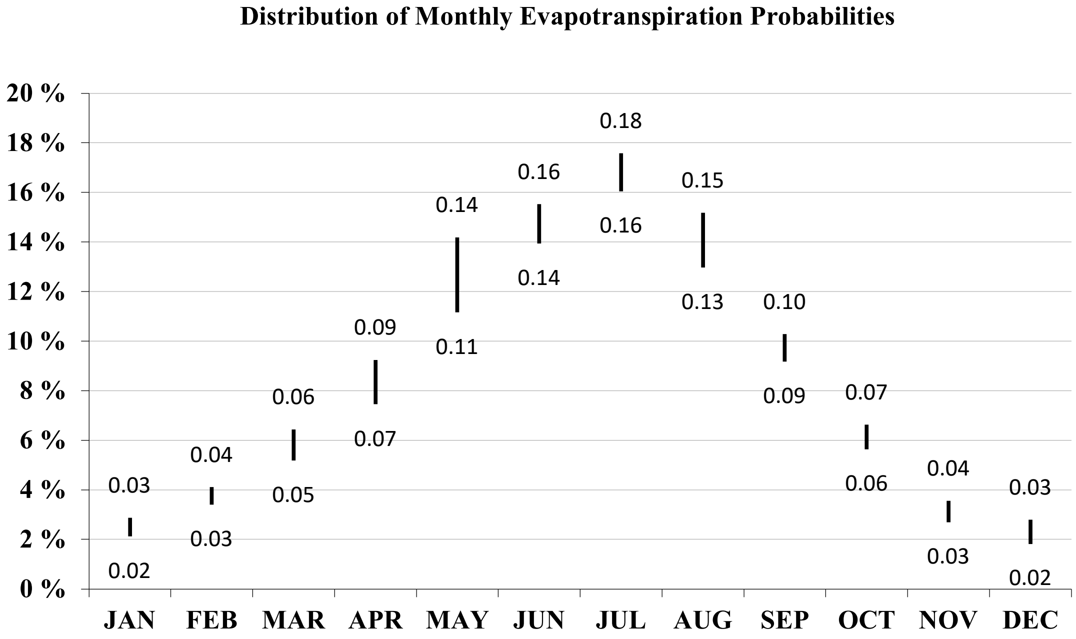

Figure 4.3. Probability distribution of evapotranspiration, with extreme values.

In this way, agroclimatic stations were classified in relation to the rainfall variable according to the results, and three scenarios based on real rainfall data across the whole historical series were considered:

- Scenario 1: When the mean monthly rainfall is above the average, the median of the maximum rainfall is chosen as data, and considering years with the highest rainfall as those exceeding 581 mm;
- Scenario 2: Average monthly rainfall;
- Scenario 3: When the average monthly rainfall is below the average, the median of the minimum rainfall is chosen as the data, and considering the years with the lowest rainfall to be those below 292 mm.

4.2.4. Reference constants: soil type, root depth, canopy cover, and degree of crop development.

The determination of the irrigation needs and the instigation of water stress were established following the water balance method, so that the consumed water was considered to be the sum of the irrigation water and rainfall [31]. In this balance, the useful or available water in the soil for the plant was between the upper and lower limits.

In the case study, the type of soil chosen was loam–clay (being the most common in the area), with the following characteristics: wilting point (θWP) (cm3/cm3) 0.17; field capacity (θFC) (cm3/cm3) 0.36; soil bulk density (γb) (cm3/cm3) 1.33 [32]. The humidity available for the plant was estimated using a 75% allowable depletion level (ADL), which is the standard recommended level [33]. A useful root depth of 1.0 m was established according to various previous studies [13-15]. Crop evapotranspiration (ETc.) was estimated according to the methodology proposed by Allen et. al. [34]:

$$ET_c = ET_o * K_c * K_r \qquad (1)$$

Where: ET_o is the reference crop evapotranspiration, K_c is the dimensionless crop coefficient, and K_r is a dimensionless evaporation reduction coefficient.

The Kc values used (Table 4.1) are those suggested by Pastor et al. [23]. In the case study, it was considered that the value of the reduction coefficient Kr took a value of 1, because the crop shades more than 50–60% of the soil surface, according to Castel and Fereres [35]. Regarding the phenology of the crop in the zone, the average date for full bloom took place in May [36], and pit hardening was dated as beginning in July.

Table 4.1. Monthly variation of the Kc coefficient.

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Kc	0.5	0.5	0.65	0.65	0.65	0.6	0.6	0.6	0.6	0.65	0.65	0.5

4.2.5. Calculation program.

For the calculation of the irrigation schedule and flow, the water balance methodology was used, as stated in the FAO guideline No. 56 [34]. The program used is an adaptation of IFAPA's "*Water Needs for Olive Groves*" calculation and determination program [37], which is open access, requires prior registration, and has been published online since 2015 (https://www.juntadeandalucia.es/agriculturaypesca/ifapa/servifapa/recomendador-olivar), in which the aforementioned variables were introduced, with the average data for the rainiest and driest seasons of the 18 agroclimatic stations.

4.2.6. Irrigation strategies.

All scenarios of water needs (100%, 50%, and 33%), in three different climatic scenarios (maximum, average, and minimum rainfall) considered three irrigation strategies (Figure 4.4), selected from the most common in the study area:

- Strategy 1 (IDD): Irrigation every day of the month [22]. This simulation is intended to reflect irrigation installations with no time or water availability constraints during the irrigation period (March–September), where water use is always operating at maximum efficiency;

- Strategy 2 (ID20): Irrigation 20 days per month. These are installations with temporal or water availability limitations (approximately 30%). This strategy is similar to IDD, but leaving weekends free, similar to a conventional working calendar [38]. Given the organization of irrigation systems, it may be interesting to evaluate irrigation schedules with time constraints on irrigation due to working conditions (e.g., excluding weekends) or energy conditions (e.g., different electricity prices depending on the day of the week). From this perspective, irrigation schedules with the limitation of a maximum system use of 20 days per month are analyzed;
- Strategy 3 (RDI): Regulated deficit irrigation. These installations do not have water available for a specific period of time, which coincides with the summer shutdown period of olive groves. There are different studies of deficit irrigation strategies in different crops [39], as well as for olives, in which important irrigation cuts are proposed, both in traditional olive groves [40] and in intensive or super-intensive olive groves [13-41]. In the study area, in practice, these cuts are established in the period between July and August. The application of irrigation under moderate water stress conditions produces an increase in both olive oil quality and accumulation rate [42-43]. In this particular case study, the month of August was established as without irrigation.

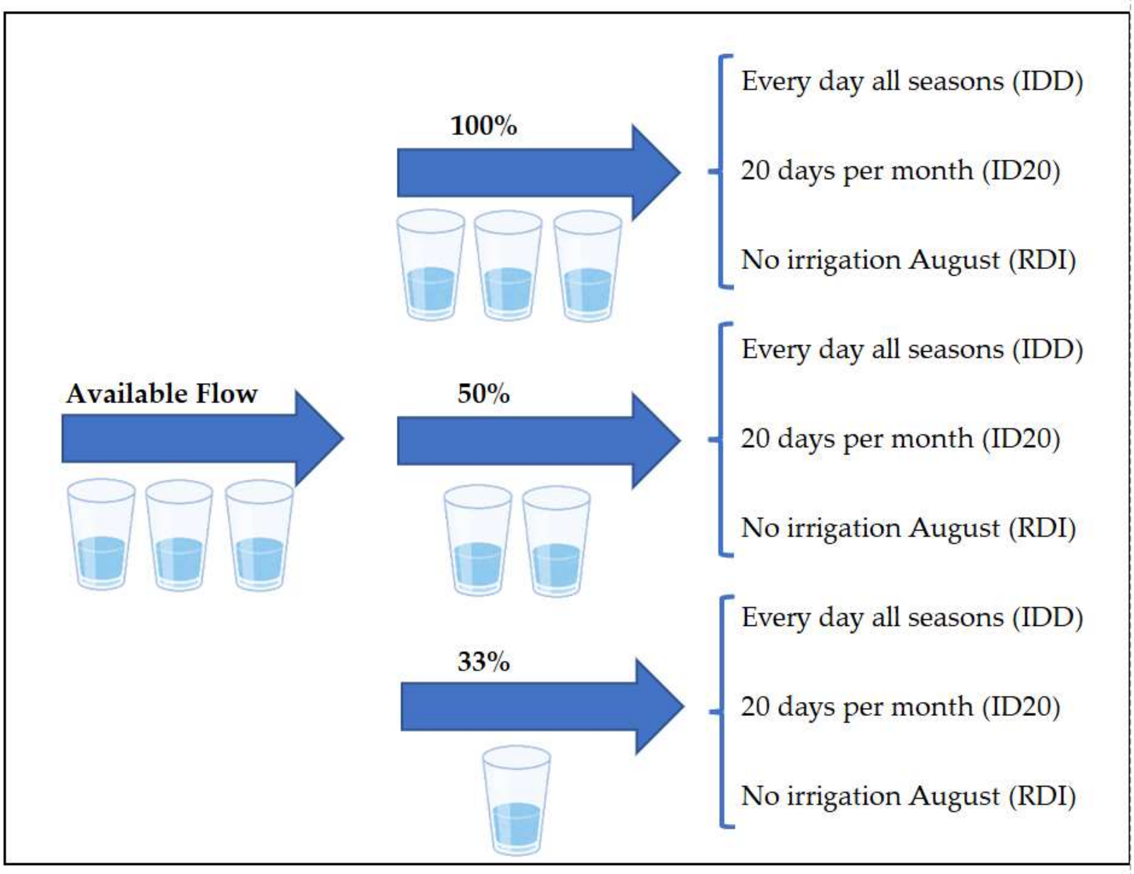

Figure 4.4. Summary of the irrigation scenarios considered in the modelling. These scenarios were also evaluated in three different climatic conditions.

4.3. Results.

The results obtained are presented in Figure 4.5.

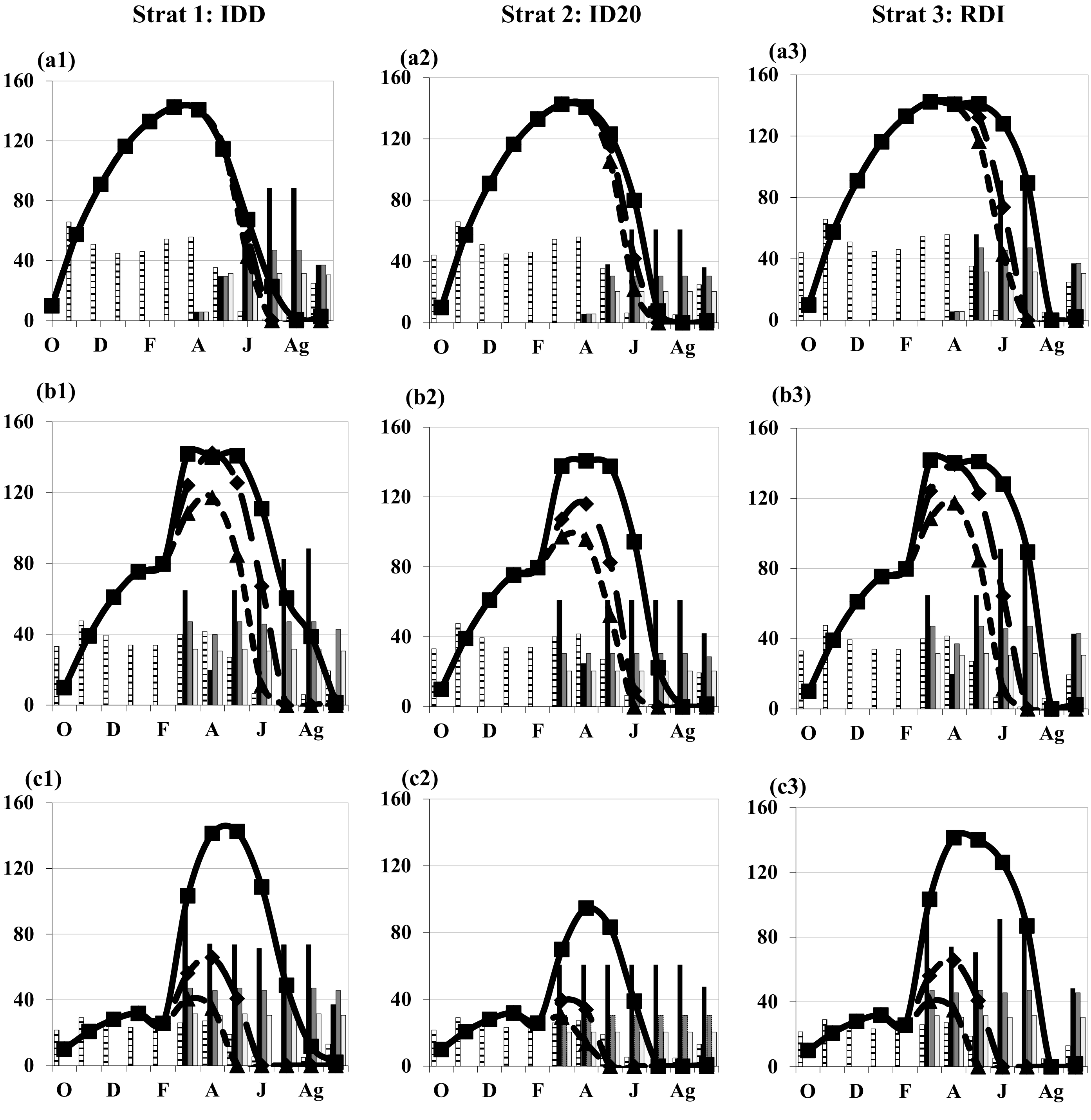

Figure 4.5. Patterns of the soil water reserves in three strategies: daily irrigation (a1, b1, and c1), irrigation 20 days per month (a2, b2, and c2), and no irrigation in August (a3, b3, and c3), under maximum (a1,2,3), average (b1,2,3), and minimum rainfall conditions (c1,2,3). Solid line, 1-sector strategy; long dashed line, 2-sector strategy; dashed line, 3-sector strategy. Bars with a square pattern represent effective rainfall; solid bars represent irrigation in the 1-sector strategy; clear bars represent irrigation in the 2-sector strategy;

white bars represent irrigation in the 3-sector strategy. The horizontal X axis (or abscissa axis) represents variations in the soil water reserves during the period of the irrigation campaign. The vertical Y axis (or ordinate axis) represents rainfall and irrigation.

Table 4.2. Summary of applied water (AW, mm), seasonal time of irrigation (TI, hours), and water reserves (WR, mm) in the three rainfall conditions (rainy, average, and dry season), with the three irrigation schedules (daily, 20 days per month, and no irrigation in August (RDI)) in the 3 flow strategies.

