UNIVERSIDAD DE JAÉN

DEPARTAMENTO DE INGENIERÍA MECÁNICA MINERA

ÁREA MECÁNICA DE FLUIDOS

TESIS DOCTORAL

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IMPLEMENTACÍON DE UN SISTEMA DE INFORMACIÓN GEOGRÁFICO PARA LA CALIDAD DEL AGUA DE RIEGO DEL OLIVAR EN LA PROVINCIA DE JAÉN

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JAÉN, 10 de mayo de 2018

UNIVERSIDAD DE JAEN

Implementación de un Sistema de Información Geográfico para la calidad del agua de riego del olivar en la provincia de Jaén

Tesis Doctoral

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Certifican:

Que el trabajo recogido en la presente Memoria, titulada: "*Implementación de un Sistema de Información Geográfico para la calidad del agua de riego del olivar en la provincia de Jaén*", presentada por Juan Manuel Peragón Juárez, ha sido realizado bajo nuestra dirección y consideramos que presenta contenido científico suficiente, por lo que autorizamos su presentación y defensa para optar al grado de Doctor por la Universidad de Jaén,

Jaén, mayo de 2018

Fdo: Francisco José Pérez Latorre.

Fdo: Antonio Delgado García

Agradecimientos

A mi director de tesis, D. Francisco José Pérez Latorre, por su motivación, dedicación, tiempo, interés, inmejorable trato personal y por haberme guiado con sus enseñanzas en cada día que hemos compartido. Por su gran vocación profesional: "sine agricultura nihil", sentimiento del que me ha hecho partícipe.

A mi co-director de tesis, D. Antonio Delgado García, por formar parte de este trabajo, por su valioso tiempo, esfuerzo, dedicación, anhelo por el buen hacer, por mostrar el camino y poner un punto de sensatez a tantas líneas escritas.
A ambos, por creer en la realización de este trabajo.

A todos los que, en algún momento, han sido partícipes del hecho de que pueda estar hoy escribiendo estas líneas.

A mi familia y amigos que, aunque en ocasiones no han entendido mi tozudez y perseverancia, me han animado y ayudado a seguir en mí empeño.

Al pilar fundamental de apoyo que he tenido, en los buenos y malos momentos, por su comprensión, cariño y fuerza, por estar siempre a mi lado y confiar en mí, eternamente agradecido a mi mujer, Mari Carmen.

A mis hijos, Laura y Gonzalo, para que todo este esfuerzo les sirva de motivación.

"Per geometriam veritas"

Abreviaturas

GIS: Sistema de información geográfico

EMC: Evaluación multicriterio

EMO: Evaluación multiobjetivo

P: Precipitación

Tmax: Temperaturas máximas

Tmin: Temperaturas mínimas

Tmed: Temperaturas medias

Pe: Precipitación efectiva

ETo: Evapotranspiración potencial

Ia FAO: Índice de áridez

FAO: Organización de las Naciones Unidas para la Alimentación y Agricultura

Ca^{2+}: Calcio

Mg^{2+}: Magnesio

Na^{+}: Sodio

Cl^{-}: Cloruro

HCO_3^{-}: Bicarbonato

CO_3^{2-}: Carbonato

SO_4^{-}: Sulfato

NO_3^-: Nitrato

NH_4^+: Amonio

PO_4^{3-}: Fosfato

K^+: Potasio

B: Boro

ECw: Conductividad eléctrica del agua

ECe: Conductividad eléctrica del extracto de saturación suelo

ECc: Conductividad eléctrica umbral

pH: Coeficiente que índica el grado de acidez o basicidad de una solución acuosa

pHs: valor teórico calculado de pH al cual un agua con una determinada alcalinidad y contenido en Ca está en equilibrio.

CST: Concentración de sales totales

SAR: Relación de adsorción de sodio

$SAR_{Ajustada}$: Relación de adsorción de sodio ajustada

RSC: Carbonato sódico residual

Ca^{2+}/Mg^{2+} ratio: relación Ca^{2+}/Mg^{2+}

º fH: Dureza del agua expresada en grados franceses

Is: Índice de Langelier

Alk: Concentración de CO_3^{2-} + HCO_3^-

Alkc: Carbonatos que debe tener el agua para evitar la precipitación

Alke: Cantidad de carbonatos a eliminar

p: Logaritmo negativo de la concentración; p(Alk), p(Alkc)

NUE: Eficiencia en el uso de nitrógeno en fetirrigación

$N_{fertilizer}$: Tasa de fertilización de nitrógeno para el cultivo

YR: Rendimiento relativo del cultivo

LR: Requerimientos de lixiviación

CF: Factor de concentración

LF: Fracción de lavado

Cf: Concentración final de la mezcla de agua

Ca: Proporción de agua superficial en la mezcla

Cb: Proporción de agua subterránea en la mezcla

Qa: Concentración de agua superficial

Qb: Concentración de agua subterránea

Qf: Concentración de ambas fuentes de agua (Qa + Qb)

IWE: Índice de eficiencia del agua de riego

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Resumen

En la presente Tesis Doctoral se pretende contribuir al uso eficiente del agua de riego del olivar en la provincia de Jaén, en función a la calidad de las fuentes de agua disponibles para riego (superficial y subterránea), y teniendo presente la influencia de factores agroclimatológicos.

Como método de trabajo ha desarrollado un Sistema de Información Geográfico (GIS) basado en herramientas de decisión multicriterio-multiobjetivo (EMC-EMO), capaz de ayudar en los procesos de toma de decisión, que integran y analizan espacialmente información compleja, asignan una solución en unas coordenadas geográficas específicas, proporciona análisis de alternativas, fácil de actualizarse de manera inmediata, y de integrarse con otras herramientas de decisión. Se ha construido una base de datos espacial compuesta por una serie de capas de información que contienen datos localizados en el espacio y con componentes de carácter temporal, ya sean mensual, semestral (haciéndolo coincidir con los periodos de riego/no riego del olivar: octubre-marzo y abril-septiembre) y/o anual.

En base a la aplicación de procedimientos EMC-EMO, se han superpuesto capas de información de datos climáticos, índices climáticos, calidad de agua superficial, calidad de agua subterránea, tipo de suelo, orografía y zonas de riego de olivar, todos ellos con los tratamientos estadísticos de temporalidad precisos. Esto ha permitido zonificar la provincia de Jaén en diferentes territorios, generando una gradación en el riesgo de utilización de aguas de mala calidad y creando un marco conceptual para el manejo sostenible de los recursos hídricos.

Los resultados, tras el análisis de la información, han proporcionado soluciones complejas que integran distintos aspectos del manejo del cultivo con la relación suelo-

agua-olivar, tales como: (i) la degradación del suelo, (ii) sobre los trastornos nutricionales de las plantas, (iii) la obstrucción de los sistemas de riego, y (iv) la degradación de las reservas de agua por contaminación. Con esta metodología, se han determinando como resultados de la herramienta propuesta: (i) las cantidades de ácido a añadir y tiempos de inyección para paliar los riesgos potenciales de obstrucción en los sistemas de riego localizado, (ii) cantidades de nitrógeno que se aplican al olivar con el agua de riego y con los tratmientos de limpieza, (iii) los requisitos de lixiviación para optimizar el rendimiento relativo de los cultivos, y (iv) la viabilidad de la utilización conjunta para el riego de olivar de aguas superficiales y subterráneas. Estos resultados no solo de evitarán una acumulación excesiva de sal en el suelo y los riesgos de contaminación por retornos de agua, sino que contribuirán también a la sostenibilidad económica en el manejo de los sistemas de riego del olivar.

La metodología propuesta ha permitido proponer soluciones complejas en el manejo del agua de riego en olivar en la provincia de Jaén, que integran muchos criterios de decisión. Estos criterios, y los métodos para analizarlos, no están habitualmente al alcanze de los agricultores. La herramienta de decisión basada en GIS propuesta ha sido efectiva definiendo estrategias a escala regional en el manejo del riego, con propuestas de manejo del riego acordes con las calidades del agua. Además, permite aprovechar sinergias y economías de escala en la adopción de medidas para minimizar los riesgos asociados a la calidad del agua de riego.