		IDD			**ID20**			**RDI**		
		100%	**50%**	**33%**	**100%**	**50%**	**33%**	**100%**	**50%**	**33%**
Rain	**AW**[1]	305.9	212.0	161.2	262.2	157.7	107.4	284.1	182.6	129.7
	TI [2]	2013	2790	3182	1725	2075	2119	1869	2403	2560
	WR[3]	899.1	863.7	850.6	902.7	848.3	818.1	1051.8	899.1	850.6
Aver	**AW**[4]	397.3	316.7	217.5	370.5	210.9	142.3	377.7	266.8	186.0
	TI [5]	2614	4168	4293	2438	2775	2809	2485	3510	3671
	WR[6]	900.1	727.0	587.6	800.1	580.5	511.1	908.2	718.4	587.6
Dry	**AW**[7]	497.5	325.3	217.5	412.3	212.8	142.3	472.9	278.2	186.0
	TI [8]	3273	4280	4293	2713	2800	2809	3111	3660	3671
	WR[9]	674.6	279.0	191.9	403.9	189.6	159.4	715.6	279.0	191.9

4.3.1. Strategy 1: Deficit irrigation schedule from March to September, irrigation every day of the month (IDD).

Figure 4.5(a1-c1) shows the pattern of soil water reserve considering three different scenarios of rainfall and three flows. In rainy seasons (Figure 4.5a1), water reserves were depleted from July to August in the 50% strategy, and from July to September in the 33% strategy. No water stress was estimated in the 100% strategy. The amount of applied water also varied between these strategies (Table 4.2): 33% used 161.2 mm, whereas 100% consumed 305.09 mm. The 50% strategy presented an intermediate amount: 212 mm. The time of irrigation also changed but in a contrasting manner: from 3182 hours per year (33%) to 2013 hours per year in 100%, with an intermediate value of 2790 irrigation hours in the 50% regime.

For the average rainfall situation (Figure 4.5b1), there was no water stress period when 100% was used. In 50% and 33% irrigations, the depletion of the soil water reserves occurred at the same time (July), although in the first case, it lasted two months, and in the second case, it extended until the end of the irrigation season. As for the amount of water applied, the results were 397.3 mm for 100%, 316.7 mm for 50%, and 217.5 mm for 33%. Regarding the irrigation time, the results were higher as the flows increased; thus, for 100% it was 2614 hours, for 50% it was 4168 hours, and for 33% it was 4293 hours.

Finally, in the most limiting season (Figure 4.5c1), i.e., the minimum rainfall scenario, no water stress period was estimated for 100%, but in the other scenarios, these periods increased. The 50% strategy would present a period of water stress from June to September, whereas the 33% strategy would present even greater stress, with soil water depleted from May to September. Water consumption would clearly increase (Table 4.2): in the 100%, it would be 497.5 mm; in the 50% strategy, it would be 325.3 mm; and in the 33% strategy, it would be 217.5 mm. Seasonal irrigation time would also increase in all strategies: 3273 hours in 100%, and even more time in the 50% (4280 hours) and 33% (4293 hours) regimes.

4.3.2. Strategy 2: Deficit irrigation schedule from March to September, irrigation in 20 days of the month (ID20).

Figure 4.5(a2-c2) shows results for this scheduling strategy considering three rainfall scenarios. The maximum rainfall scenario (Figure 4.5a2) presented a water stress period in all strategies and flows. In the 100% strategy, water stress was estimated only in August. However, in the 50% and 33% strategies, these periods were longer in both, i.e., from July to September. The amount of applied water changed from 262.2 mm in the 100% scheme to 107.4 mm in the 33% scheme, which represents a considerable reduction of more than 50%. (Table 4.2). The 50% strategy was intermediate, with an estimated amount of applied water of 157.7 mm. The irrigation time was maximized in the 33% strategy, at 2119 hours per season, and minimized in the 100% strategy (1725 hours). The 50% strategy was intermediate, but closer to the maximum value, requiring 2075 hours.

The average rainfall season presented the same results as the rainy season regarding the period of water stress (Figure 4.5b2). However, the reduction in rainfall of an average season in comparison to a rainy season increased the applied water by around 40% (370.5 mm in the 100% flow strategy, to 210.9 mm in the 50% strategy, and to 142.3 mm in the 33% strategy; Table 4.2). The increase in the irrigation time was smaller between the rainy and average rainfall seasons (around 30%), with a maximum (2809 hours) in the 33% strategy and minimum 2438 hours in the 100% strategy (the 50% strategy was estimated at 2775 hours).

Finally, the minimum rainfall scenario clearly changed the results in comparison with the two presented above (Figure 4.5c2). All flow strategies presented water stress periods; for the 100% strategy it was only from July to August, but for the 50% and 33% strategies, it was from May to September. This decrease in rainfall would increase water consumption in all flow schemes, with maximum values in the 100% strategy (412.3 mm) and minimum of 33% (142.3 mm), with an intermediate value in 50% (212.8 mm). In addition, time of irrigation also increased until 2809 hours in 33%, very near to 50% strategy (2800 hours), with minimum values in 100% (2713 hours).

4.3.3. Strategy 3: Deficit irrigation schedule from March to September, with controlled irrigation in August (RDI).

Figure 4.5(a3-c3) shows data when the strategy of no irrigation during August is considered. During the rainy season (Figure 4.5a3), all flow strategies presented a water stress period. In the 100% scheme, water stress was estimated to only occur in August, but in the other two, the period was wider: from July to September in the 33% strategy but from July to August in the 50% strategy. In such conditions, the most water was applied in the 100% strategy with 284.1 mm and minimum in the 33% strategy 129.7 mm, with an intermediate value in the 50% strategy with 182.6 mm (Table 4.2). The times of irrigation were estimated to be 1869 hours (100%), 2403 hours (50%), and 2560 hours (33%).

In the average rainy season (Figure 4.5b3), the stress period was longer in the 33% strategy (three months), than in the 50% (2 months), and 100% strategies (1 month); however, in the 100% regime, it occurred during the month of August, whereas in the 50% and 33% strategies, it began in July. The overall results were decreases in flows, decreases in water applied, and increases in irrigation time. The 100% strategy presented an applied water of 377.8 mm, and the 50% and 33% strategies were 266.8 mm and 186 mm, respectively. On the other hand, the irrigation time varied from 2485 hours (100%) to 3671 hours (33%), presenting an intermediate value of 3510 hours (50%).

Finally, under minimum rainfall conditions (Figure 4.5c3), the periods of water stress increased in all strategies. These were from June to September in the 50% strategy and from May to September in the 33% strategy. Only in the 100% strategy did the water stress period not increase, and was estimated to occur only during the month of August. The amount of applied water clearly increased: with 472.9 mm in the 100% strategy, 278.2 mm in the 50% strategy, and 186 mm in the 33% strategy. This level of applied water produced an increase in irrigation time of 3111 hours in the 100% strategy, 3660 hours in the 50% strategy, and 3671 hours in the 33% strategy.

4.4. Discussion.

Results of the different scenarios presented a wide range of water consumption and water stress periods, which could affect the profits for olive farms. Farmers in most of the considered scenarios would manage deficit irrigation scheduling because of the considerable limitations in the availability of water, in terms of application time and amount (Figure 4.5). The selection of an irrigation strategy has to mainly consider two factors: when this water stress period would occur, and the amount of applied water used [44]. Expected yields would be greatly changed according to the timing of these water stress periods. The earliest water stress was estimated in May for the minimum rainfall scenario in the 33% strategy in all irrigation scheduling (Figure 4.5), and in the 50% strategy when ID20 scheduling was modelled (Figure 4.5 c2). May is the standard date of full bloom in this zone. Several studies have described this phenological period as being the most drought-sensitive in olives [13-45-46-47]. These conditions are very uncommon in the Mediterranean basin, and for this reason, olive is generally, a rainfed fruit crop, although climate change could increase the number of seasons when this occurs [48]. Therefore, the 33% strategy is the least sustainable because water resources would be wasted in the most limiting rainfall scenarios, and even small differences with unirrigated conditions would be expected.

Several considered scenarios could delay water stress period after full bloom and thus avoid the greatest reduction in yield. This is the case of the minimum rainfall conditions in the 50% strategy with daily irrigation and RDI scheduling (Figures 4.5c1 and 4.5c3). The long pit hardening period is considered to be the most drought-resistant period in olive trees [49-50]. It is common to suggest 49–56 days after full flowering as the most likely date for the onset of this period [51] which, for the study area, could be estimated to start around the beginning of July. Then, in June, water stress likely occurs during endocarp growth. In this phenological stage, yield reductions have been estimated at around 20% in moderate water stress levels [41-52]. However, severe water stress levels could even affect the next season's yield [53-54-55]. Therefore, such strategies could be suitable if they were to ensure a considerable reduction in the amount of water applied, and olive farmers could assume this significant reduction in yield. A period of water stress after pit hardening, likely around July in this zone, would reduce the effect on yield. Severe water stress levels in mid-summer did not significantly affect the yield in several other irrigation studies, although the trends were similar to a previous investigating which presented a yield reduction of 20%. However, these results were obtained in denser olive orchards; lower levels of water stress would be expected in traditional orchards. In moderate water stress conditions, yield reductions would be almost null, even more if autumn rainfall is expected before harvest [13-53]. Moreover, oil accumulation may not be affected by water stress during this period [56]. Although other studies suggest that, before harvest, oil accumulation could be reduced due to moderate water stress [55], such conditions could be reduced for autumn rains. Thus, all irrigation scheduling in the 100% scenario would be suitable, as would the 50% scenario if no minimum rainfall conditions occurred. This discussion is focused on olives destined for the oil mill because they can recover with the autumn rains, but not for table olives, because the size of the fruit is very sensitive to water stress and is very important in this method of production [15]. Finally, the quality of oil would be also affected and would permit a differential product, increasing antioxidant products [11].

Water availability changes strongly between olive orchards, and even between seasons, because severe restrictions could be applied during drought periods. In Spain, the maximum amount of seasonal irrigation is limiting, and the common availability of water in olive orchards is 150 mm [57]. This amount of water applied is much smaller than that estimated in all 100% and 50% scenarios (Table 4.2). This result suggests that the sustainability of irrigation in traditional olive farms is very limiting if additional precise irrigation schedules are not considered. In these conditions of very low water availability, the risk of negligent profit improvements in comparison to olive groves without irrigation is very likely. In relation to this, no significant differences have been found in a traditional "Cornicabra" olive grove at a distance of 12 * 12 m with more restrictive water quantities than in the present study (75 mm) and reaching significantly higher water stress levels than irrigation with 100% ETc. during stone hardening [14]. Thus, this amount of water could be used to secure optimum or near-optimum water status in the most limiting phenological stage (i.e., full bloom), and not for a sustainable irrigation deficit. In such conditions, accurate determination of the water status is vital [58].

4.5. Conclusions.

Irrigation sustainability in traditional olive orchards has to consider several aspects to ensure an efficient water management regime. Conservation of water resources is the most important factor, although the use of water to improve olive farmers' profits should also be considered. The current study demonstrates that the most common irrigation strategy in one of the most important traditional olive production zones around the world is not suitable. The 33% strategy presented the longest period of water stress and, most importantly, it occurred in the most critical phenological stages, when there was minimum rainfall. Thus, adapting the currently available water resources to a sustainable deficit irrigation in which the reduced rainfall scenario could strongly reduce yield is a waste of water and waste of farmers' money. This suggests that traditional olives orchards have to change to 100% or 50% strategies. According to the lowest water needs, 50% is likely the most interesting strategy. In this scenario, water stress would be delayed until non-critical phenological stages. However, these strategies suppose a great increase in applied water, which may not be sustainable, mainly in the minimum rainfall scenario. In these conditions, the 50% strategies could be considered an accurate, concentrated irrigation scheduled which at least ensures near-optimum conditions in the most sensitive phenological stages.

4.6. References.

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5. Estimation of the Water Reserve in the Soil Using GIS and Its Application in Irrigated Olive Groves in Jaen, (Spain).

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Abstract: Soil water reserves are very important for irrigation scheduling in arid and semiarid conditions. In these regions, irrigated olive groves could save water and improve water resource management if the spatial and temporal patterns of water reserve were known. In this work, a large region characterized by olive monoculture located in Jaén, Spain was studied, as well as its water requirements and the evolution of the water reserve in the soil according to the time of year by using public data sources. In this way, climatic data, NDVI monthly mean, soil type, physicochemical and hydrological properties of the soil have been integrated in GIS by means of easy-to-use techniques. The results obtained from both the water balance and the evolution of water in the soil show that in the region studied, it is not advisable to manage a single irrigation schedule, as is currently the case, and that it is necessary to implement different irrigation times and strategies depending on the location of the plot. These results can serve as a basis for the design of specific irrigation schedules on daily, hourly or real-time time scales depending on the availability of data and the degree of precision sought.

Keywords: agriculture, monoculture, olive groves, irrigation, water balance, water reserve, water efficiency, GIS, scheduling.

5.1. Introduction.

According to World Bank data, agriculture is one of the main economic sectors in the world, with an aggregate value of more than USD 3.68 trillion [1]. However, its importance goes far beyond this. Sustainable agriculture generates income; can help overcome many of the challenges facing humanity, such as the fight against hunger or biodiversity conservation; and can guarantee production, since the demand for food and agricultural products will continue to grow over the next decade, along with their productivity, trade and sustainable use [2].

On the other hand, the climate change outlook predicts an increase in average temperatures by 4 °C, and a decrease in precipitation in arid and semiarid midlatitude regions [3]. This increase in temperature would produce an increase in evapotranspiration and a change in flowering dates that could impact irrigation strategies and olive cultivar variety choice [4]

Irrigation is very important in arid or semiarid environments where seasonal drought limits agricultural production [5]. Irrigated crops represent approximately 21% of the total area of cultivated land worldwide (approximately 306.7 million hectares) and a production of approximately 40% of the world's food [3]. It is estimated that 69% of water is used by irrigated agriculture globally [6]. From the point of view of productivity, it is estimated that in average terms, an irrigated hectare produces six times more than a rainfed one [5]. In the case of Spain, irrigated agriculture occupies approximately 20% of the total cultivated area and is responsible for 55% of the final agricultural production (FAP) [7].

Olive groves are one of the major permanent crops worldwide. The olive surface represents 25% of the total permanent cultivated area worldwide, with 11.6 million hectares distributed in 63 countries around the five continents and extending over slightly more than 0.25% of the total cultivated land area. Of the total global olive grove area, 70% is distributed in rainfed cultivation, while the remaining 30% is irrigated [8].

Worldwide, one of the most characteristic regions of olive monoculture is the province of Jaen, in southern Spain. It is the world's largest producer of olive oil, so a large part of Jaen's economy is based on olive monoculture (in fact, the olive grove plantations occupy the majority of the territory) [9]. It represents more than 25% of the total olive grove area in Spain and 42% of Andalusia's total cultivated land. Its production on average is approximately 50% of the Spanish total of olive oils and more than 20% of the world's total [10]. This territory has an area of approximately 13,489 km2, so due to both its size and biodiversity, it presents different agronomic conditions. The olive plantation surface in this location is around 5.93 × 105 hectares, of which 2.88 × 105 are rainfed and 3.04 × 105 are irrigated [11]. Most of the irrigated area is arranged in broad frames of traditional cultivation (88% of the irrigated olive grove area versus 12% of intensive olive groves) [12].

This study area is located in the arid and semiarid zones of the Mediterranean region, so water availability is a major constraint in crop production due to low rainfall and long periods of summer drought [13]. Although the olive crop shows good adaptation to drought, it responds very favorably to irrigation [14].

The incorporation of irrigation practices in the olive grove has allowed for the transformation of a rainfed crop with low profitability to a high-value crop that increases the farmer's income, making it possible to obtain the maximum economic benefit and employment of labor per unit volume of water applied. Furthermore, in the area studied, the productivity of irrigation water used in olive cultivation is higher in socioeconomic terms than that of most traditional irrigated crops [15,16].

Water availability for olive groves is commonly below irrigation needs. Then, though they are irrigated, trees would be in water stress conditions during significant periods of the season. This deficit irrigation (DI) could affect the most sensitive phenological stages of the olive crop; flowering, fruit set and oil accumulation [17].

Thus, water deficit conditions have an impact on water stress in vegetation, which in turn has negative effects on crop productivity and can even affect plant survival in young groves [18].

Another common feature to most olive grove irrigation farms is the implementation of localized irrigation systems and a fairly uniform irrigation schedule, which depends on both water availability and a fixed maximum annual volume of 1500 m3/ha in traditional 10 × 10 m plantations [12].

Generally, the less dense an olive grove is, the lower the level of water stress, and therefore, the greater the irrigation water savings [19]. This lower tree density could permit deficit irrigation scheduling, which would allow for around 50% of water to be saved with mild or moderate water stress. This water stress level likely would not reduce fruit yield [20]. However, this irrigation scheduling requires the accurate measurements of the water reserve in the soil. Remote sensing techniques and geographic information systems (GISs) have been used to determine the evolution of water in the soil and to establish water management, namely both its use and productivity. Remote sensing makes it possible to study the spatial distribution and temporal evolution of biophysical properties or characteristics related to crop development by using a sequence of images [21]. The evaluation of crop variability through satellite images has been widely employed by correlating spectral information with biological processes of the terrestrial ecosystem [22]. On the other hand, geographic information systems (GISs) allow for the management of geographic information and its association with any type of descriptive information [23].

The use of the water reserve in soil in irrigation schedules and calendars means a lower expenditure of available water resources. However, we find that usually in large irrigated areas of the same crop, the same irrigation schedule is used without taking into consideration this reserve, which has a negative impact on the management of generally scarce water resources.

The aim of this work is to propose an easily accessible methodology to accurately determine the evolution of soil water content for a given crop (olive grove) over a wide region. The objective will be to obtain the best possible information to elaborate the most accurate irrigation schedules possible in order to improve the efficiency of irrigation water use.

5.2. Materials and Methods.

5.2.1. Description of the Study Area.

The study area comprises the province of Jaen (Spain, Figure 5.1) and covers an area of 13,489 km2, in which olive groves are the most important Mediterranean fruit crop in the surface area [11]. This crop is the main socioeconomic engine in the province [16-Molina Moral 2022] and is constituted by 9 agricultural zones [24].

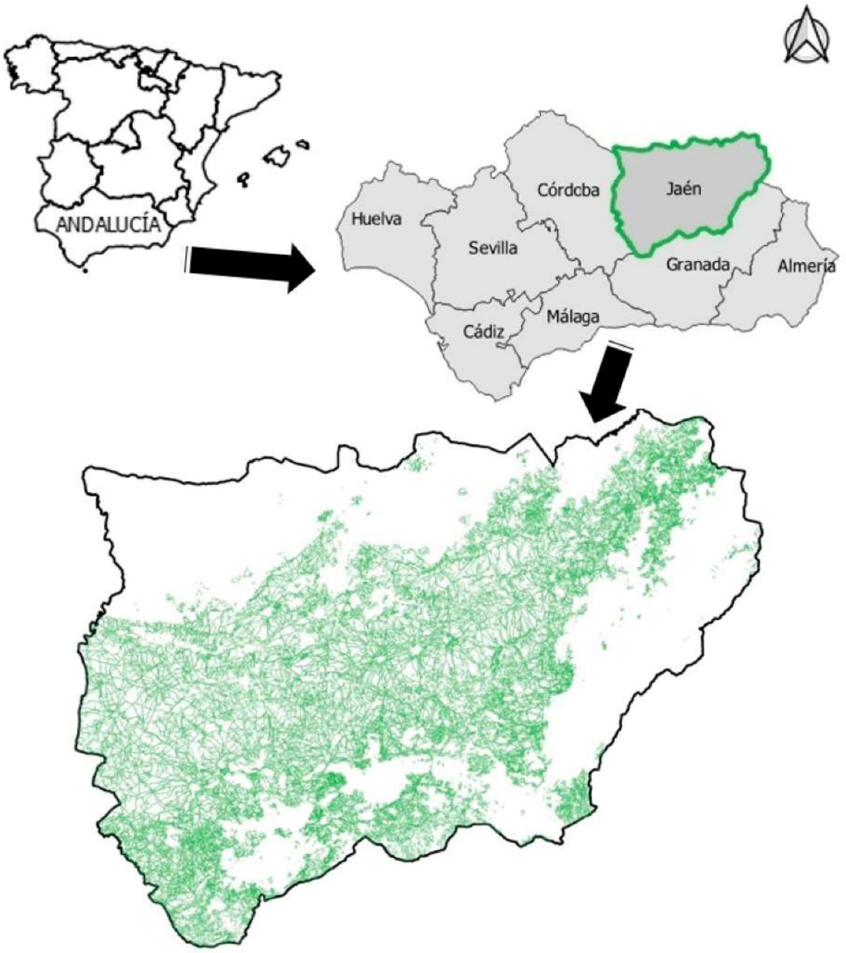


Figure 5.1. Localization of the study area and olive grove area, (olive grove surface in green).

5.2.2. Data source.

The temporal evolution of the water reserve in the soil was monitored using the following data sources:

- Climatic data are those obtained from the agrometeorological stations of the Agroclimatic Information Network of Andalusia (*RIA*) [25].
- Determination of the value of the crop coefficient: the monthly average NDVI indices were used from *TERRA-MODIS* satellite images obtained from the Andalusian Climate Information Network [26].

- Classification of the different types of soils: the soil map of Andalusia at a scale of 1:400,000, prepared in 2005 by the Ministry of Environment (Environmental Information Network of Andalusia, *REDIAM*) [27], was used based on the map published in 1989 by the Ministry of Agriculture and the Higher Council for Scientific Research; digitized; and readjusted with reference to the orthoimages of the Landsat-TM satellite, whilst also taking into account its characteristics [28].
- The physicochemical and hydrological properties of the soil were obtained and the water reserve in the soil was determined using the collection of soil maps of the Institute of Natural Resources and Agrobiology of Seville (*IRNAS-CSIC*) [29,30].
- The delimitation and location of the area and crop cover were obtained using the Information System on the Natural Heritage of Andalusia related to land occupation (*SIPNA*) [31]. This system establishes six hierarchy codes and has the occupation codes of the Information System on Land Occupation in Spain (*SIOSE*) as a cartographic base at a scale of 1:10,000.

The modeling and processing of the data were carried out using the free software QGIS 3.18 [32]. The workflow used to obtain the data of the variables analyzed is shown in Figure 5.2.

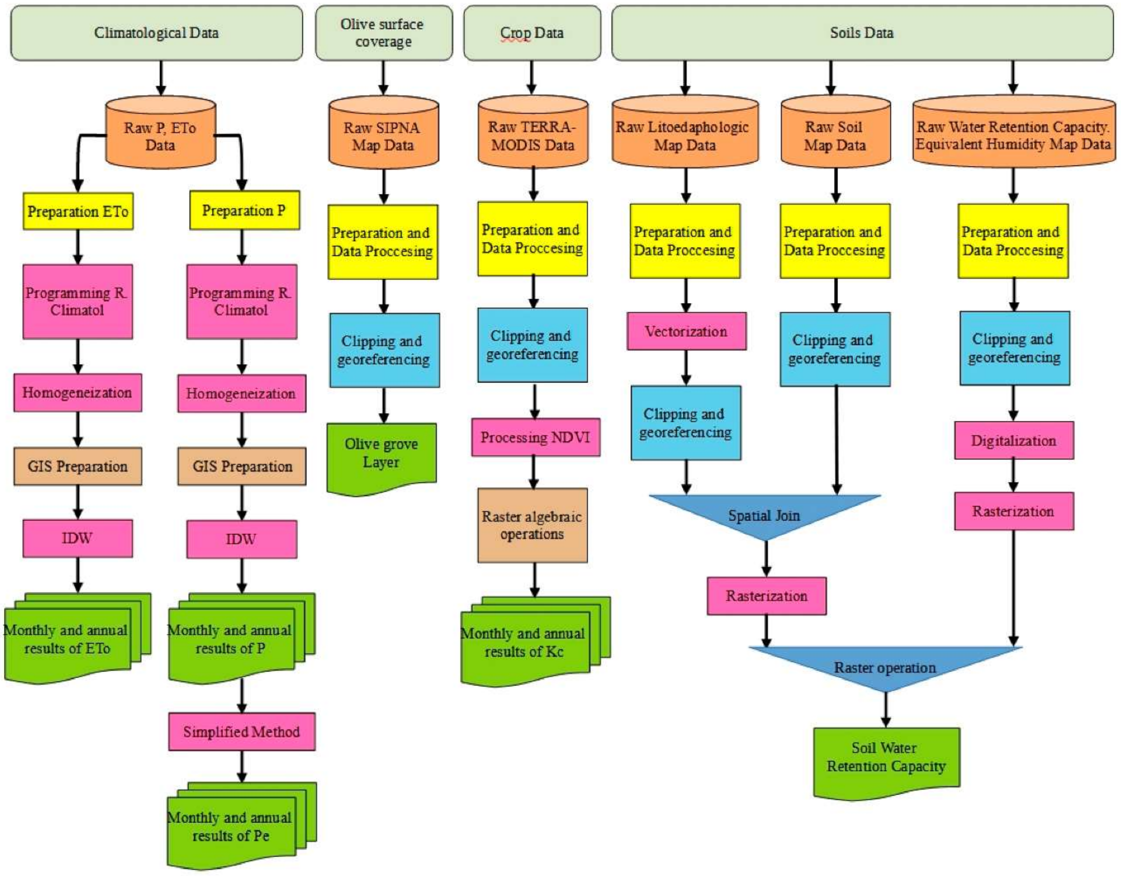


Figure 5.2. Detailed flow diagram of the methodology, (GIS is geographic information systems; IDW is inverse distance interpolation; SIPNA and TERRA-MODIS are described in Section 2.2; climatological data P and ETo are described in Section 2.3; NDVI and K_c are described in Section 2.4; soil data are described in Section 2.5).

Finally, a practical application of the described methodology was carried out by applying it to the study reduced to the municipal scope of the municipality of Cazalilla. (Supplementary Material File S2). In any case, these results represent a first approximation that should be more made precise and detailed in order to provide more adequate results as the scope of the study is reduced at the municipality district area, irrigation community, farm and/or plot levels.

5.2.3. Climatic Data.

To obtain the climatic data, a total of 18 automatic EMC/EMA-type weather stations [25,33,34] distributed throughout the provincial area and belonging to the Andalusian Agroclimatic Information Network dependent on the Ministry of Agriculture, Livestock, Fisheries and Sustainable Development (RIA) were used [25], (Supplementary Material S1).

Given the possibility of the existence of anomalies in the data [35,36], the R.Climatol package [37–39] programmed in R language [40] was used during the study period 2006–2020.

Relative homogenization employs the SNHT (Alexandersson–Moberg) test and establishes a reference station calculated from a weighted average of neighboring stations that takes into account the distance between the different stations and a reference station [41,42]. A climatological series is homogeneous if its variations are caused by weather and climate variations, or if it is representative of the climate in the surroundings of the observation point [43].

The Penman–Monteith equation was used to calculate reference evapotranspiration (ETo). Precipitation (P) was defined as the water in the atmosphere that falls onto the Earth’s surface in liquid, solid, or liquid–solid form from clouds. Effective precipitation (Pe) is the usable precipitation, i.e., precipitation not lost by runoff or deep percolation. It can also be considered as the amount of precipitation that is stored in the soil without being lost though runoff or deep percolation and remains available to use by vegetation. It is the fraction of total precipitation that is used by plants. Its determination can be performed using simplified methods [44–46], regionalization [47] or GIS techniques of geostatistics,[48].

The results obtained were represented in the study area by using GIS techniques with the application of the inverse distance weighted (IDW) interpolation method [49,50], with a pixel resolution of 5 m. Effective precipitation (Pe) is considered to be 75% of the rainwater [51] that manages to infiltrate into the soil without being lost to runoff or deep infiltration [15–52].

5.2.4. Determination of the Crop Coefficient.

The crop coefficient K_c varies during the growing period and depends on the development of the vegetation cover. Its determination is based on an advanced formulation of the procedure [44], which breaks it down into the sum of the basal crop coefficient K_{cb}, referring to transpiration [53,54]; and the K_e coefficient, called the evaporative coefficient, which includes evaporation from the bare soil. This model is referred to in the scientific literature as $K_c - ET_o$, when it performs the determination of K_c in two steps [55,56] or IV-ET_o when it integrates the vegetation indices [57] and allows the establishment of a good linear relationship, which is widely demonstrated both theoretically [58,59] and empirically [60]. Other authors take into account evaporation from wet bulbs [61].

The crop coefficient K_c is determined through the following expression:

$$K_c = K_s * K_{cb} + K_e \tag{1}$$

where:

- K_s: the stress coefficient, with values from 0 (maximum stress) to 1 (no stress);
- K_{cb}: the basal crop or transpiration coefficient;

- K_e: the evaporative coefficient, which depends on the growth and development cycle of the canopy.

Values of K_s and K_e were estimated using those of the usual drip system and weekly irrigation [62], ($K_s = 1$, $K_e = 0.05$ was adopted). Calera et al. [63] estimated K_{cb} with the vegetation index NDVI:.

$$K_{cb} = 1.44 * \text{NDVI} - 0.1 \qquad (2)$$

The above equation allows us to obtain Kc values from an image in which NDVI has been previously calculated for each pixel. The sequence of images, in turn, allows us to study the monthly evolution of the canopy, showing both spatial and temporal variability. Therefore, we can obtain:

$$ET_c = ET_o * ((1.44 * \text{NDVI} - 0.1) + 0.05) \qquad (3)$$

To differentiate between irrigated and unirrigated olive groves, information from the Andalusian Natural Heritage Information System (SIPNA) [31] was used.

The normalized difference vegetation index (NDVI) was introduced by Rouse et al. [64] and is a measure of the value of photosynthetically active biomass. Its values are a function of the energy absorbed or reflected by plants in various parts of the electromagnetic spectrum in a range from −1 to +1. Two bands are used for its calculation and determination: near-infrared (NIR) and red (RED), which are different depending on the observation satellites used. The formula for its calculation is as follows:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \qquad (4)$$

For the determination of the K_c coefficient of the olive grove, we used the TERRA satellite images captured by the MODIS sensor (Moderate Resolution Imaging Spectroradiometer), with a spatial resolution of 250 m, obtained from the Andalusian Climate Information Network [26]; referred to the normalized difference vegetation index (NDVI); and studied the time series of this parameter during the study period considered [65–68]. A total of 177 images corresponding to the period 2006–2020 were used, and after being corrected and georeferenced, they were processed and represented in reference to the scope by analyzing and studying their temporal evolution to obtain the monthly and annual mean values and their GIS representation in raster format.