En el primer capítulo de esta Tesis Doctoral, se ha realizado una introducción general al olivar de la provincia de Jaén, estableciendo una descripción geográfica, climática, de tipología de suelo, e hidrológica de la zona de estudio, provincia de Jaén. Agronómicamente se centrá en el cultivo de olivar que es el predominante en la provincia, y en la afección que puede ocasionar el uso de las fuentes de agua disponibles, superficial y subterránea, en el riego del olivar.

En el segundo capítulo, el objetivo principal fue la caracterización de riesgos en el uso del agua de riego disponible, utilizando para ello datos de calidad de agua, meteorológicos, de suelo y cultivo. Se realizaron mapas de diversos tipos de riesgo: degradación del suelo, trastornos nutricionales de las plantas, obstrucción de los sistemas de riego y problemas en los sistemas de almacenamiento de agua, obteniendo una aproximación general al estado actual de la situación.

El tercer capítulo se orientó a la gestión de la calidad del agua y la información climática para evaluar las necesidades de lixiviación del agua (fracciones de lavado) para el riego de olivar con el fin de evitar la acumulación excesiva de sales en los suelos optimizando el rendimiento relativo del cultivo del olivar.

El cuarto capítulo de la presente Tesis Doctoral, se enfocó el manejo integrado del riesgo de obstrucción de emisores en riego localizado y la fertilización nitrogenada. Para ello, se desarrollo una herramienta capaz de deterinar las cantidades de ácido nítrico a añadir y los tiempos de inyección para evitar obstrucciones. Los datos de composición del agua de riego y los requerimientos de ácido se integraron, proporcionando información sobre la cantidad total de N suministrado con agua de riego acidulada y sobre el requerimiento adicional de N que se debería añadir como fertilizante para cubrir las necesidades de cultivo. La herramienta permitiría un interesante manejo integrado de la inyección de ácido para evitar obstrucciones y la fertilización nitrogenada a nivel de comunidad de regantes.

En el capítulo cinco se centró en el uso eficiente del agua de riego evaluando las mejores prácticas de gestión del riego en el olivar de la provincia de Jaén. Se consideró como opción para el manejo sostenible del riego basado en la calidad de aguas, la mezcla de aguas superficiales y subterráneas dónde fuese posible. En caso contrario, se estimaron los requerimientos de lavado. La herramienta basada en GIS permitió localizar la solución más apropiada en la provincia de Jaén. También permitió el análisis económico de diferentes alternativas de manejo del agua de riego en cada zona de la provincia definida, permitiendo el análisis comparativo de todas ellas.

Una discusión general de los resultados se realiza en el sexto capítulo, y la exposición de las principales conclusiones del presente estudio se muestra en el capítulo siete. Es necesario resaltar, que aunque el estudio se ha centrado en la provincia de Jaén, las herramientas de decisión propuestas basadas en GIS son fácilmente actualizables y aplicables a otras zonas de riego. Por lo general, las técnicas GIS se han utilizado como una herramienta para almacenar, analizar y mostrar información espacial de manera eficiente para la gestión de los recursos hídricos. En la presente tesis se demuestra que la información espacial se puede procesar con éxito mediante técnicas GIS para proporcionar las mejores soluciones en cada zona de un área regable permitiendo incluso un análisis económico a escala regional. Este es un tema relevante no solo con vistas a analizar los beneficios económicos potenciales. Con frecuencia, en la implementación de cambios en el esquema de irrigación, prevalecen los beneficios sociales y se requieren grandes inversiones públicas. En este sentido, las soluciones propuestas basadas en herramientas GIS pueden ayudar a los responsables de las políticas gubernamentales a tomar decisiones. Este tipo de herramientas basadas en GIS también puede adaptar las decisiones a cambios rápidos en la composición del agua. Por último, se exponen las futuras líneas de trabajo y la difusión del mismo en los capítulos séptimo y octavo, respectivamente.

Los resultados presentados en esta Tesis Doctoral están recogidos en las siguientes publicaciones:

- Publicación 1. Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., 2015. A GIS-based quality assessment model for olive tree irrigation water in southern Spain. Agricultural Water Management 148:232-240.
- Publicación 2. Peragón, J.M., Delgado, A., Rodríguez-Díaz, J.A., Pérez-Latorre, F.J., 2016. A GIS-based decision tool for reducing salinization risks in olive orchards. Agricultural Water Management 166:33-41.
- Publicación 3. Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., 2017. A GIS-based tool for integrated management of clogging risk and nitrogen fertilization in drip irrigation. Agricultural Water Management 184:86-95.
- Publicación 4. Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., Tóth, T. 2018. Best management irrigation practices assessed by a GIS-based decision tool for reducing salinization risks in olive orchards. Agricultural Water Management 202:33-41.

Abstract

This Doctoral Thesis aims to contribute to the efficient use of irrigation water in the olive orchards in the province of Jaén, based on the quality of water sources available for irrigation (surface and underground), and bearing in mind the influence of agroclimatological factor.

To this end, we developed a Geographic Information System (GIS) based on multicriteria-multiobjective decision tools (EMC-EMO). This system is capable of assisting decision-making processes, integrating and analyzing spatially complex information, and assigning a solution to specific geographic coordinates. It also provides analysis of alternatives, an be quickly updated, and it is posiible to be integrated with other decision tools. A spatial database composed of a series of information layers containing data located in the space and with temporary components, either monthly, semi-annual (coinciding with the irrigation / non-irrigation periods of the olive orchards: October -March and April-September) and/or annual.

Based on the application of EMC-EMO procedures, layers of information on climate data, climatic indices, surface water quality, undergroundwater quality, soil type, orography and olive irrigation areas can be overlapped. All layers have precise temporality statistical treatments. This allowed us to zonify the Jaén province in different territories, generating a gradation in the risk of using poor quality water and creating a conceptual framework for the sustainable management of water resources.

As result,, after the analysis of the information, it was obtained complex solutions that integrate different aspects of crop management with the soil-water-olive relationship, such as: (i) soil degradation, (ii) nutritional disorders of the plants, (iii) the obstruction of the irrigation systems, and (iv) the degradation of the water reserves due to contamination.

The following were determined as results of the proposed tool: (i) the amounts of acid to be added and injection times to mitigate the potential risks of obstruction in the localized irrigation systems, (ii) amounts of nitrogen that are applied to the olive orchards with the irrigation water and with the cleaning treatments, (iii) the leaching requirements to optimize the relative yield of the crops, and (iv) the viability of the joint use for the irrigation of olive groves of superficial and underground waters. These results will not only prevent an excessive accumulation of salt in the soil and the risks of contamination by water returns, but will also contribute to the economic sustainability in the management of irrigation systems in the olive orchards.

The GIS system provided complex solutions in the management of irrigation water in olive groves in the Jaén province, which integrate many decision criteria. These criteria, and the methods for analyzing them, are not usually accessible to farmers. The proposed GIS-based decision-making tool has been effective in defining strategies at the regional level for irrigation management in accordance with water quality. In addition, it allows us to take advantage of synergies and scale economies in the adoption of measures to minimize the risks associated with the irrigation water quality.

In the first chapter of this Doctoral Thesis, a general introduction was made to the olive orchards of the Jaén province, establishing a geographical, climatic, soil typology, and hydrological description of the study area, i.e. the province of Jaén in south Spain. The research focuses on the cultivation of olive orchards that is the predominant one in the province, and on the affection that can cause the use of available water sources, superficial and underground, when used for irrigation of the olive orchard.

In the second chapter, the main objective was the characterization of risks in the use of available irrigation water, using data on water, climeate, soil, and crop quality.

Maps of various types of risk were made: soil degradation, nutritional disturbances of plants, obstruction of irrigation systems and problems in water reserves systems, obtaining a general approximation to the current state of the situation.

The third chapter was focused on the management of water quality and climate information to evaluate the leaching needs of water (leaching fractions) for the irrigation of olive orchards in order to avoid the excessive accumulation of salts in soils for optimizing the relative yield of olive orchard.