5.2.5. Determination of Soils Types.

Soil is a key factor in water balance as it allows for water storage, and therefore, its availability for the crop, so in deficit irrigation it will allow for the establishment of the irrigation schedule with greater precision. Its characteristics and properties (texture, depth, physical properties, drainage and infiltration) allow us to consider the soil water reserve to enable and improve irrigation efficiency in arid or semiarid areas, as well as the development and productivity of the crop [69]. One of the most important conditioning factors when applying deficit and regulated irrigation is the storage capacity or water reserve of the soil [70,71].

The soil map of Andalusia at a scale of 1:400,000 was adopted as the soil database [27]. The soils appear in cartographic units characterized by associations grouped at the second-order level following the FAO classification criteria and the 1985 European Union Soil Map with spatial resolution of 105 m [72,73]. For soil classification, several documents were studied and taken into consideration: the database of edaphological proper-ties of Spanish soils [28], the determination of agrological classes at the provincial level [74] and the keys for soil taxonomy [75–77]. Thirty-one edaphic units were described in the scope of the present study (Table 5.1) out of a total of 64.

Table 5.1. Edaphic soils unit of the study area, (legend table first above).

Soil Type				**Horizon diagnostic qualifier**			
C	Cambisols	Ph	Phaelozems	Ca	Calcareous	Hu	Humic
F	Fluvisols	R	Regosols	Cr	Chromic	Or	Orthic
L	Lithosols	Ra	Rankers	Dy	Dystric	Ha	Haplic
Lu	Luvisols	Re	Rendzines	Eu	Eutric	Pe	Pelic
N	Nitisols	V	Vertisols	GL	Gleic	Ve	Verthic
				omm	over metamorphic materials	omp	over plutonian materials

Code	**Edaphics Units**	**Code**	**Edaphics Units**	**Code**	**Edaphics Units**
1	EuF and EuC	**22**	PeV and CrV	**47**	CaC, CaLu and CrLu with CaL and CaF
2	CaF	**23**	CrV and VeC with CaC, CaR and PeV	**48**	VeC, CaR and CrV with CaC
5	EuR, L and EuC with Ra omm	**31**	EuC, EuR and L with Ra	**49**	VeC, CrV and CrC with CaR
6	EuR, L and EuC with Ra opm	**37**	EuC, CrLu and OrLu	**51**	OrLu, Glu and EuC
9	CaR and EuR	**38**	EuC, CrLu and OrLu	**53**	CrLu and R
10	CaR	**39**	DyC, HaPh and Ra with HuC, DyR and L	**55**	CrLu, L and EuR with DyN
11	CaR and L with CaC	**40**	CaC with CaR	**57**	CaLu, CaC and EuC with CrLu, CaR and L
13	CaR and CaC with L, CaF and Re	**41**	CaC with CaR	**58**	CaLu, CaC and CrLu with CaR
14	CaR and CaC with CaLu and CaF	**42**	CaC with CaR, CaF and CaLu	**59**	CaLu, CrLu and Glu
19	L, CrLu and Re with CaC	**43**	CaC and CaR with CaL, CaF and VeC		
21	PeV, Re and CaR	**44**	CaC, CaR and L with Re		

In order to obtain the soil properties, we used the lithological maps of classes and subclasses of Andalusia elaborated at a scale of 1:400,000 and spatial resolution of 105 m from the cartographic and geological information of the Geological and Mining Information System of Andalusia from the detailed edaphological information of the SDBm-SEISnet database (1083 soil profiles) [29,30] compared and completed using the soil database of the province of Jaen [28]. It was possible to establish the dominance relationship referring to the different types of existing soils, finding 14 dominance codes out of a total of 21 for the whole of Andalusia (Table 5.2).

Table 5.2. Dominance edaphic codes unit and textures of the study area.

Dominance Code	Dominance Meaning	Texture
0	No data	
1	Soils dominated by fluvisols	clay
2	Soils dominated by eutrophic regosols	sandy loam
3	Soils dominated by calcareous regosols	sandy clay loam
4	Lithosol-dominated soils	sandy clay loam
6	Pebbly vertisol-dominated soils	sandy clay loam
7	Soils dominated by chromic vertisols	clay loam
10	Eutrophic cambisol-dominated soils	clay loam
11	Soils dominated by dystric cambisols	clay loam
12	Calcic cambisol-dominated soils	clay loam
13	Vertic cambisol-dominated soils	clay loam
14	Vertic luvisol-dominated soils	loam
15	Chromic luvisol-dominated soils	sandy loam
16	Calcareous luvisol-dominated soils	sandy clay loam
18	Soils dominated by eutrophic planosols	clay loam

The determination of soil water retention capacity as a function of soil type was per-formed by processing, digitizing and rasterizing Map No. 6: water retention capacity and equivalent humidity (whole profile) from the collection of the IRNAS-CSIC [29,30].

5.2.6. Determination of Water Content in Soil

Although the main variable determining soil moisture is precipitation, other factors (soil type, vegetation, topography and slope) influence its distribution both spatially and temporally [78,79]. Localized irrigation enables the application of irrigation in olive groves with slopes of up to 35–45%, although it notably influences distribution uniformity and application efficiency [80].

From a hydrological point of view, regarding the distribution and circulation of water in the soil, the following variables are usually used: slope, roughness, aspect, orientation, topographic moisture index, etc. [81–84]. However, when determining soil moisture, the explanatory variables that present a higher correlation are the physical and hydric properties of the soil. Thus, the aforementioned variables present a low linear relationship, and therefore a lower correlation [85].

Soil moisture content is measured according to its physicochemical properties, with the application of direct (gravimetric) or indirect methods (tensiometers, electrical resistivity, neutron probe, gamma ray attenuation, time domain reflectometry (TDR) or frequency domain reflectometry (FDR)) [86,87]. Other works use pedotransfer functions (ETFs) [88] or their estimation using GIS spatial modeling techniques [89], the combination of results from climate stations with soil sampling and subsequent analysis [90], the application of hydrological models such as SWAT [91,92] or the use of wireless soil sensors or soil sensor networks [93–95]. The maximum amount of water that a soil can retain is referred to as the available moisture interval [96].

The available moisture interval (AWI) and water retention capacity (SWRC) were determined as a function of soil type in the study area [97]. AWI refers to the amount of water theoretically available to plants that they can absorb. AWI was calculated as the difference between the values of the field capacity (FC) and permanent wilting point (PWP) levels [98,99]. On the other hand, soil water retention capacity (SWRC) refers to the AWI in the soil profile up to the depth where the roots are located [100]. Therefore, we have:

$$\mathrm{AWI} = \mathrm{FC} - \mathrm{PWP} \tag{5}$$

$$\mathrm{SWRC} = \left[\frac{(\mathrm{FC} - \mathrm{PWP})}{100}\right] * \mathrm{Z} * (1 - \mathrm{f}) \tag{6}$$

where:

- AWI: available moisture interval, (in %);
- FC: field capacity, (in %);
- PWP: permanent wilting point, (in %);
- Z: exploratory depth of roots (100 cm was adopted);
- f: percentage of rock fragments (in parts per unit);
- SWRC: soil water retention capacity (in mm).

To obtain the water balance, the procedure described in Figure 5.3 was followed [101]. With this balance, we can quantify, for each period of time analyzed (in this case, each month), the behavior of soil moisture and determine both the excesses (those values that exceed soil saturation, and which give rise to runoff), and the moisture deficits (at levels close to the permanent wilting point).

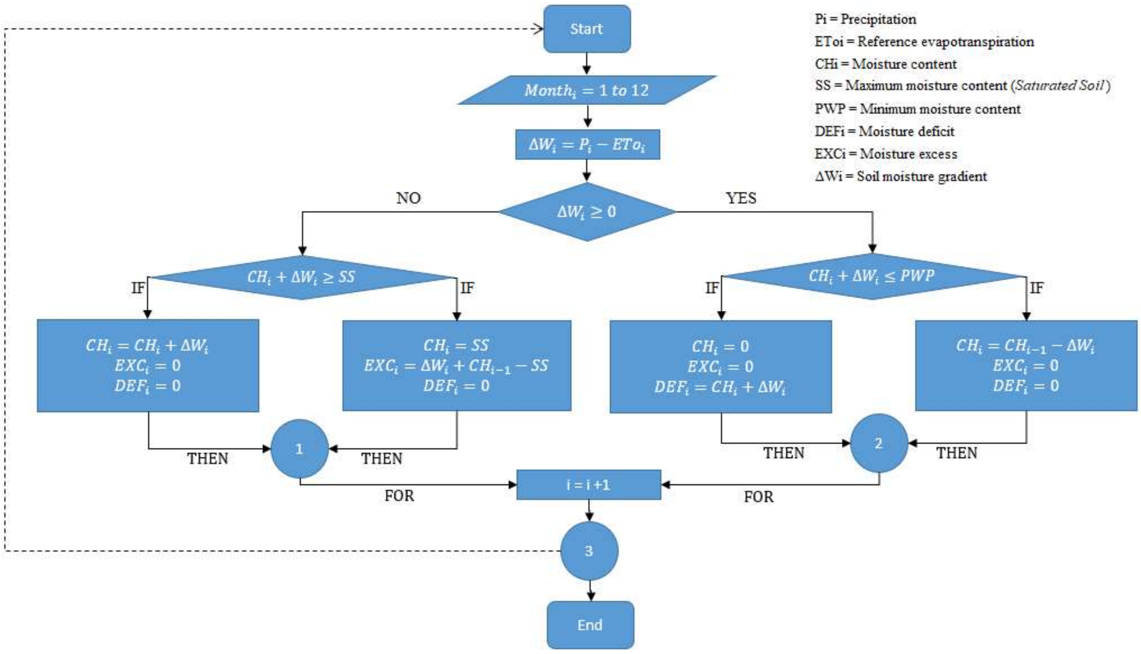


Figure 5.3. Methodological scheme for calculating the water balance.

In the study of wide regions, it is necessary to assume a series of simplifications for the calculation of the water balance. In the present study, it was considered that the only water input comes from precipitation (inputs), and only reference evapotranspiration was considered (outputs). Percolation, runoff and capillary rise (lateral or vertical water movements) were not taken into account. The balance was established for the hydrological year (the hydrological year is from 1st October until 30th September).

At the crop level, water requirements were established by applying the simplified water balance equation based on the principle of conservation of masses [102,103].

Thus, we can obtain:

$$ET_c - (Pe + Ir) - SR - In = \pm \Delta W \quad (7)$$

where:

- ET_c: crop evapotranspiration;
- Pe: effective precipitation;

- Ir: irrigation;
- SR: surface runoff;
- In: infiltration of water in the soil.

Considering the previously described simplifications, we can assume that neither runoff (SR) nor infiltration (In) occurred. In addition, no irrigation was considered (Ir equal to 0), so the final form the above equation is as follows:

$$ET_c - Pe = \pm \Delta W \qquad (8)$$

This water balance was estimated monthly to identify the periods in the season when precipitation could be too scarce and could enhance problems of water stress. Finally, water reserve (WR) was calculated as the variations in soil moisture using the accumulation of water balance in each month:

$$WR_n = WR_{n-1} \pm \Delta W \qquad (9)$$

where:

- WRn is the water reserve in the current month.
- WRn−1 is the water reserve in the previous month.
- ΔW is the water balance each month.

5.3. Results.

5.3.1. Climate Variable Values.

The climatic variables analyzed were the data corresponding to the monthly averages of evapotranspiration and precipitation during the period 2006–2020 obtained from the agroclimatic stations of the study area, (Supplementary Material S1). Figure 5.4

shows the frequency distributions of the data obtained for precipitation (P) and reference evapotranspiration (ETo) at the agroclimatic stations.

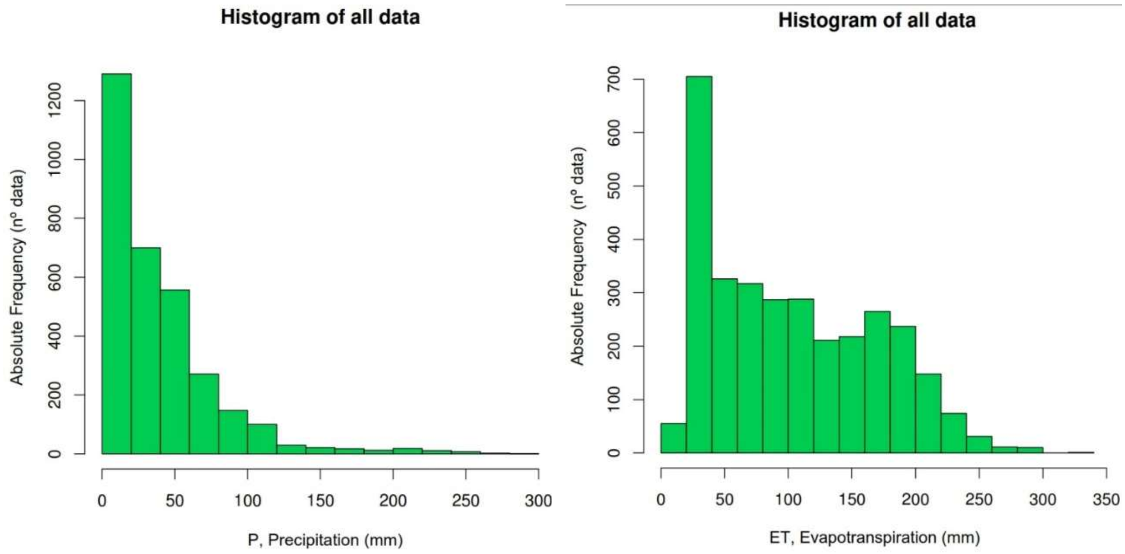


Figure 5.4. Frequencies of monthly precipitation and evapotranspiration during the period 2006–2020.

The annual distribution of ETo and P showed water deficit conditions due to high values of evapotranspiration and low precipitation. Figures 5.5 and 5.6 show the monthly results of ETo and Pe. ETo was extremely high in all the studied zones from May to September, where the south-east zone presented the greatest values.