The fourth chapter of this Doctoral Thesis dealed with the integrated management of the risk of obstruction of emitters in localized irrigation and nitrogen fertilization. For this, a tool was developed capable of determining the amounts of nitric acid to be added and the injection times to avoid obstructions. The data of the irrigation water composition and the acid requirements were integrated, providing information on the total amount of N supplied with acidulated irrigation water and on the additional N requirement that should be added as fertilizer to cover crop needs. The tool would allow an interesting integrated management of the injection of acid to avoid obstructions and nitrogen fertilization at the community level of irrigators.

In chapter five, the efficient use of irrigation water was assessed by defining the best irrigation management practices in the olive orchard of the Jaén province. It was considered the blending of surface and undergroundwater where possible as an option for the sustainable management of irrigation based on water quality. Otherwise, the leaching requirements were estimated. The tool based on GIS allowed the location of the most appropriate solution in the Jaén province. It also allowed the economic analysis of different irrigation water management alternatives in each zone of the defined province, allowing the comparative analysis of all of them.

A general discussion of the results is made in the sixth chapter, and the presentation of the main conclusions of the present study is shown in chapter seven. It is necessary to highlight that although the study has focused on the Jaén province, the proposed decision tools based on GIS are easily updatable and applicable to other irrigation areas. In general, GIS techniques have been used as a tool to store, analyze and show spatial information efficiently for the management of water resources. This thesis shows that spatial information can be successfully processed using GIS techniques to provide the best solutions in each site of an irrigation area. It allows even an economic analysis at a regional scale. This is a relevant issue not only with a view to analyzing the potential economic benefits. Frequently, in the implementation of changes in the irrigation scheme, social benefits prevail and large public investments are required. In this sense, the proposed solutions based on GIS tools can help politicians to take decisions. This type of GIS-based tools can also adapt decisions to rapid changes in the composition of water. Finally, the future lines of research are exposed in the seventh and eighth chapters.

The results presented in this Doctoral Thesis are included in the following publications:

- Publication 1. Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., 2015. A GIS-based quality assessment model for olive tree irrigation water in southern Spain. Agricultural Water Management 148:232-240.
- Publication 2. Peragón, J.M., Delgado, A., Rodríguez-Díaz, J.A., Pérez-Latorre, F.J., 2016. A GIS-based decision tool for reducing salinization risks in olive orchards. Agricultural Water Management 166:33-41.

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Capítulo 1. Introducción y objetivos

1.1. Marco teórico

1.1.1. Justificación de la investigación

En muchos países mediterráneos, como en otras zonas áridas y semiáridas del mundo, los procesos de salinización y sodicidad en los suelos y la fitotoxicidad por ciertos iones están típicamente relacionados con el riego, constituyendo una preocupación cada vez mayor, como en el Este y parte del Sur de España (Toth et al., 2008; Aragues et al., 2011). En España, el aumento de la superficie de olivar de regadío ha implicado el uso de agua de baja calidad para el riego en muchas áreas, sobre todo en el Sur del país (Aragues et al., 2005; Aragues et al., 2010). Una evaluación precisa de la calidad del agua es un requisito básico para evitar problemas del manejo de los sistemas de riego. Sin embargo, la evaluación de la calidad del agua de riego a escala regional, con diferentes fuentes de agua, puede suponer un problema complejo. La aplicación de la estrategia de riego depende de las condiciones locales, tales como el clima, el suelo, las plantas, la disponibilidad de agua y gestión del riego. Para un estudio completo en una región determinada han de sumarse a los parámetros de calidad del agua, al menos, datos de precipitación efectiva, evapotranspiración, propiedades del suelo, y la geomorfología, pues pueden afectar el riesgo relacionado con el uso de aguas de baja calidad. El aumento de la demanda ha implicado el uso cada vez mayor de fuentes de agua con mala calidad y ha supuesto una enorme presión sobre el sector agrícola en el uso eficiente de los recursos de agua disponibles para obtener mejoras de los rendimientos (Orgaz y Fereres, 2004). El incremento en la eficiencia del riego (volumen de agua consumida por los cultivos en relación al volumen de agua aplicada) se indica dentro del Plan Hidrológico Nacional, el Plan Nacional de Regadíos y el Plan de Choque de Modernización de

Regadíos como una estrategia fundamental para optimizar el aprovechamiento de los recursos hídricos disponibles (MARM, 2002, 2006).

La cuenca del Guadalquivir sufre un importante déficit hídrico anual por lo que el organismo regulador de la cuenca (Confederación Hidrográfica del Guadalquivir) ha propuesto una serie de condiciones a los regantes en cuanto a dotación de agua. En el caso del olivar en Jaén, se ha asignado una dotación anual por hectárea de 1500 m^3. Esta disponibilidad de agua implica un suministro de agua insuficiente para obtener la plena producción en olivar. Por ello, en la cuenca del Guadalquivir son habituales las estrategias de riego deficitario en olivar (Pastor et al., 2002). El olivo es una especie con una buena respuesta al riego, incluso en condiciones de suministro limitado, lo que hace posible una estrategia rentable de riego deficitario (COI, 2007). Los sistemas de riego localizado permiten mantener un contenido de agua en la zona radicular cercano a la capacidad de campo. Ello conlleva que las sales están más diluidas y el agua más disponible para las plantas. Hanson et al., (2009) demostraron que la alta eficiencia del riego por goteo, que parcialmente moja la superficie del suelo, se produjo principalmente en condiciones de riego deficitario.

En la situación actual, con el incremento del uso de aguas subterráneas de baja calidad para el riego, se puede agravar el riesgo de salinización del suelo. Además, la escorrentía superficial puede arrastrar sustancias sales y sustancias contaminantes (como los nitratos) hacia áreas permeables en las que se recargan acuíferos. Este fenómeno puede ser especialmente intenso en los cultivos de regadío (IGME, 2010). Por lo tanto, una posible solución óptima para estos riesgos potenciales podría ser la mezcla de agua de distinta procedencia (Mahfuzur et al., 2014; Prendergast et al., 1994), minimizando el riesgo de afección y vulnerabilidad de las aguas subterráneas frente a la contaminación.

El uso conjunto de aguas superficiales y subterráneas puede ser una estrategia a utilizar en el caso que nos ocupa, pues podría solucionar al menos dos de los principales problemas actuales, pues aumentaría el suministro del agua de riego y se podría mejorar la calidad del agua de riego a través de la dilución (Qureshi et al., 2004). Esta es una de las posibles soluciones. Pero aplicar esta solución escapa de las posibilidades de los agricultores e implica la existencia de herramientas capaces de gestionar una gran base de datos a diferentes niveles y de proveer de las mejores alternativas de manejo. Por otra parte, las soluciones al manejo del agua de riego implica una visión transversal del problema, que debe implicar: (i) análisis del riesgo, (ii) posibles soluciones a los problemas de la calidad del agua de riego en términos de: salinización del suelo, fitotoxicidad y mantenimiento de instalaciones de riego, y (iii) análisis económico de las soluciones. Por ello, para verificar y validar la oportunidad de la presente Tesis Doctoral, se ha tenido que tener en cuenta las necesidades de todas las partes interesadas en el cultivo del olivar, incluyendo políticos y agentes de extensión, para proporcionar soluciones según las condiciones y circunstancias. Para ello, se ha procedido al estudio de los objetivos y proyectos del II Plan Estratégico de la provincia de Jaén, aprobados por el Patronato de la Fundación "Estrategias para el desarrollo económico y social de la provincia de Jaén" el 10 de noviembre de 2011, en el que se determinan los grandes proyectos/proyectos estructurales para la provincia en el periodo 2012-2020, así como a su actualización publicada en mayo de 2016 (Herrador y Martín, 2016). En dicho Plan destacan las estrategias relaconadas con la gestión adecuada de los recursos hídricos, las de fomento para la conservación y el aprovechamiento de los recursos naturales de la provincia, el desarrollo rural sostenible y principalmente las relacionadas con mejor aprovechamiento de las aguas con destino al riego.