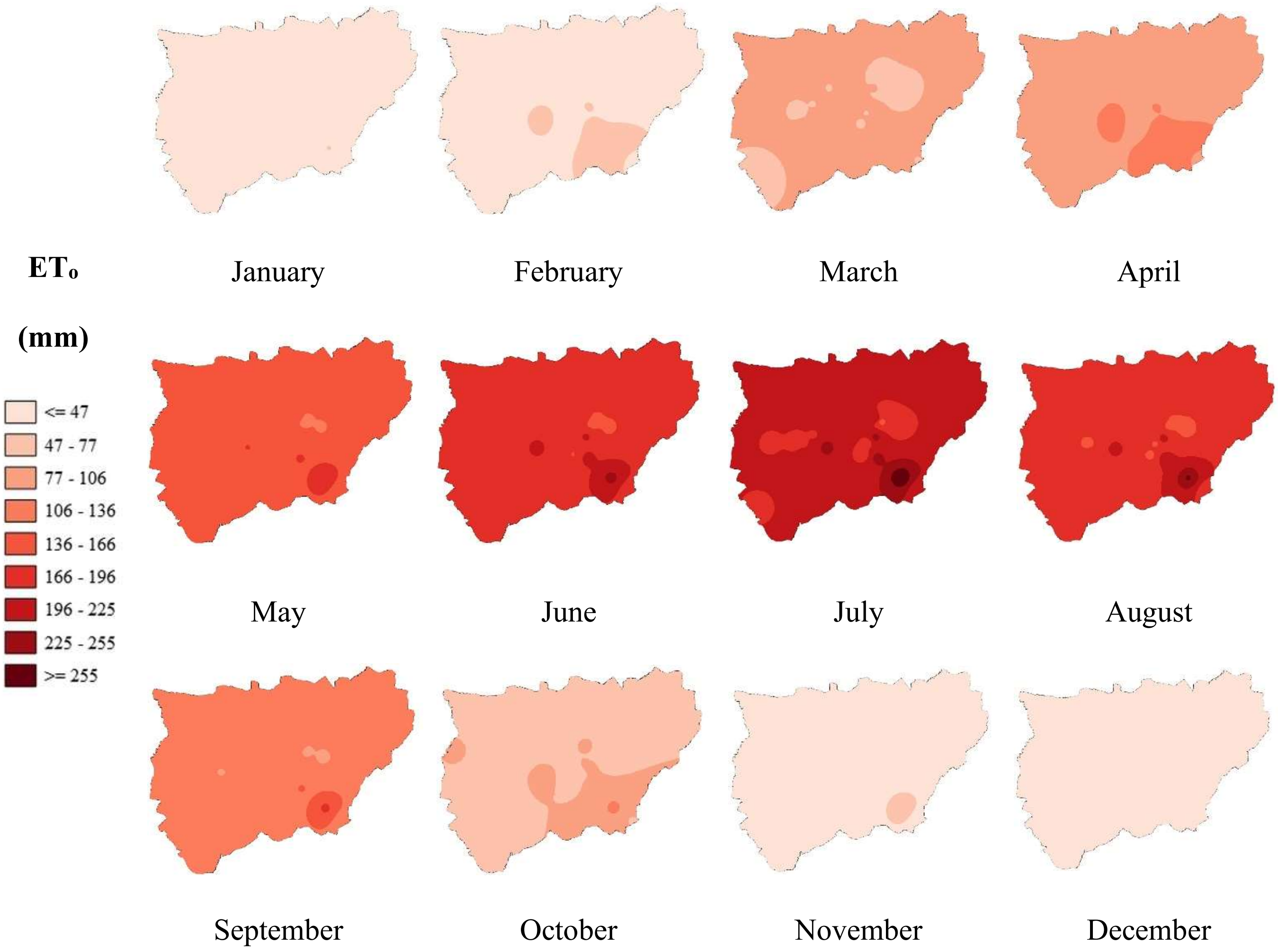


Figure 5.5. Monthly variation in ETo. (Source of data: agrometeorological stations of the agroclimatic information network of Andalusia. The scale of color is presented on the left of the figure).

On the contrary, Pe was almost null from June to August in all the zones (Figure 5.6). The month with the greatest amount of Pe was, on average, November. Although Pe was measured in May and September, the real period of rainfall could be considered only from October to April. The south-east commonly presented the lowest amount of rainfall in this latter period.

On an annual scale, the mean annual evapotranspiration is 1237 mm/year, while the mean annual precipitation does not exceed 455.5 mm/year. Within the studied region, there was an important variation ranging from 386.1 mm in J01 (Huesa) to 552.6 mm in

J16C (Marmolejo), which reflects the existence of a longitudinal and altitudinal rainfall gradient.

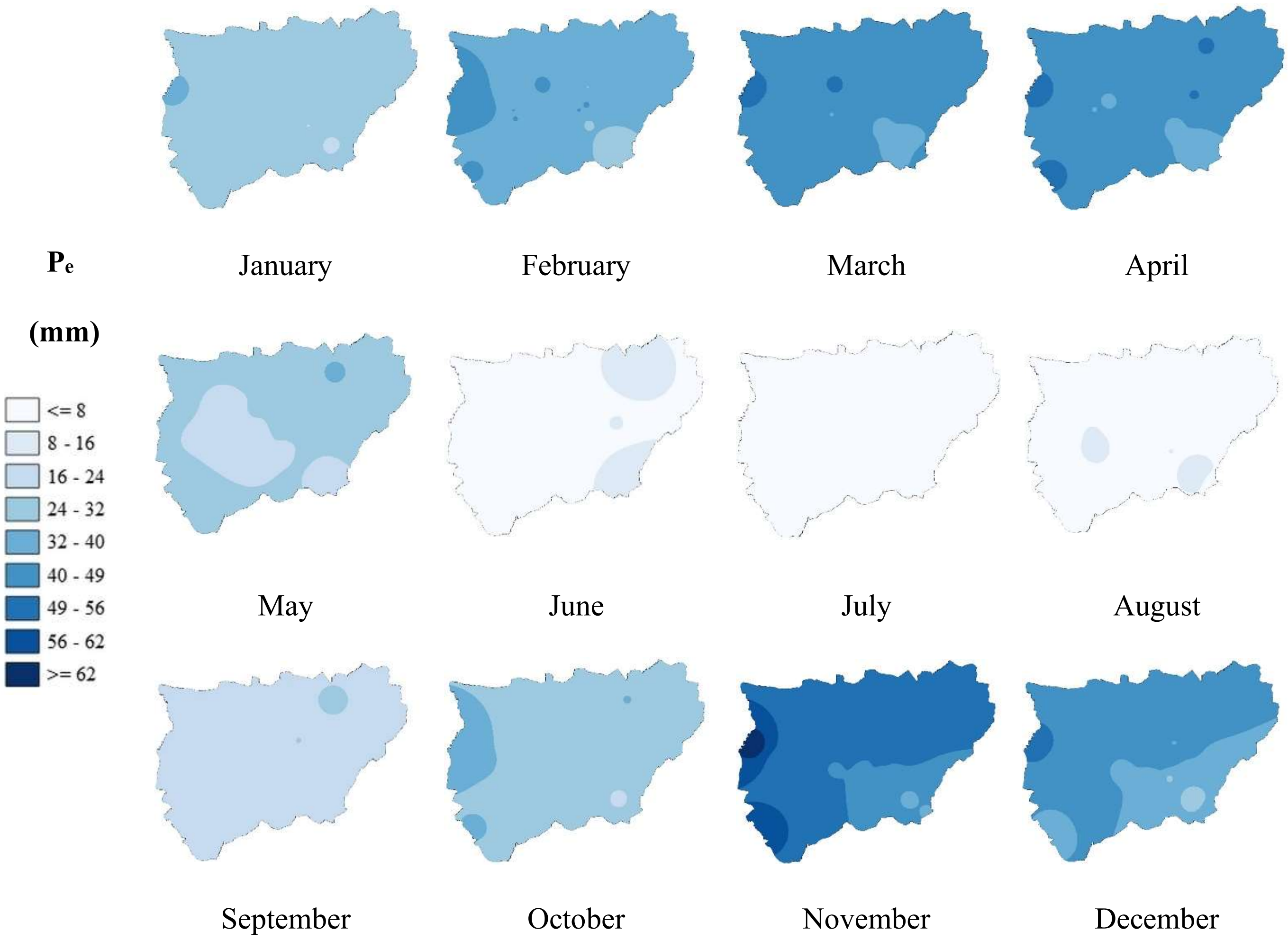


Figure 5.6. Monthly variation in Pe. (Source of data: agrometeorological stations of the agroclimatic information network of Andalusia. The scale of color is presented on the left of the figure).

5.3.2. Crop-Specific Values.

The analysis of the data obtained showed maximum values of NDVI in the autumn–winter period and minimum values during the spring–summer period (Figure 5.7). The decrease in NDVI during the phases of the greatest reproductive activity (flowering and fruiting) may be due to source–sink ecophysiological mechanisms. Similarly, when temperatures are high (>35 °C), progressive stomata closure may occur, and therefore, a decrease in or stagnation of shoot growth may occur [104]. Figure 5.8 shows a graph representing the relationship between the NDVI and monthly K_c values obtained in the period considered.

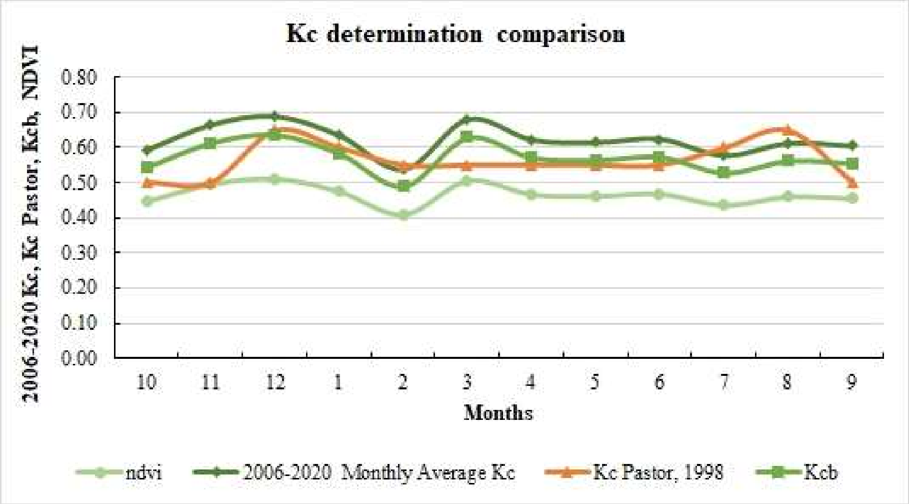


Figure 5.7. Average monthly values of NDVI and K_c. (All Kc and NDVI values are dimensionless. K_c Pastor [105]).

The relationship between these two variables is of quadratic type with a very high coefficient of determination ($R^2 = 0.8696$) [106]. There was a decrease in K_c values throughout the season. This is a well-known pattern of K_c in olive trees and is commonly related to the stomatal response to evaporative demand.

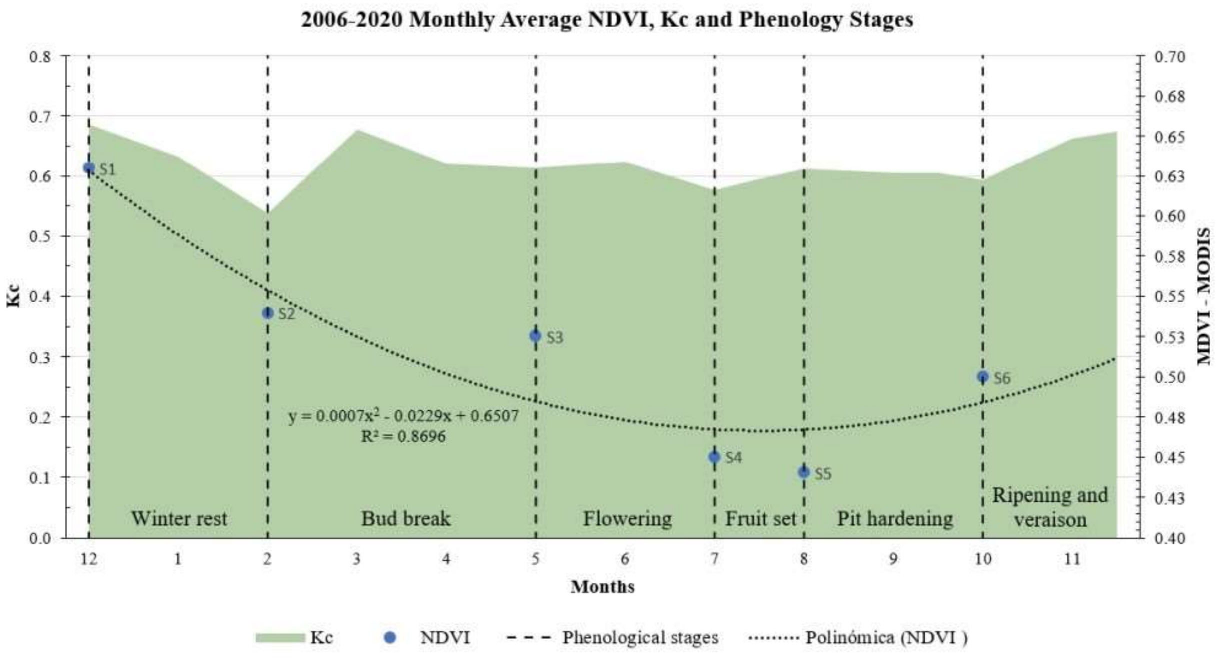
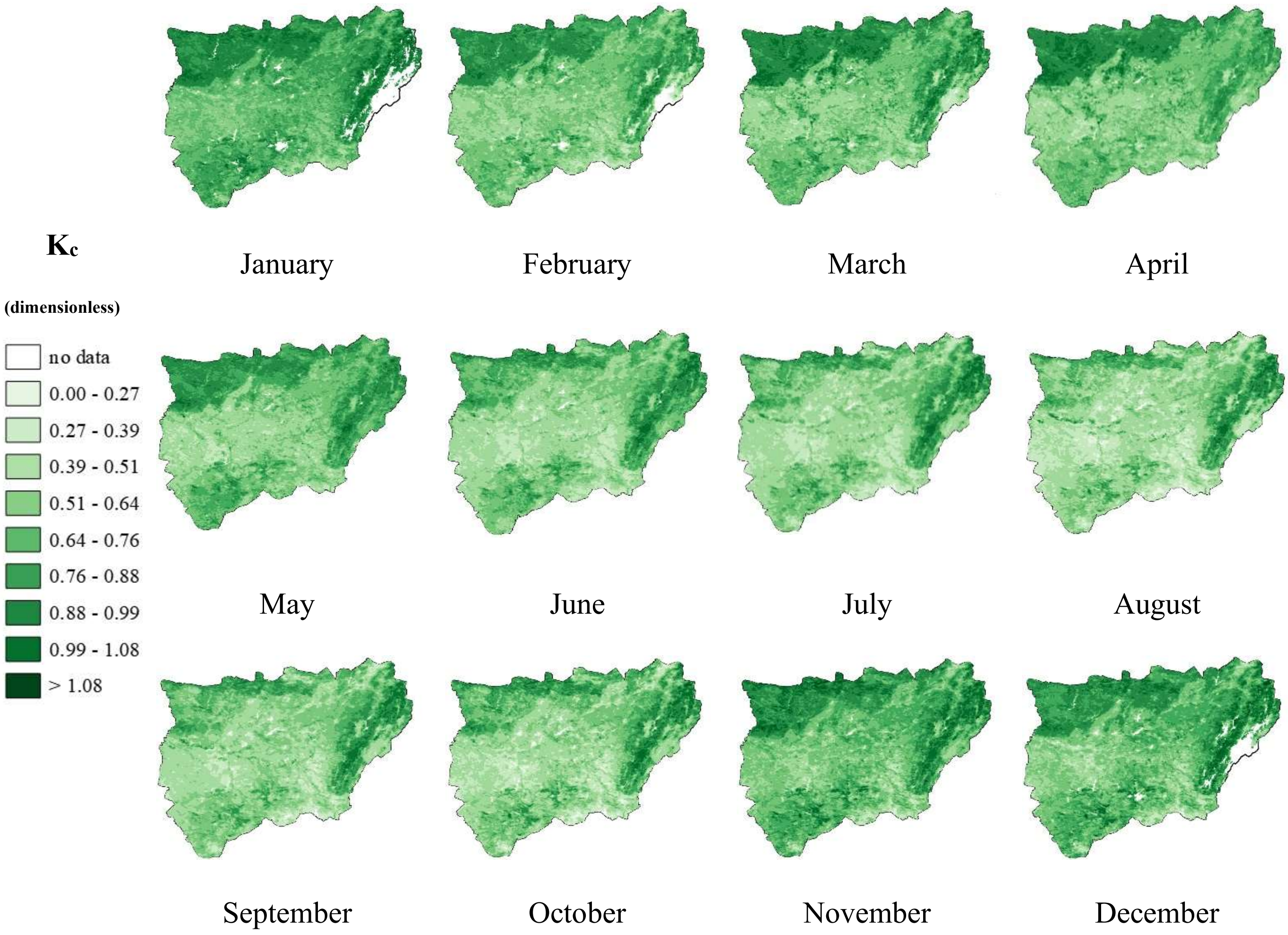


Figure 5.8. Relationship among NDVI, K_c and phenological stages (K_c and NDVI are dimensionless).

The monthly Kc values obtained by applying Equation (1) for the olive crop range from 0.27 to 1.08 (Figure 5.9). The greatest values of K_c were obtained in the north and north-west of the studied region. The pattern was similar in all of them, with maximum values in winter and minimum values during summer. The range of K_c during the common irrigation season from June to September was approximately 0.5, which is in accordance with the value reported in the literature [105–107].



January February March April

May June July August

September October November December

Figure 5.9. Monthly variation in K_c. (The scale of color is presented on the left of the figure).

The monthly evolution of crop evapotranspiration (ET_c) is presented in Figure 5.10. However, great variability for ET_c values was found in the study area throughout the season. All the regions presented extremely high ET_c values, mainly from May to August (more than 80 mm). ET_c values lower than 50 mm were found from October, but even in this month, some regions presented some data of approximately 80 mm. During the period of the greatest values (from May to August), the north-west and east zones presented the maximum ET_c.

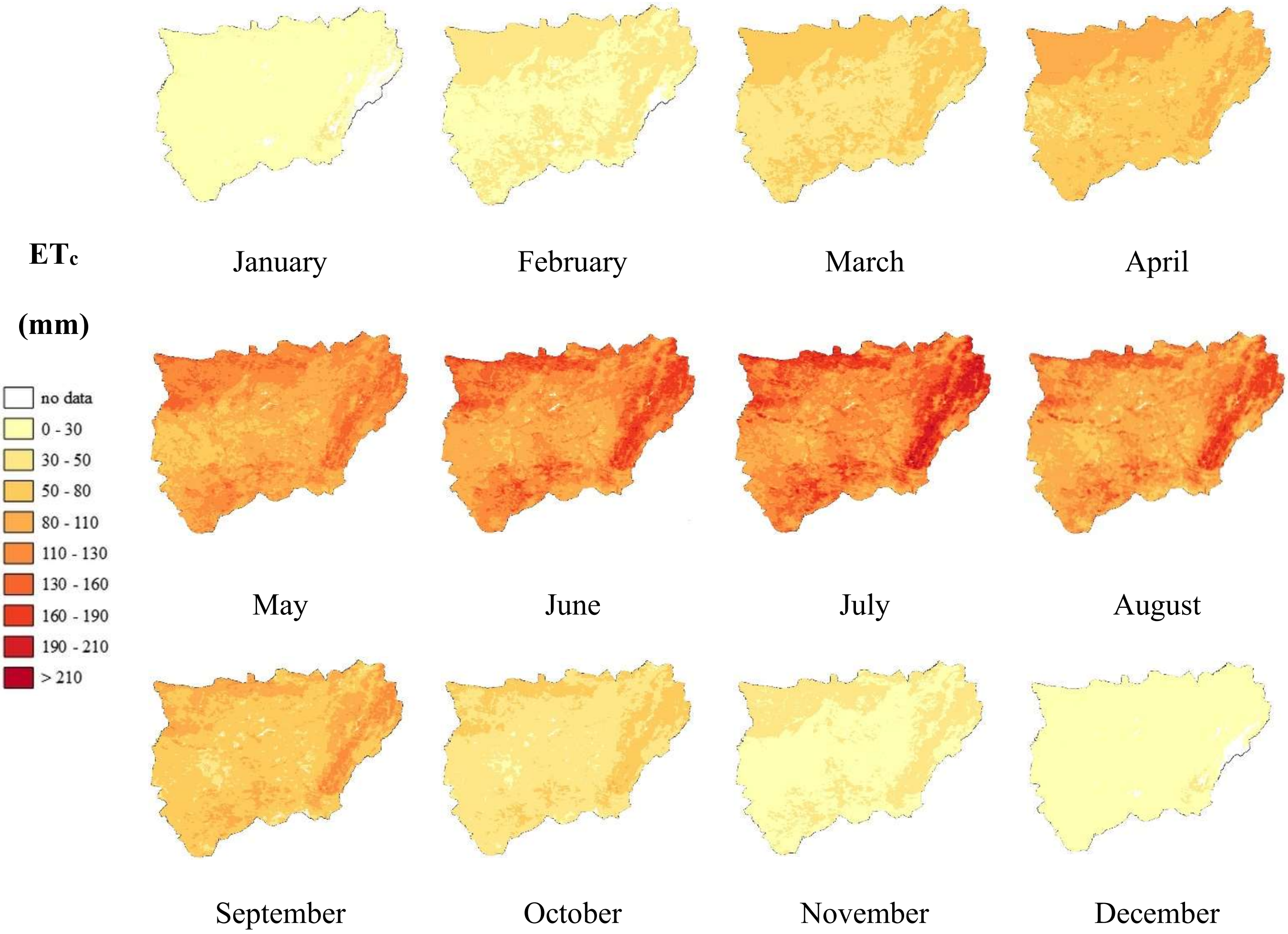


Figure 5.10. Monthly variation in ET_c. (The scale of color is presented on the left of the figure).

5.3.3. Values of Soil Variables.

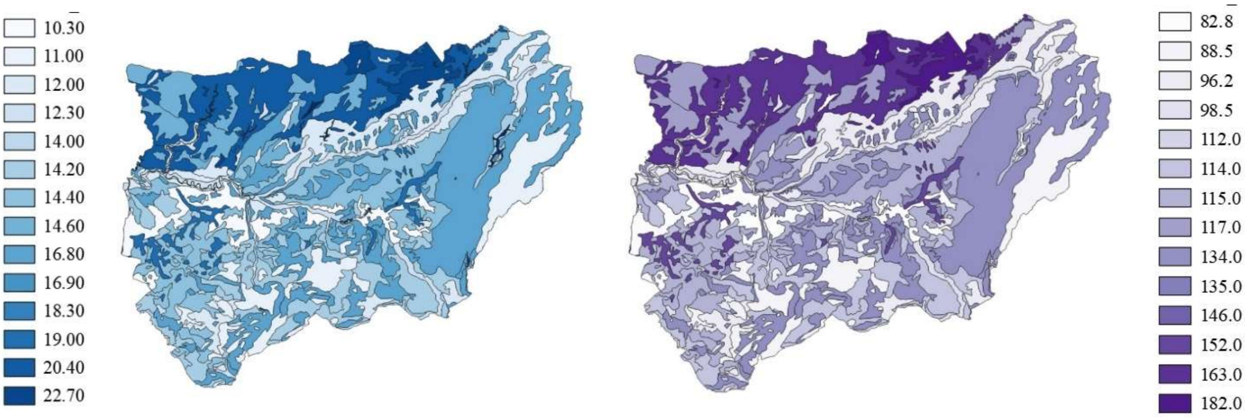
The range of variation in soil water variables on the map for average bulk density and depth explored by crop roots of 100 cm is shown in the following table (Table 5.3).

Table 5.3. Range of variation in soil water variables.

Variable	**θg**		**θv**	
Saturation point (SAT)	30.28	38.65	43.10	55.00
Field capacity (FC)	17.33	36.22	24.89	48.17
Permanent wilting point (PWP)	8.34	26.97	11.03	35.87
Usable water (SWRC)	58.14	127.91	82.75	182.04

The useful and usable water or maximum amount of water that the soil can retain is that corresponding to the difference between the field capacity and the permanent wilting point [96,98,99].

For the determination of the soil’s available water retention capacity for plants (SWRC) [100], the influence of rocky fragments was taken into account whilst considering that an optimal proportion of these is between 10 and 30%, so a proportion of 20% was adopted [108], obtaining a range between 82.8 and 182.0 mm (Figure 5.11).



Available water interval (AWI) in mm. Soil water retention capacity (SWRC) in mm.

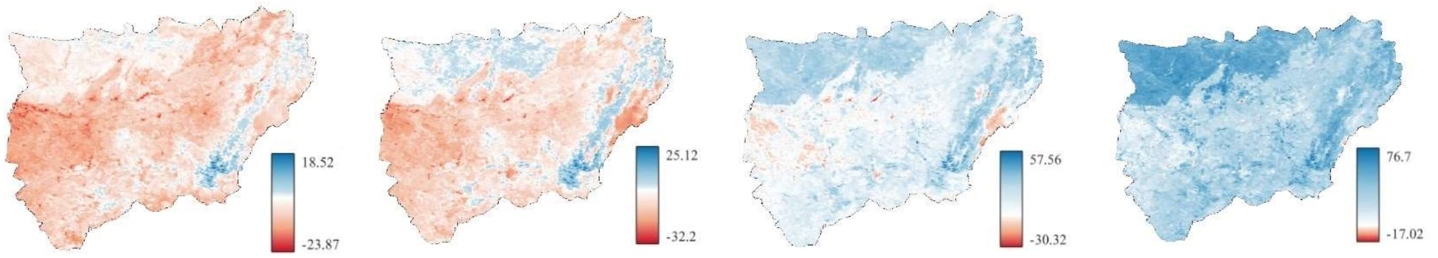
Figure 5.11. Spatial distribution and values of useful water (AWI) and usable water (SWRC).

Soil water storage capacity allows for its utilization by the crop, and influences the previous water balance calculated by considering this reserve to improve irrigation efficiency [71]. Figure 5.11 presents a great variation in SWRC. The greatest capacity of

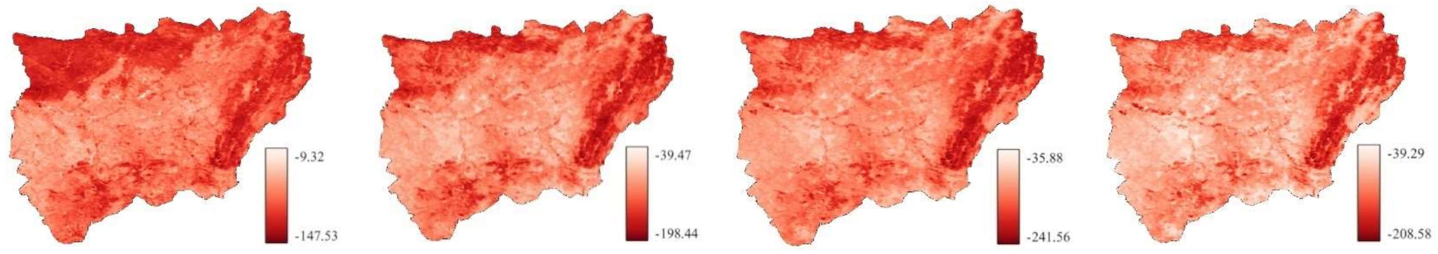
SWRC was located in the north of the studied zone, with values greater than 180 mm. On the other hand, there were several locations in the center and in the east that presented values lower than 90 mm, even quite near to the maximum. Such variability in the SWRC could affect the water management in olive groves.

5.3.4. Water Balance

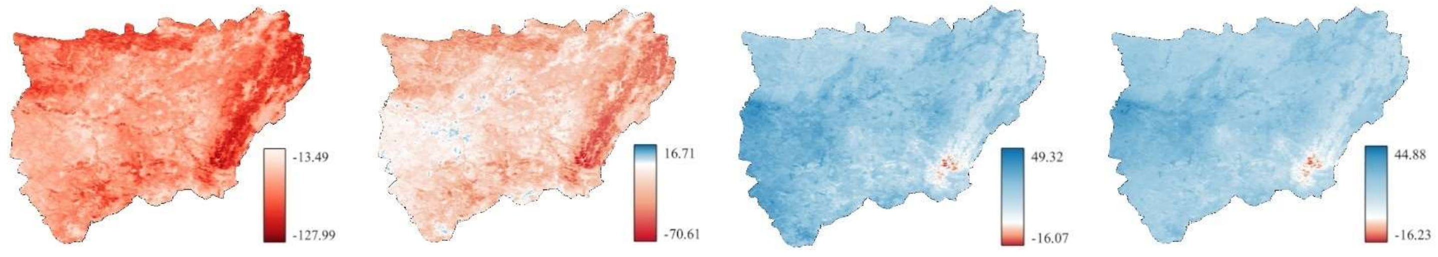
By applying the water balance equation to the monthly maps, the monthly variation in this measurement was determined. Nine intervals were established, in which the red colors correspond to a negative balance and the white-to-blue colors to a positive balance (Figure 5.12).



January February March April



May June July August



September October November December

Figure 5.12. Monthly variation in water balance (ΔW).

At the annual level, the values of the water balance obtained changed in a range of around 77 to a maximum peak value of −242 mm during the month of July. This indicates that globally, the level of precipitation collected does not compensate for the losses caused by evapotranspiration from May to September, and therefore justifies the need for irrigation to enhance the development and productivity of the crop.

During the first months of the year (January to April), we observed that a positive water balance was mainly concentrated in the northern and eastern areas, which corresponded to the mountainous forest areas of Sierra Morena and Sierra de Cazorla, Segura and Las Villas, with a maximum value of around 77 mm in April. On the other hand, in this period, there was a negative water balance in January and February in the center of the studied zone.

It is also highlighted that during the period from May to September, the evapotranspiration exceeded rainfall in all the months and zones, a situation that favors the presence of water stress and its effect on the critical phenological periods of flowering (May), fruit set (July) and stone hardening (August). Maximum evapotranspiration values were found in the northern and eastern zones of the area. On the other hand, they were more moderate in the central, western and southern zones, which have a marked and eminent agricultural character.

The positive water balance was delayed until November, but even in this month, there was a small zone in the south-east where negative values were found.

5.3.5. Variation in Water Reserve in the Soil, (WR)

The water reserve pattern is presented in the hydrological year (from October to September) because this would permit a better design of a strategy of water management.

According to water balance and Pe distribution (Figures 5.6 and 5.12), the soil profile was empty at the beginning of October.

The water reserve increased in the month of October in a localized and discrete manner in certain areas in the center and west of the area under study. The real recovery of the soil profile occurred in November in most of the zones, and only in the east zone was such recovery delayed until April. Maximum values were estimated in the month of April, with around 149 mm. It was also observed that at the beginning of the agricultural year during the autumn season, the water balance in the soil was greater in the central and western zones, which are predominantly agricultural and mainly used for olive cultivation, while during the spring, it was concentrated in the northern and eastern zones. From April onwards, the water reserve in the soil began to decrease drastically at the same time as temperatures increased, and consequently, the water needs for the crop increased (Figure 5.10).