Del análisis de la situación, surge la necesidad de innovación en el desarrollo de marcos conceptuales en el manejo sostenible del cultivo del olivar y los recursos hídricos empleados en la provincia de Jaén. Enfocado a este problema, en el presente estudio, se reúnen múltiples variables con naturaleza compleja y se han implementado modelos de evaluación multicriterio- multiobjetivo (EMC–EMO) que permiten su análisis y la toma de decisiones.

La integración de las técnicas de Evaluación Multicriterio (EMC) y Evaluación Multiobjetivo (EMO) con herramientas de análisis estadístico y los Sistemas de Información Geográfica (GIS) constituyen una poderosa metodología para abordar el tratamiento diversas variables a escala regional: recursos hidrícos, manejo de los cultivos, propiedades del suelo, climatología, geomorfología, calidad de agua, etc., desde nuevas perspectivas y dimensiones, flexible en su forma y permitiendo rescatar la opinión de expertos y actores sociales. El uso de los sistemas de información geográfica (GIS) ofrece la posibilidad de integrar información masiva espacial de diferentes fuentes y sus criterios con atributos geoespaciales (Feick y Hall, 2004). Permiten desarrollar modelos basados en análisis espacial, simular escenarios y prever consecuencias de determinadas decisiones de planificación integral (Melhs et al., 1997). También hacen posible el análisis de alternativas, con la posibilidad de actualizarse de manera inmediata, y de integrarse con otras herramientas de decisión (EMC_AMO) en la gestión de los sistemas de riego y manejo de los cultivos (Shahbaz el al., 2007), en la evaluación de regadíos (Hidalgo, 2010), y en la calidad del agua de riego (Mirlas, 2012; Romanelli et al., 2012; Lau et al., 2005).

1.1.2. Antecedentes y estado actual

Desde el punto de vista de la calidad del agua de riego empleada en cultivos, el principal efecto negativo sobre los mismos es debido al alto contenido en sales, como se reflejan en estudios clásicos (Turner et al., 1980), con una tendencia al incremento debida en muchos casos a una mala gestión del riego. En 2002 la FAO estimaba que de 20 a 30 millones de hectáreas de tierras regables estaban seriamente afectadas por salinidad y de 0,25 a 0,50 millones de hectáreas se perdían anualmente por esta causa (Martinez, 2006). Aunque el riego aumenta los rendimientos de los cultivos en tierras áridas y semiáridas del mundo, esta práctica agrícola puede promover, entre otros problemas, la salinización, sodizacion y contaminacion de las tierras agrícolas por un manejo inadecuado tanto de los sistemas de riego como del manejo de los cultivos (Corwin et al 2007; Isidoro y Grattan 2011). La agricultura de regadío es esencial para la producción agrícola y, consecuentemente, para la seguridad alimentaria. La sostenibilidad de la agricultura de regadío requiere un equilibrio adecuado de sal en el suelo (Aragues, 2011; Keren 2012). La salinización del suelo es una consecuencia potencial muy negativa del riego y no puede ser ignorada (Letey et al., 2011). En este sentido será necesario conocer los problemas de salinidad que afectan la productividad de algunos regadíos, especialmente en las zonas áridas y semiáridas (FAO, 2004; UNEP, 1992), donde escasas e irregulares precipitaciones provocan bajos rendimientos (Melgar et al., 2009).

El presente trabajo se centra geográficamente en la provincia de Jaén y agronómicamente en el cultivo de olivar. Esta zona y cultivo representan un ejemplo evidente de rápida expansión del riego, principalmente en los últimos 20 años, con un incremento de más de 200.000 has de nueva implantación. Esta expansión no ha ido unido a una investigación en la calidad de agua de riego utilizada. De esta forma se ha producido un incremento en la cantidad consumida y una mayor probabilidad en la utilización de aguas de mala calidad para el riego. En la zona de estudio, las precipitaciones no sólo son escasas en una gran parte del territorio, sino que se distribuyen irregularmente a lo largo del año agrícola, siendo la evapotranspiración el mecanismo predominante que causa la acumulación de sal en suelos agrícolas de regadío (MARM, 2006). Para prevenir el exceso de acumulación de sales solubles en los suelos de regadío es necesaria más agua de la necesaria para satisfacer las necesidades de evapotranspiración de los cultivos, que deben pasar por la zona de las raíces para lixiviar las sales solubles en exceso (Aragües, 2011). Estas adiciones de agua para riego han sido expresadas como requerimientos de lixiviación (U.S. Salinity Laboratory Staff, 1954; Rhoades, 1974). La relación entre el rendimiento de los cultivos y la cantidad de agua requerida es esencial para determinar el manejo óptimo del riego (Letey et al., 1985). El riego con aguas salinas requiere la aplicación extra de agua para la lixiviación de sales de la zona de la raíz, con el fin de evitar la acumulación excesiva de sales que pudieran limitar el potencial rendimiento de los cultivos (Letey et al., 2011, Skaggs et al., 2012). Cuando se riega con aguas de mala calidad, la aplicación de riegos deficitarios es una práctica desaconsejada, debiéndose aplicar en cada momento: las necesidades del cultivo más un volumen complementario para realizar el lavado de las sales (FAO, 2006).

Debido a la disminución de disponibilidad de agua, principalmente en zonas semiáridas, el riego de la mayoría de las nuevas plantaciones de olivos se basa en fuentes de baja calidad de agua disponibles caracterizándose por una relativa alta salinidad (Wiesman et al., 2004). Por otro lado, también existen estudios que indican que si se realiza un manejo correcto del riego en una plantación con densidad adecuada, se podrían emplear aguas de elevado contenido salino (Vega et al., 2001). En el caso particular del olivo su respuesta frente a la salinidad ha sido estudiada por diversos autores (Aragues et al, 2005; Bernstein, 1964; Gucci y Tattini, 1997; Maas y Hoffman, 1977; Munns, 1993; Wiesman et al., 2004). Así Hartman et al. (1966) lo consideran una especie de tolerancia intermedia a la salinidad. Otros estudios apuntan a niveles de conductividad eléctrica del agua de riego en torno a 4 dS m^{-1} para que el olivo reduzca su producción (Maas y Hoffman, 1977). Dependiendo de la variedad, se han establecido límites para que haya daño al árbol entre 6 dS m^{-1}, (Bouaziz, 1976) y 12 dS m^{-1}, (Rugini y Fedeli, 1990). La FAO (1985) clasifica los olivos como moderadamente tolerantes a la salinidad, con una conductividad eléctrica umbral (ECc) del extracto de saturación del suelo entre 3 y 6 dS m^{-1} (Aragüés et al, 2005; Bernstein, 1964; FAO, 1985; Maas y Hoffman, 1977). Estudios posteriores han mostrado que existe diferente sensibilidad, según la variedad de olivo al contenido de sales (Benlloch et al., 1994; Tattini, 1992).

Además del alto contenido en sales, han de evaluarse el contenido en las aguas de riego de posibles elementos tóxicos como el Na, altos contenidos en ciertos elementos que pudieran causar daños en las infraestructuras de riego (dureza del agua), suministro desequilibrado de nutrientes a los cultivos (típicamente el N), o problemas en los depósitos de agua, debido a la presencia de nutrientes (N o P) que favorecen el desarrollo de algas. Por lo tanto, las directrices de riego deben tener en cuenta la evaluación de la calidad del agua de riego teniendo en cuenta de manera integrada diferentes efectos potenciales. Esta calidad se determina por la concentración y la composición de los solutos presentes. Como efectos negativos en el suelo hay que tener presente no sólo enriquecimiento en sales solubles del suelo, sino también los efectos en la composición cationes intercambiables, y en particular el aumento de sodicidad en el suelo (Levy 2012; Keren, 2012).

El empleo de los GIS puede integrar eficientemente información masiva proveniente de diferentes fuentes como el caso que nos ocupa. Permite incluir los datos de calidad de agua en diversos puntos de muestreo, en diferentes tiempos, con datos tomados en diferentes épocas del año, en un solo sistema para su análisis EMC-EMO (Soria et al., 1998). Los GIS son un sistema de tratamiento digital de la información (Sancho, 1996) que ofrecen la posibilidad de prever consecuencias de determinadas decisiones de planificación integral de campos muy diversos. Los GIS permiten que el análisis espacial sea más comprensivo al integrar datos relevantes del medio que se pueden organizar y manejar (Sakthivadel et al., 1999) para servir de apoyo a la toma de decisiones (Chuvieco, 1996; Bosque et al., 1994). Por ello, el tratamiento GIS de datos con métodos geoestadísticos, análisis espacial multicriterio y multuobjetivo (EMC-EMO), y su georreferenciación, ha permitido establecer un modelamiento y mapeo, cuyo marco conceptual varía de acuerdo al tipo de criterio, la disponibilidad de datos, la escala espacial de análisis y el objetivo del estudio (Burrough y MacDonnell, 1988; Juan et al., 2010).

El programa GIS empleado en la presente Tesis Doctoral ha sido gvSIG. gvSIG, que es un software "open source" y "free software" (programa de código abierto y libre distribución). Está basado en la geomática o tecnología geoespacial, que permite integrar la componente geográfica en los sistemas de información. Es capaz de trabajar con datos masivos de información de cualquier tipo u origen, tanto en formato raster como vectorial, con arquitectura modular y carácter multiplataforma. Además, permite trabajar con formatos de otros programas de acuerdo con los parámetros de la OGC (Open Geospatial Consortium), que regula los estándares abiertos e interoperables de los Sistemas de Información Geográficos. Permite acceder a información vectorial y raster, así como a servidores de mapas que cumplan las especificaciones del OGC: WMS (Web Map Service), WFS (Web Feature Service), WCS (Web Coverage Service), Servicio de Catálogo y Servicio de Nomenclátor. Está desarrollado en lenguaje de programación Java, funcionando con los sistemas operativos Microsoft Windows, Linux y Mac OS X, y utiliza librerías estándar de GIS reconocidas, como Geotools o Java Topology Suite (JTS). Asimismo, gvSIG posee un lenguaje de scripting basado en Jython y también se pueden crear extensiones en Java utilizando las clases de gvSIG. Las herramientas que implementa permiten una gran precisión en edición cartográfica, incluye funciones avanzadas para usos en teledetección, morfometría e hidrología, tecnología 3D y otras funciones básicas como diseño de impresión y soporte. Se trata de un software libre para la gestión de la información geográfica al más alto nivel. Premiado por la NASA en 2015 y 2016, y por la Unión Europea en 2017 como mejor proyecto europeo transfronterizo de software libre. El proyecto está actualmente gestionado por la Asociacion gvSIG, constituida por 5 empresas miembros, 61 empresas colaboradoras y 51 entidades no empresariales (universidades, institutos geográficos, etc.).

1.2. Marco de estudio

Para la realización de esta Tesis Doctoral se han utilizado e incluido un conjunto de datos con información de distintos aspectos:

- Espacio físico: provincia de Jaén, sus comarcas y términos municipales, es decir, la división territorial que se abarca.
- Olivar en la provincia de Jáen, principal cultivo de la misma con una gran importancia en la estructura socioeconómica y productiva.
- Hidrología superficial y subterránea, ubicando las estaciones de toma de datos de ambos tipos de agua.
- Climatología, destacando las estaciones climáticas disponibles en la provincia.
- Edafología, tipos de suelos, textura, profundidad y pendientes.
- Calidad de las aguas, destacando la salinidad, sodicidad y potencial fitotoxicidad tanto en aguas superficiales como subterráneas, sus causas y posibles efectos negativos e interpretación.

1.2.1. Espacio físico: provincia de Jaén

La provincia de Jaén es una provincia española, situada al este de la comunidad autónoma de Andalucía, y en el sureste de la península ibérica. Su superficie es de 13.489 km², ocupando el 2,67% del territorio nacional (figura 1.1).

Figura 1.1. Situación de Jaén en España y Andalucía

Limita por el oeste con Córdoba, por el norte, con Ciudad Real, por el este, con Albacete, y por el sur, con Granada. Su capital es la ciudad de Jaén. Quedó constituida como provincia en la división administrativa de 1833. Administrativamente está dividida en 97 municipios y 9 comarcas agrarias (Mapama, 2011) (figura 1.2).

Figura 2.2. Provincia de Jaén: Comarcas y Municipios
Fuente: Diputación de Jaén, 2010

En cuanto a la estructura productiva provincial, presenta algunas características específicas (CESPJ, 2011):

- Un sector agrario dependiente del monocultivo del olivar, con insuficiente generación de valor añadido, principalmente por la fase de comercialización. Su carácter de producción cíclica afecta al desarrollo de los demás sectores, sobre todo en las zonas rurales.
- Un sector de la construcción muy ligado a los ciclos agrícolas.
- Un sector industrial en el que predomina la empresa de reducida dimensión y poco tecnificada.
- Un sector servicios. Se concentra básicamente en el que generan las diferentes administraciones, el comercio y una incipiente industria hostelera.

1.2.2. Olivar en la provincia de Jaén

La provincia de Jaén es el mayor productor mundial de aceite de oliva. De esta forma, uno de los sectores más relevantes de la economía provincial es el agrario, tanto en términos de valor económico de las producciones finales, como en términos de generación de empleo. Dicho sector tiene en Jaén, el cultivo del olivo como pilar fundamental (Figura 1.3).

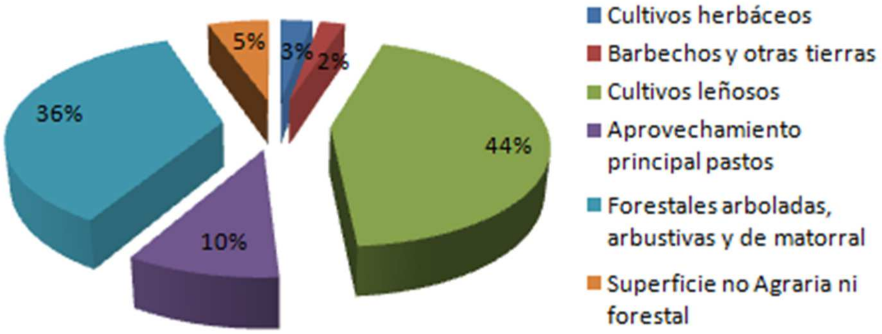

Figura 3.3. Distribución de tierras en la provincia de Jaén

Del total de la superficie provincial 1.349.609 has, el 49 por 100 (659.972 has) lo ocupan las tierras de cultivo. Del total de superficie ocupada por cultivos leñosos (591.072 has), 585.113 has son dedicadas a olivar, lo que representa el 99 por 100 del total de los cultivos leñosos existentes en la provincia. Con esta extensión de olivar, la provincia de Jaén posee alrededor del 26 por 100 de la superficie cultivada en toda España y el 42 por 100 de la andaluza.

En relación a la importancia socioeconómica del olivar y del aceite de oliva en la provincia de Jaén, cabe destacar que en términos económicos este sector representa el 30 % del Producto Interior Bruto de la provincia. Se configura como el principal elemento dinamizador de la economía, pues en prácticamente todos los pueblos de esta provincia el olivar se sitúa como el principal activo económico y por tanto, el sustento y elemento fijador de la población rural de esta provincia. El concepto de «aceites y derivados» representa más del 90% de la producción final agrícola de la provincia, porcentaje que adquiere una importancia manifiesta si se considera que el sector agrario en el conjunto de actividades económicas supone alrededor del 20% (Junta de Andalucía, 2008). En la figura 1.4, se muestra la evolución del olivar en las últimas décadas.