Soil water reserve was zero from May in most of the studied zones. The representation of the variation in the water reserve in the soil showed that during a long period of time (more than 33.3% of the year), its value was zero throughout the study area (Figure 5.13).

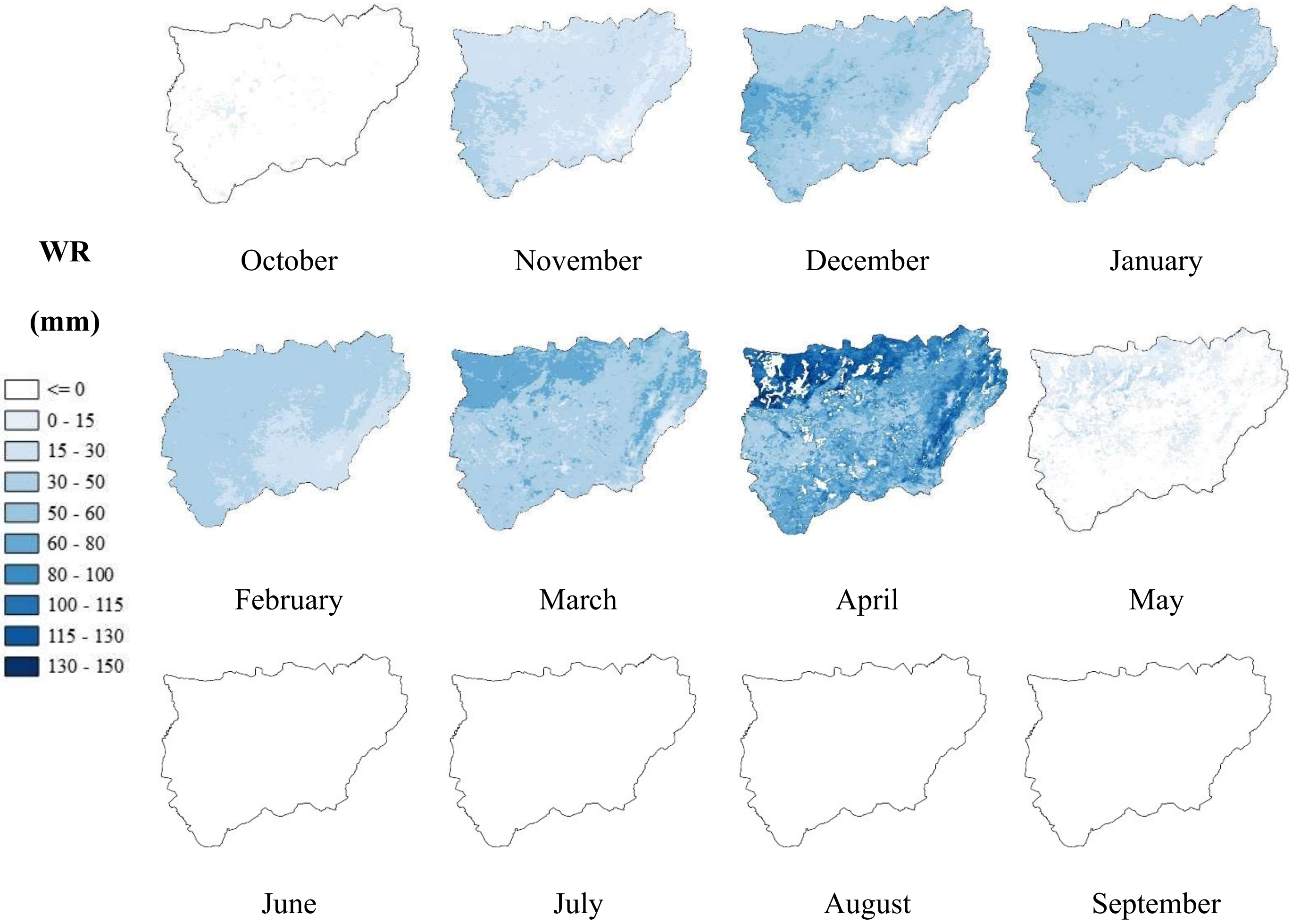


Figure 5.13. Monthly variation in soil water reserve. (WR is water reserve in the soil. The scale of color is presented on the left of the figure).

5.3.6. Irrigation scheduling

Taking into consideration the different layers of information previously developed, its application to any other crop (within the scope of the study area) would consist of determining the evolution of the K_c coefficient values in order to subsequently apply the simplified water balance equation (Equation (7)). This water balance was performed monthly given the generic characteristics of the study [109], although once the irrigation installation is completed and the crop defined, it can be performed daily [110], weekly

[111] or seasonally, according to the crop cycle and/or arrangement of satellite images [112,113].

5.4. Discussion.

Climatic changes are increasing the irrigation needs and the surface of irrigated lands. Moreover, the decrease in rain will produce a decrease in the available water. Therefore, water management will be improving at groves and at the basin level. This supposes different ways where farmers and technicians will have to optimize the available resources. They can mainly be put into two groups: hydraulic design and irrigation scheduling. Both are related and could limit the other. The current work is focused on the first one, the suggestion of a tool for delimiting homogenous zones and providing information for irrigation design, which will allow for easier irrigation scheduling using actual data. Data of the current work suggest that at least two zones could be considered with different periods of available water. Current data assumed simplifications that reduced the estimation accuracy (for instance: Pe estimation), but showed that even in these conditions, there were deficiencies in the irrigation decisions. Therefore, data suggested significant changes in the water management of the zone in comparison with the traditional fix calendar. In the northern and eastern zones, irrigation could be significantly delayed from March (current recommendation) to May. This strategy could extend the irrigation season until October when rainfall is still scarce. On the other hand, the central, western and southern zones had greater irrigation needs. Then, the irrigation season should be longer than the previous one, from April to November. This period started later than is commonly suggested, but also would need to finish later to decrease the effect of water stress in the oil accumulation period.

The current work suggests an approach for organizing water resources in a big zone, even a basin. The results identified periods of water reserve depletion and zones where it occurred early (Figure 5.13). These data would not avoid water stress but they could help in the decision of irrigation scheduling in conditions of scarce amounts of water. The whole period from inflorescence development to fruit set was reported as a very critical phenological stage in relation to yield [114,115]. These periods occurred in our zones from March to May, which is the shift between the greatest level of available water and the beginning of depletion. Current data showed that the north and east zones could secure greater yields than the rest because of their greater water reserve (Figure 5.13). Such variability is common all around the world, though olive trees have a narrow zone of growing. Examples of this variability are the works of Goldhamer (1999) [14] and Lavee et al. (2007) [116], who suggested different deficit irrigation scheduling. The former reported that decreased irrigation during summer (pit hardening) did not reduce yield [14]. However, the latter suggested no irrigation until pit hardening, though they indicated that in conditions of scarce amounts of winter rain this strategy could be not advisable [116]. The lack of agreement between both is likely related with the available water reserve in the soil.

The improvement of the current approach is very important, especially if accurate estimations at the farm level were considered. The weak variables in the current work are likely the Pe and K_c estimations. Other components considered in the water balance, such as ETo or soil type, would be easily estimated using public data. Because the current work was focused on hydraulic design, the average data of several seasons would correctly estimate ETo and soil maps would estimate the capacity of water storage. Pe is difficult to estimate even with local data, because there are different components that could affect it, mainly the amount of rainfall [117]. Although the seasonal pattern would be very similar, the amount of Pe during Autumn–Winter could affect the irrigation needs and the start and the end of the irrigation periods. The current approach, 75% of Pe, overestimated the recommendations of Villalobos et al., (2016) named the “FAO method”, suggested for arid zones [117]. However, the current approach could be useful in these local conditions because the amount of precipitation is commonly very low (most of them lower than 50 mm, Figure 5.4) which could increase the Pe from this method. Fernández et al., (2011) in a location near to the studied zone (around 150 km from Seville but with similar patterns and amounts of rain), also used this approach of 75% rainfall in the comparison of several plant water status indicators in olive trees [51].

Water needs are also very affected by ET_c, which in the current work was mainly spatially changed for K_{cb} and ET_o data. K_{cb} is affected by tree development but also by soil management. Steduto et al., (2012) reported several K_c for olive trees depending of locations, date of the season and soil management [107]. The estimation of K_{cb} based on NDVI reported values similar and with the same pattern of decrease during summer because of the increase in evaporative demand (Figures 5.7 and 5.8) [107]. NDVI has been reported as very useful tool in olive trees for estimating spatial variations at grove level [118]. Therefore, the current approach based on this measurement would provide enough information for an accurate water balance.

The main limitations of the current approach would be the assumption of 1 m of root zone. This value assumes that all groves are mature and would underestimate water needs in young. However, because the current work is focused on the hydraulic design, this limitation is null. Irrigation design has to provide information about maximum needs along the years in order to optimize pump dimensioning. This supposes that only mature groves have to be considered. The effect on young olive groves will be managed with seasonal irrigation scheduling. On the other hand, in some zones, soil depth could be lower than 1 m, and again, overestimate soil water storage. These data could affect the current final estimation and would be improved in further works.

Finally, in terms of the precision of the results obtained from the different public information layers, the most limiting was that corresponding to the determination of the NDVI, which has a spatial resolution of 250 × 250 m.

5.5. Conclusions.

Knowledge of the availability of water in the soil in large areas of an irrigated crop is necessary when planning the management of water resources, especially in areas with limited available water resources.

Its definition allows decisions to be made both on irrigation engineering (determination of the number and extent of irrigation sectors) and on the optimization of irrigation scheduling and timing (doses and frequency) to provide available water resources in a more efficient way.

In the present work, the evolution of the water reserve in the soil for a given crop was determined through the management of public data. The adaptability of the methodology used makes it possible to study any other crop or cultivation pattern in any other zone, taking into account the values of the respective K_c coefficients to allow for the evaluation and determination of the water balance and water reserve in the soil; although in these cases, the application and justification of agronomic and technical criteria, as well as socioeconomic criteria, are precedent.

The results obtained from the monthly variation in both the water balance and the water reserve in the soil in the area studied indicate that the use of public sources of irrigation scheduling data may take into account spatial and temporal distribution patterns and its specificities. Additionally, fixed irrigation calendars should be avoided to enable more efficient schedules.

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6. Conclusiones.

6.1. Conclusiones generales.

- La utilización de distintas metodologías por diversos organismos de carácter público da lugar a divergencias considerables en los datos ofrecidos que dificultan el conocimiento y la determinación de datos básicos a utilizar en investigación (p.e. hectáreas totales de riego de un determinado cultivo en una región). Esta situación requiere el esfuerzo de las instituciones públicas para la definición de una clara estrategia en la recogida de estos datos en la que se adopten metodologías de carácter complementario que permitan su comparación y desagregación, todo ello en un entorno de acceso libre, gratuito y actualizado.
- La aplicación de criterios de sostenibilidad en los olivares de riego tradicionales no debe basarse simplemente en la conservación de los recursos hídricos unida a una gestión eficiente del agua basada en criterios técnicos. También deben tenerse en consideración otros aspectos, (sociales, culturales y medioambientales), que mejoren los beneficios de los agricultores y aseguren la supervivencia del medio agrícola o rural.
- La estrategia de riego en tres sectores, basada en la ingeniería de riego de dividir la explotación en tres zonas con imposibilidad de regar a un mismo tiempo más de un sector, es la más comúnmente empleada en los riegos localizados de olivar en la provincia de Jaén, (zona de producción más importante del mundo). Según los resultados obtenidos en la investigación realizada de forma habitual es incapaz de proporcionar la suficiente cantidad de agua en los momentos o etapas fenológicas más críticas para el olivo (primavera: mediados de junio – fase de

crecimiento del endocarpio, y otoño: mediados de septiembre a finales de noviembre – fase de acumulación de aceite).

- Las estrategias de riego más adecuadas en olivares de la provincia de Jaén para asegurar condiciones cercanas a las óptimas se corresponden con una ingeniería de riego basada en la sectorización en uno o dos sectores como máximo. En cuanto a la periodicidad se deberían realizar calendarios de riego de programación diaria, y con respecto a las dosis y la fecha de aplicación es aconsejable utilizar técnicas de riego deficitario controlado o regulado.
- El conocimiento de la disponibilidad y evolución del agua en el suelo en las plantaciones de olivar de riego es imprescindible desde la óptica de la planificación en la gestión de los recursos hídricos, especialmente en zonas con recursos hídricos disponibles limitados, pues permite la toma de decisiones en distintos ámbitos; desde la ingeniería de riego (determinación del número y extensión de los sectores de riego), como en la optimización de la programación y calendario de riego (dosis y frecuencia). En ambos casos el objetivo es aportar los recursos hídricos disponibles de la forma más eficiente.
- La utilización de metodologías de sistemas de información geográfica SIG/GIS unidas a la existencia de datos públicos de fácil acceso permiten, de una forma sencilla de implementar, la determinación de la evolución del balance hídrico y la reserva de agua en el suelo y sus variaciones temporales y espaciales para un determinado cultivo, (que en nuestro caso es el olivar). La adaptabilidad y escalabilidad de la metodología y herramientas utilizadas posibilitan estudiar cualquier otro cultivo en cualquier otra zona, siendo posible obtener resultados incluso a nivel de explotación o parcela en función del nivel de precisión

adoptado.

- Los resultados obtenidos a nivel provincial respecto tanto de la variación mensual del balance hídrico como en la ocurrida en la reserva de agua del suelo en la zona estudiada aconsejan que deben evitarse los calendarios de riego predeterminados tanto en fecha como en el lugar, pues no todas las zonas comparten unas mismas necesidades temporales y espaciales en la dosis de agua, (en el caso de estudio, la provincia de Jaén).

6.2. Nuevas líneas de investigación futuras.

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

- Estudio de la influencia de los sistemas de riego y adopción de la estrategia óptima respecto de la productividad, así como de la calidad y cantidad de aceite de oliva.
- Estudio y evaluación de la eficiencia energética respecto de distintas estrategias de riego y sectorización.
- Evaluación de la adaptabilidad de distintos sistemas de cultivo y diferentes variedades de olivo a distintas zonas en riego en la provincia de Jaén.
- Estudio y valoración de los requerimientos hídricos y la productividad de distintos cultivos de alto valor añadido aplicando criterios de eficiencia hídrica y energética.
- Desarrollo de técnicas de sistemas de información geográfica (SIG/GIS) mediante la utilización de datos actuales y series temporales de satélites de carácter público y libre acceso para la identificación de periodos de estrés hídrico.