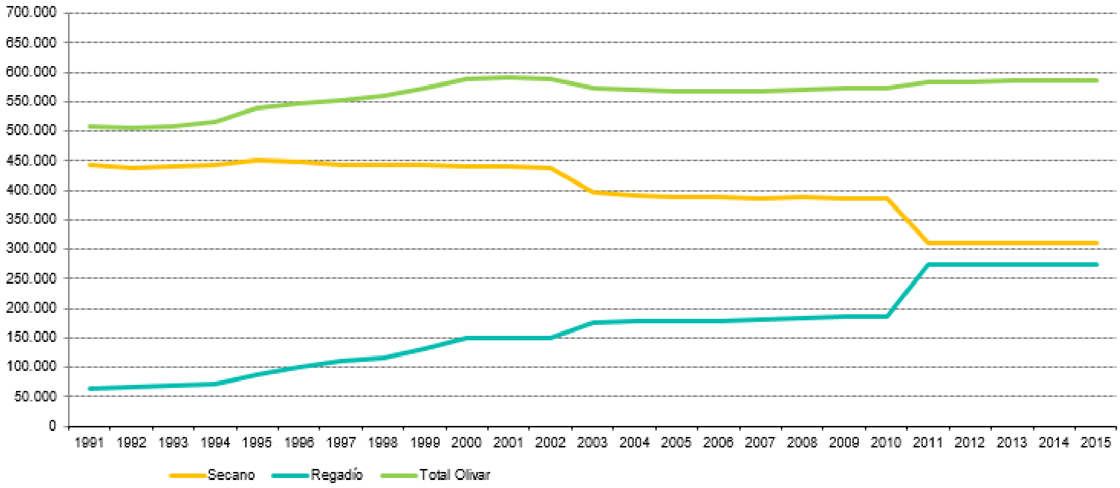

Figura 4.4. Evolución de la superficie dedicada a olivar en la provincia de Jaén. Años 1991-2015
Fuente: Junta de Andalucía. Anuario Estadístico de Andalucía. Elaboración Propia

Respecto a las variedades de olivo, destaca la variedad 'Picual' que se emplea en la producción de aceite de oliva, siendo la predominante a nivel regional (figura 1.5).

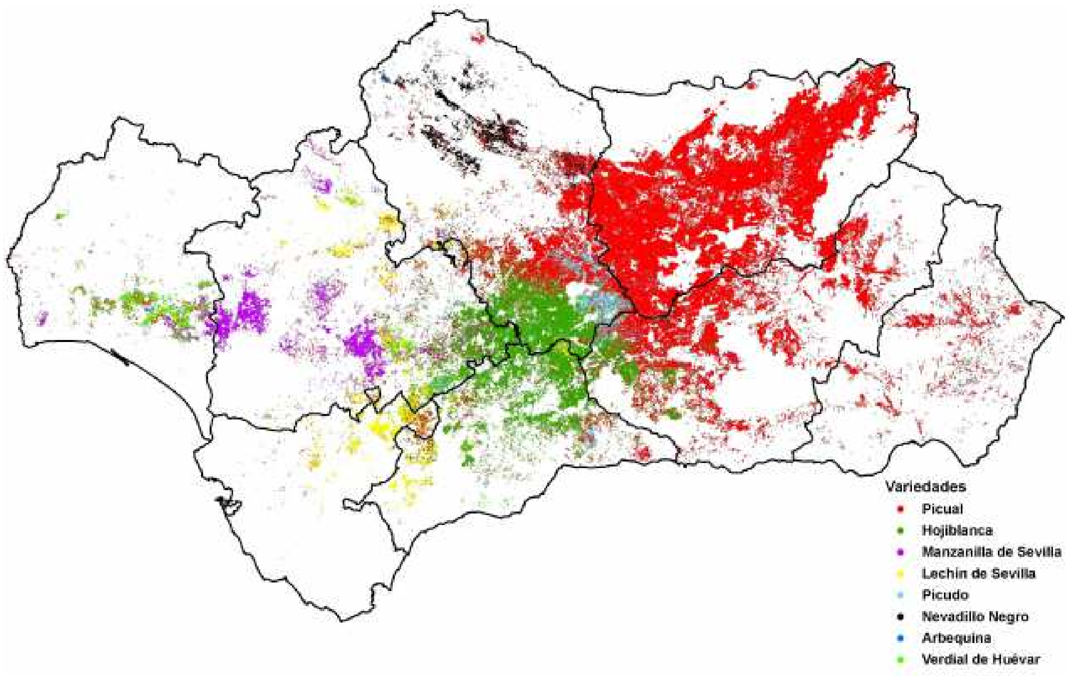

Figura 5.5. Variedades de olivar en Andalucía. Fuente: Plan Director del Olivar Andaluz (aprobado por Decreto 103/2015, de 10 de marzo, Junta de Andalucía), 2015

Tradicionalmente el cultivo del olivo se ha relacionado en la provincia de Jaén con el secano y las zonas clásicas de riego (vega de los ríos) la ocupaban especies herbáceas. Era habitual que los olivares se situaran en las laderas de los montes. También era conocido que, aunque en secano se obtienen producciones aceptables, el olivo responde muy favorablemente a las aportaciones de agua de riego, en especial cuando éstas se hacen en momentos críticos o en años de muy baja pluviometría (Pastor et al., 1999).

Con estos antecedentes en Jaén existía tradicionalmente una cierta superficie de olivar regado, pero es a partir de los años noventa del siglo anterior y principalmente en pleno periodo de sequía cuando muchos olivareros, tratando de salvar la rentabilidad de sus explotaciones, deciden la transformación en regadío de una importante superficie de olivar.

La puesta en riego de una importante superficie en tan poco tiempo creó una serie de tensiones tanto de carácter administrativo (principalmente para dar respuesta a las solicitudes concesiones de agua para riego por parte del Organismo Regulador de la Cuenca), como de carácter técnico (principalmente el establecer los calendarios y dosis de riego óptimos para el olivar). Las instalaciones de riego, al ser de reciente implantación, son mayoritariamente de riego localizado.

De forma resumida, se puede generalizar que la instalación típica en la mayoría de las nuevas instalaciones de riego sería aquella con captación de aguas de origen superficial aplicadas mediante riegos localizados, siendo el emisor más utilizado el gotero autocompensante. Debido a la escasa dotación, no se puede realizar riego a la demanda, lo que obliga a utilizar la reserva de agua del suelo. No obstante, la escasez de agua está provocando la búsqueda de recursos alternativos, subterráneos y/o residuales, a veces de forma incontrolada. En el primer caso, se perforan indiscriminadamente acuíferos cuyo potencial es desconocido. En el segundo caso, las aguas no son objeto de ningún tipo de seguimiento en la calidad de las mismas que prevenga de sus efectos negativos sobre el medio físico y ambiental.

Los calendarios de riego con aplicación de riegos recortados o escasos son los más frecuentes. Exigen determinar el contenido de agua del suelo y estimar la evolución de la reserva de agua almacenada en el suelo durante las lluvias, así como determinar el comportamiento del agua aplicada con los goteros (consumo por los árboles y profundidad a la que llega el agua).

Cabe destacar que existe un alto grado de asociacionismo entre los regantes formando comunidades y juntas de comunidades.

1.2.3. Hidrología superficial y subterránea

Para la gestión de las aguas superficiales la red hidrográfica, se ha establecido una división en cuencas y subcuencas en las que se localizan las 66 estaciones de muestreo de la red de calidad de aguas de Confederación Hidrográfica del Guadalquivir (CHG) de la provincia de Jaén (figura 1.6), así como de los puntos de toma de muestras (Anexo 1). Las subcuencas se delimitan desde las estaciones de toma de muestras aguas arriba, y las concesiones de agua para riego se establecen a nivel de subcuenca.

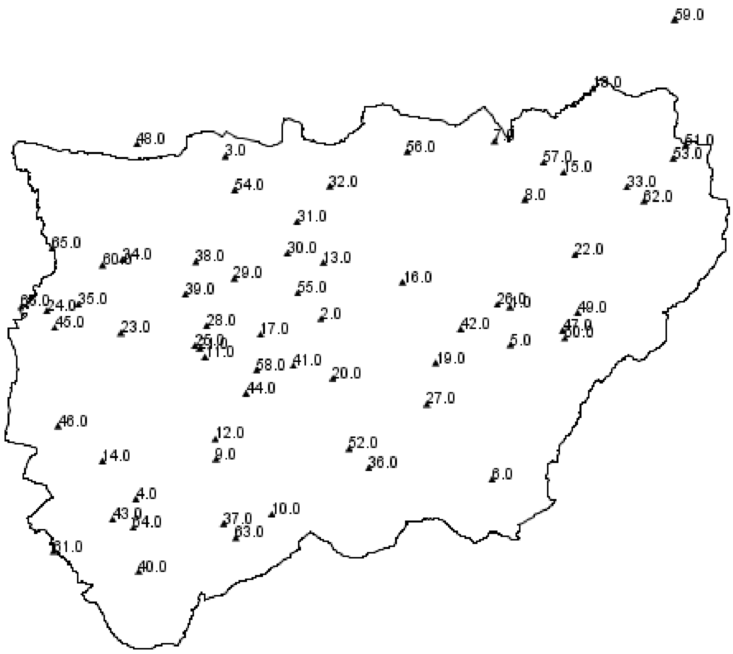

Figura 6.6. Estaciones de calidad de agua superficial en la provincia de Jaén

Las masas de aguas subterráneas en la provincia de Jaén están perfectamente definidas mediante poligonales envolventes en las que se sitúan las muestras realizadas por el Instituto Geológico y Minero de España (IGME). Se han definido 26 unidades hidrogeológicas, con una red de 136 puntos de toma de muestras (Anexo 1, figura 1.7).

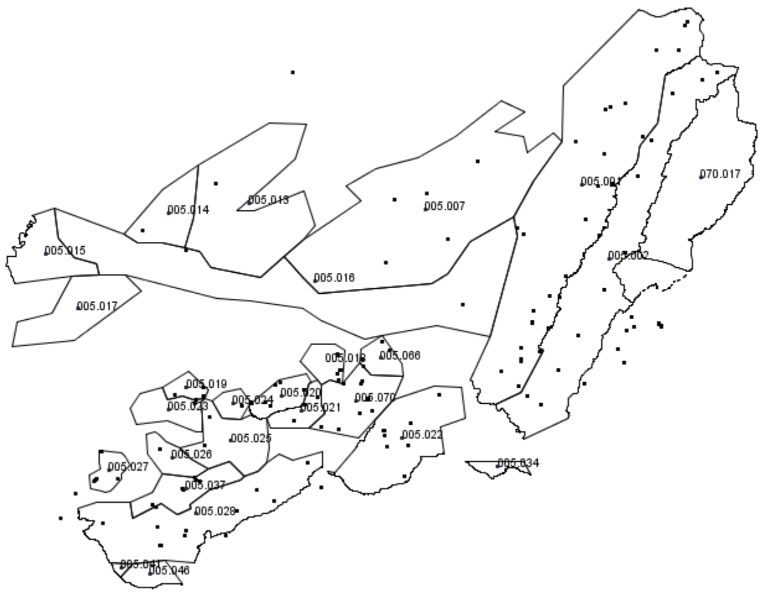

Figura 7.7. Estaciones de calidad de agua subterránea en la provincia de Jaén

1.2.4. Climatología

Las capas de información climática se utilizan como referencia para conocer la necesidad de agua del olivar. En términos generales, una mayor evapotranspiración y una menor precipitación implíca una mayor demanda de agua de los cultivos y, por lo tanto, se requeriría una mayor dosis de riego. Existen actualmente 35 estaciones climáticas automáticas y completas de la red que dispone en la provincia de Jaén la Junta de Andalucía (JJAA) (periodo 2000-2013), y el Ministerio de Agricultura, Alimentación y Medio Ambiente de España (MAGRAMA) (1976-2000) (figura 1.8) (Anexo 1) que permiten una información climática detallada para estudios de manejo del agua de riego

Figura 8.8. Estaciones climáticas en la provincia de Jaén

A grandes rasgos, en la climatología de la provincia de Jaén, domina el clima mediterráneo continental, con veranos muy calurosos y secos e inviernos fríos y relativamente lluviosos. Según la clasificación de Papadakis, el clima quedaría caracterizado por un régimen térmico "subtropical cálido" en las zonas llanas o "templado cálido" en los relieves montañosos y por un régimen de humedad "mediterráneo húmedo", aunque en los sectores suroccidental y suroriental de la provincia llega a aparecer el tipo "mediterráneo seco", según se recoge en la Memoria del mapa de suelos de la provincia de Jaén-Universidad de Granada (1987). El cultivo del olivar por tanto se adapta bien a este clima, ya que es propio de climas mediterráneos caracterizados por inviernos suaves y veranos largos, cálidos y secos.

1.2.5. Edafología

La incidencia en el cultivo del olivo de un agua de riego con una determinada calidad puede variar según el tipo de suelo (Serrano, 2008). En este sentido es muy relevante la capacidad de drenaje y de retención de agua del suelo, ya que condicionan para una dosis dada la fracción de lavado en el riego. Resulta particularmente relevante la infomación sobre texturas del suelo, ya que determina su capacidad de retención de agua.

La información disponible de suelos en la provincia de Jaén incluye el mapa de suelos a escala 1:200.000 elaborado por el Departamento de Edafología y Química Agrícola de la Universidad de Granada del año 1987 y los datos del Sistema de Información Multiterritorial de Andalucía, SIMA, extraídos del anuario estadístico de Andalucía del año 2015. En esta información se emplea la clasificación de la Organización de Naciones Unidas para la Agricultura y la Alimentación, FAO (1974, 1990). En la figuras 1.9, 1.10 y 1.11, se representan los distintos tipos de suelo, textura y profundidad, respectivamente.