6. Conclusions.

6.1. General Conclusions.

- The use of different methodologies by various public agencies gives rise to considerable divergences in the data offered, making it difficult to understand and determine the basic data to be used in research (e.g. total irrigated hectares of a given crop in a region). This situation requires the effort of public institutions to define a clear strategy for the collection of these data in which complementary methodologies are adopted to allow their comparison and disaggregation, all in an environment of free, open and updated access.
- The application of sustainability criteria in traditional irrigated olive groves should not be based simply on the conservation of water resources together with efficient water management based on technical criteria. Other aspects (social, cultural and environmental) must also be taken into consideration to improve farmers' benefits and ensure the survival of the agricultural or rural environment.
- The three-sector irrigation strategy, based on the irrigation engineering of dividing the farm into three zones with the impossibility of irrigating more than one sector at the same time, is the most commonly used in localized irrigation of olive groves in the province of Jaen (the most important production area in the world). According to the results obtained in the research carried out on a regular basis, it is unable to provide sufficient quantity of water in the most critical moments or phenological stages for the olive tree (spring: mid-June - endocarp growth phase, and autumn: mid-September to the end of November - oil accumulation phase).
- The most appropriate irrigation strategies in olive groves in the province of Jaen to ensure near optimal conditions correspond to irrigation engineering based on

sectorization in one or two sectors at most. Regarding the periodicity, daily irrigation schedules should be made, and with respect to the doses and date of application, it is advisable to use controlled or regulated deficit irrigation techniques.

- Knowledge of the availability and evolution of water in the soil in irrigated olive plantations is essential from the point of view of water resource management planning, especially in areas with limited available water resources, as it allows decision making in different areas; from irrigation engineering (determination of the number and extension of irrigation sectors), to the optimization of irrigation scheduling and timing (dosage and frequency). In both cases the objective is to provide the available water resources in the most efficient way.
- The use of GIS geographic information systems methodologies together with the existence of easily accessible public data allow, in a simple way to implement, the determination of the evolution of the water balance and the water reserve in the soil and its temporal and spatial variations for a given crop, (which in our case is the olive grove). The adaptability and scalability of the methodology and tools used make it possible to study any other crop in any other area, being possible to obtain results even at farm or plot level depending on the level of precision adopted.
- The results obtained at the provincial level with respect to both the monthly variation of the water balance and the variation in the soil water reserve in the area studied suggest that predetermined irrigation schedules should be avoided, both in date and place, since not all areas share the same temporal and spatial needs in water dosage (in the case of the study, the province of Jaen).

6.2. New lines of future research.

Following the results obtained in this thesis, some possible lines of future research are listed below:

- Study of the influence of irrigation systems and adoption of the optimal strategy with respect to productivity, as well as olive oil quality and quantity.
- Study and evaluation of the energy efficiency of different irrigation and sectorization strategies.
- Evaluation of the adaptability of different cultivation systems and different olive tree varieties to different irrigated areas in the province of Jaén.
- Study and assessment of water requirements and productivity of different high value-added crops applying water and energy efficiency criteria.
- Development of geographic information systems techniques (GIS/GIS) using current data and time series of public and open access satellites for the identification of periods of water stress.

7. Difusión de los Trabajos.

La presente Tesis Doctoral se ha realizado mediante la realización de diferentes trabajos de forma estructurada que han sido difundidos en revistas y congresos. A continuación se muestra la relación de lo indicado:

Revistas:

- Publicación 1: Molina-Moral, J.C., Moriana-Elvira, A., and Pérez-Latorre F.J., 2022. The Sustainability of Irrigation Strategies in Traditional Olive Orchards. Agronomy, 12(1): 64. 1-15 pp. DOI: [https://doi.org/10.3390/agronomy12010064].
- Publicación 2: Molina-Moral, J.C., Moriana-Elvira, A., and Pérez-Latorre F.J., 2022. Determination of the water reserve in the soil using GIS and its application in irrigation engineering. Agronomy, 12(9):2188. 1-24 pp. DOI: [https://doi.org/10.3390/agronomy12092188].

Congresos:

- XXXVIII Congreso Nacional de Riegos en Cartagena, (AERYD). Parte I, 2020. Las fuentes de información en Agricultura. Estudio y Evolución de la superficie de olivar de riego en Andalucía. Comparación con la provincia de Jaén. Nº A-01-2020. DOI: [http://dx.doi.org/10.31428/10317/8664].
- XXXVIII Congreso Nacional de Riegos en Cartagena, (AERYD). Parte II, 2021. Estudio de la gestión de las estrategias de riego en los olivares tradicionales. Nº A-03-2021. DOI: [http://dx.doi.org/10.31428/10317/10085].

- XX Simposio Científico-Técnico EXPOLIVA (Feria Internacional del Aceite de Oliva Virgen Extra e Industrias Afines), 2021. Estudio del consumo de agua y energético en los sistemas de riego localizados. Caso práctico del olivar en la provincia de Jaén. Nº: OLI-0921. ISBN: 978-84-946839-3-0.

Anexos

Supplementary Materials

Supplementary Material S1: Localization of Agroclimatic Stations.

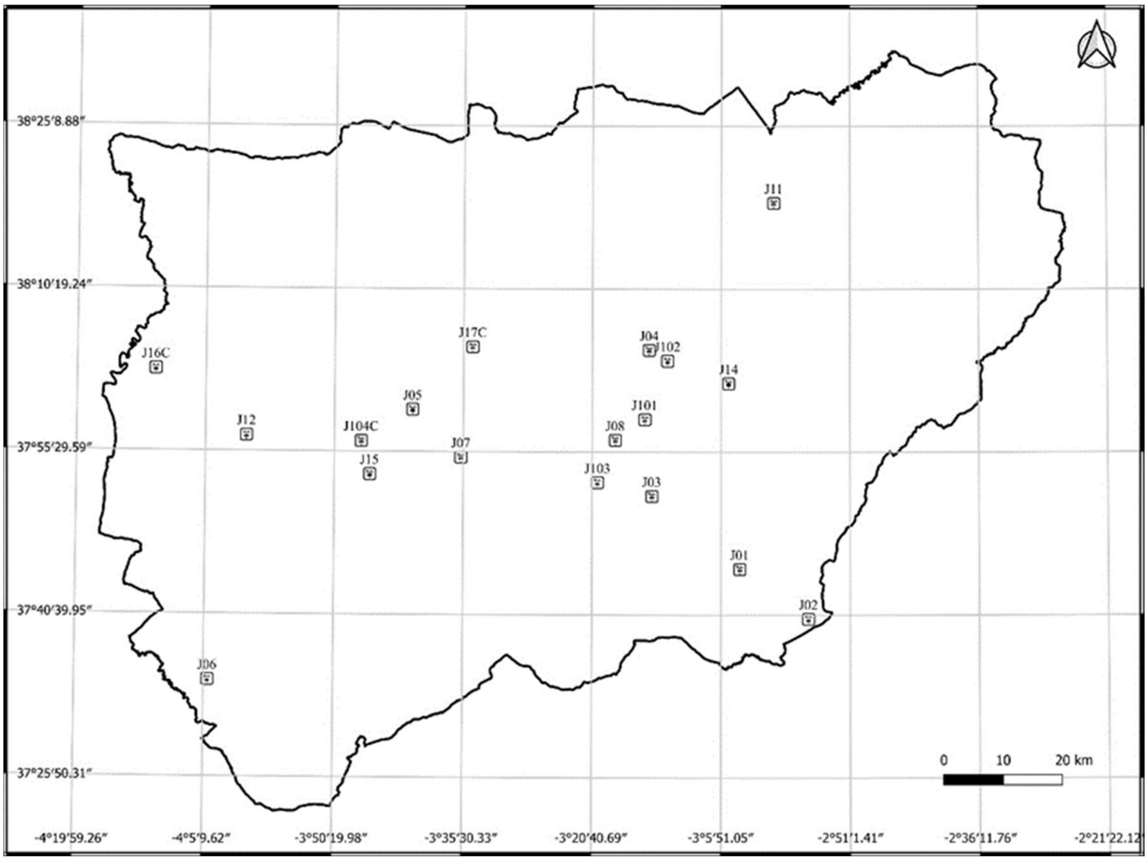


Figure S1.1. Localization of the agroclimatical stations belonging to the Andalusian Agroclimatic Information Network, (RIA, [25]).

Table S1.1. Description of the localization of the agroclimatical stations, (Geographic coordinates in datum ETR89 Reference System, Zone 30).

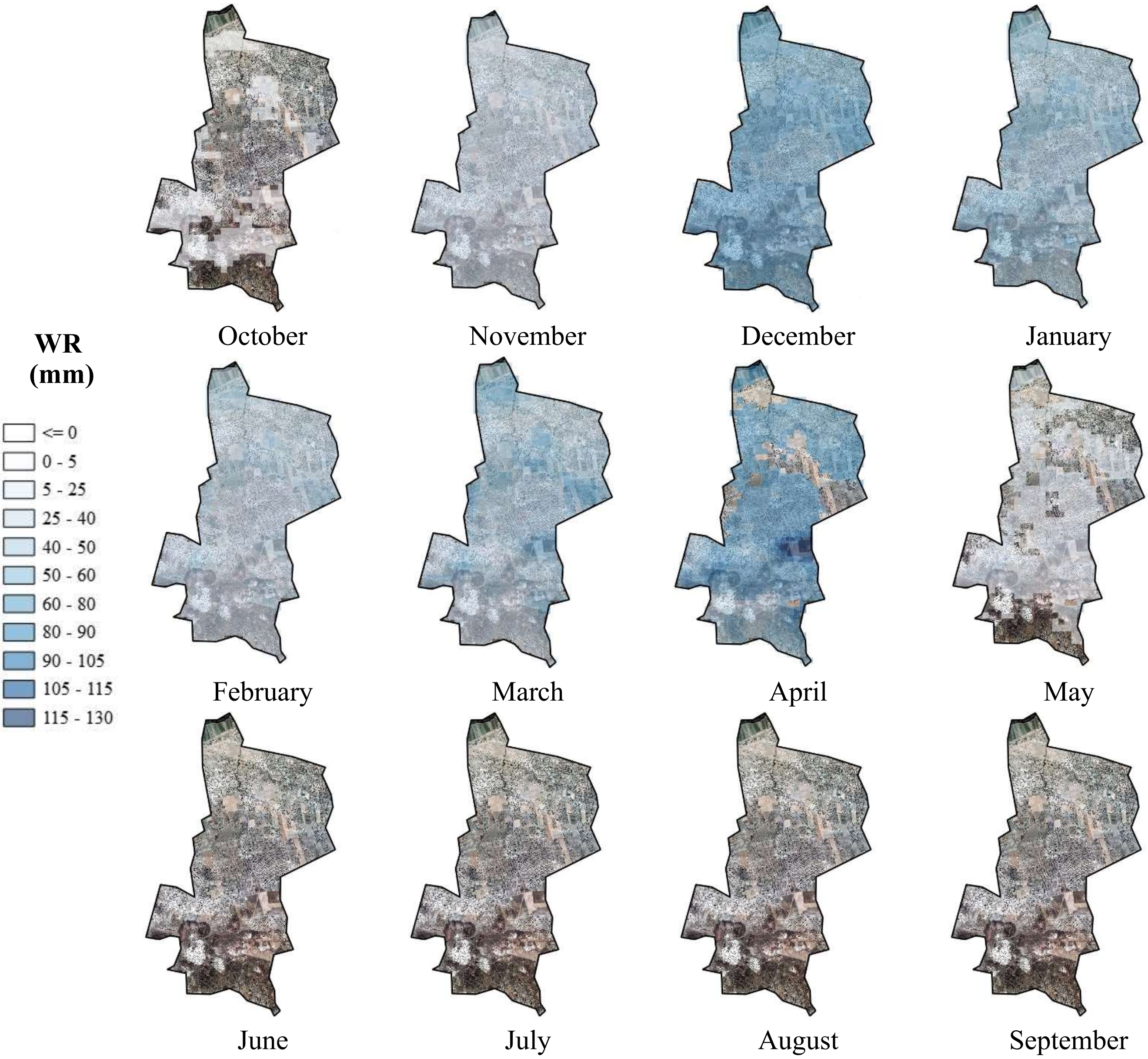
Nº Station	Code Station	Station Name	Latitude (° ' ")	Longitude (° ' ")	Altitude
1	J06	Alcaudete	37° 34' 38.15826" N	-4° 4' 42.11746" W	640
2	J11	Chiclana de Segura	38° 18' 10.33363" N	-2° 59' 47.44210" W	571
3	J01	Huesa	37° 44' 50.61022" N	-3° 3' 42.01276" W	779
4	J15	Jaén	37° 53' 26.24700" N	-3° 46' 16.59644" W	299
5	J103	Jódar	37° 52' 43.01767" N	-3° 20' 3.31623" W	486
6	J12	La Higuera de Arjona	37° 56' 55.57861" N	-4° 0' 27.76093" W	257
7	J17C	Linares	38° 5' 2.24119" N	-3° 34' 28.39659" W	282
8	J07	Mancha Real	37° 54' 59.13084" N	-3° 35' 47.32958" W	407
9	J16C	Marmolejo	38° 2' 56.34633" N	-4° 10' 57.08075" W	240
10	J104C	Mengibar IFAPA	37° 56' 27.55497" N	-3° 47' 15.56124" W	293
11	J02	Pozo Alcón	37° 40' 19.00363" N	-2° 55' 48.41190" W	881
12	J04	Sabiote	38° 4' 46.13676" N	-3° 14' 7.80210" W	791
13	J03	San José de los Propios	37° 51' 28.63774" N	-3° 13' 49.05230" W	494
14	J14	Santo Tomé	38° 1' 45.18263" N	-3° 4' 58.37804" W	537
15	J05	Torreblascopedro	37° 59' 19.46954" N	-3° 41' 21.59041" W	275
16	J101	Torreperogil	37° 58' 27.75167" N	-3° 14' 38.27638" W	535
17	J08	Úbeda	37° 56' 34.36691" N	-3° 18' 1.69439" W	343
18	J102	Villacarrillo	38° 3' 48.29188" N	-3° 12' 1.95580" W	649

Supplementary Material S2: An example of the application of the described methodology at the municipal level.

The municipality district area of Cazalilla is located in the western part of the study area, has an extension of 46.83 km2 and allocates an area of 34.34 km2 to olive oil cultivation, which represents almost 77% of the extension of its territory and shows its marked agricultural character (Figure S2.1).

Figure S2.1. Localization of the municipality district area of Cazalilla, (Jaen) with indication of the agricultural zones in Jaen, (Spain).

Applying the described methodology in this municipality it is confirmed that the variation in the water reserve takes place from October to May, although with more moderate values, so that at a general level in the municipality, irrigation schedules should be programmed from spring to autumn, that is, from April or May to October (Figure S2.2). In view of the results obtained, a more detailed analysis described the spatiotemporal varia-tion in the water reserve in the municipality, which acquired its maximum value during the month of April, with 129.27 mm in the eastern part of the municipality and the detec-tion of some extension strips in the northern, central and southern areas that depleted their reserves more quickly; therefore, irrigation schedules should be extended, starting earlier to make up for this water deficit. On the other hand, the beginning of the water re-serve during the month of October showed a maximum value of 7.68 mm, which was not homogeneous throughout the municipality, and were located locally in the northern and southern ends of the same appearing large areas in which the water reserve was zero, which showed that from November, we found water reserve values ranging between 23.79 and 42.8 mm throughout the municipality.



October November December January

February March April May

June July August September

Figure S2.2. Monthly variation of soil water reserve in the municipality of Cazalilla, (WR is water rerserve in the soil).