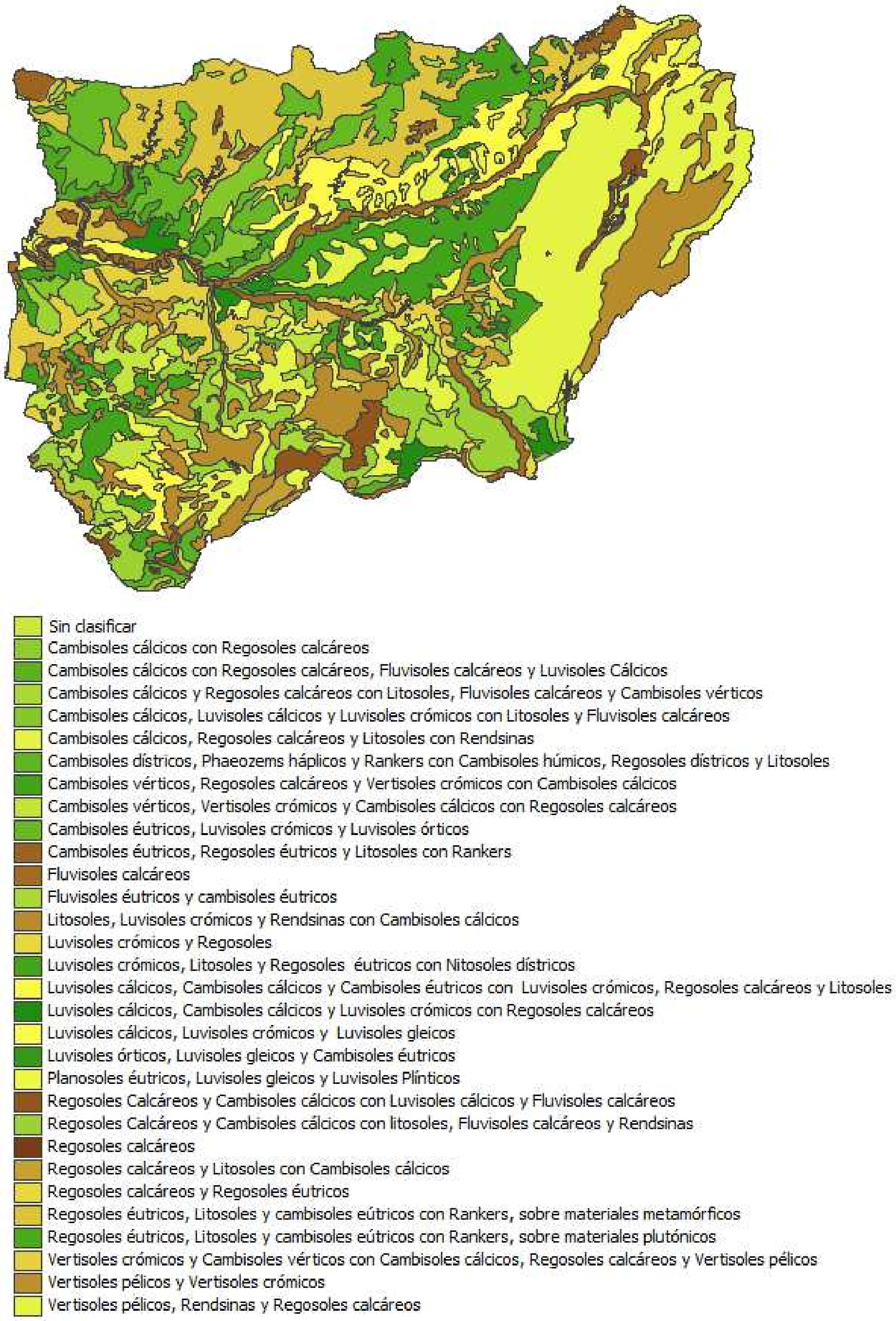

Figura 9.9. Unidades edáficas en la provincia de Jaén
Fuente: Red de información ambiental de Andalucía (REDIAM). Elaboración propia.

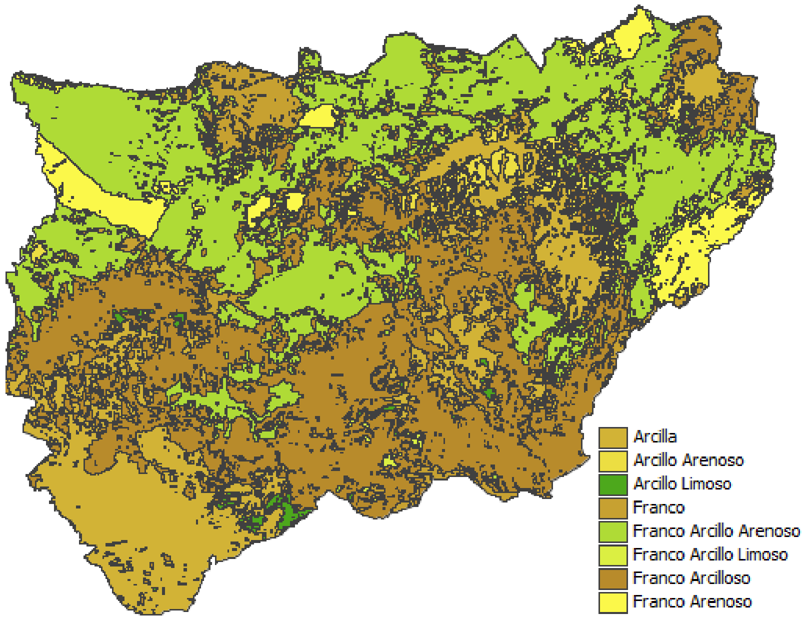

Figura 10.10. Textura de los suelos en la provincia de Jaén
Fuente: Red de información ambiental de Andalucía (REDIAM). Elaboración propia.

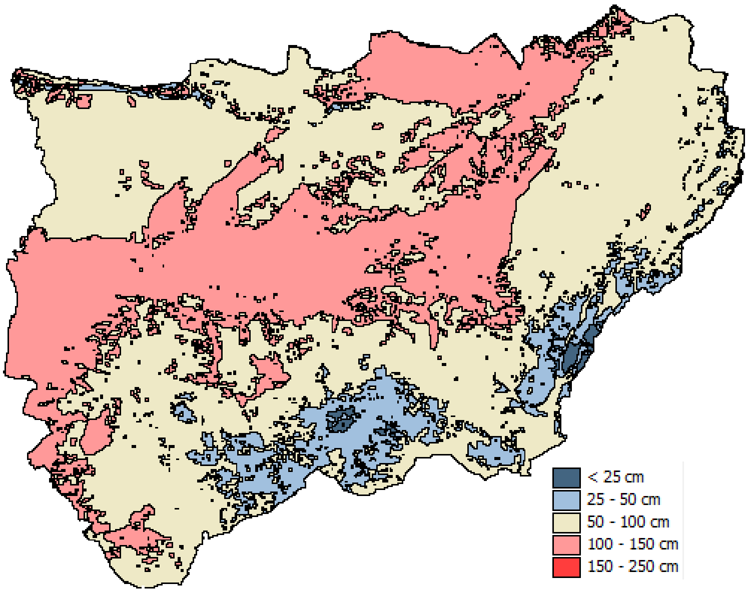

Figura 11.11. Profundidad de los suelos en la provincia de Jaén
Fuente: Red de información ambiental de Andalucía (REDIAM). Elaboración propia.

La pendiente del terreno (figura 1.12) es un carácter del que depende tanto la capacidad productiva del suelo como el riesgo de pérdida de esta capacidad. Los valores de pendiente establecen los límites del laboreo mecanizado. La erosión sufrida y la susceptibilidad a la misma están determinadas por la pendiente casi con independencia de otros caracteres, hasta el punto de que el tipo de infraestructura con la que reducir o anular el riesgo de pérdida de la capacidad productiva viene impuesto fundamentalmente por este carácter. De igual forma, influye en la posible acumulación o no de agua pudiendo facilitar procesos de salinización en determinadas microcuencas. (Diputación Provincial de Jaén-Agenda 21).

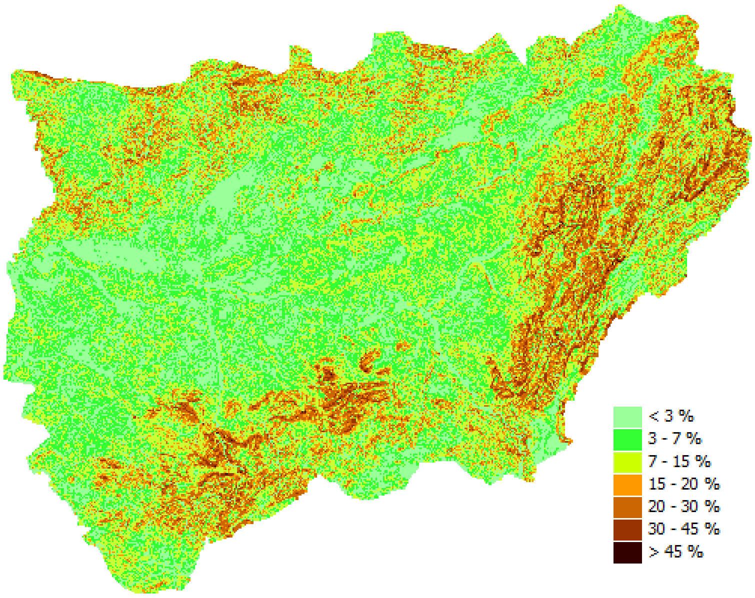

Figura 12.12. Pendiente del terreno en la provincia de Jaén.
Fuente: Elaboración propia.

1.2.6. Calidad de las aguas de riego

El efecto negativo del agua de riego negativo depende no solamente de una alta concentración de sales en el agua de riego puede afectar negativamente al desarrollo correcto de un cultivo (Freeman et al., 1994), sino también de determinados iones que pueden causar efectos negativos en las plantas superiores (toxicidad) o en suelo que las sustenta (Tattini et al., 1995). Por ello, para estimar los posibles riesgos asociados al agua de riego, además de estudiar la concentración de sales totales en el agua de riego se valorarán los siguientes parámetros:

- pH: normalmente no es un parámetro que permita determinar la calidad agronómica (salvo valores extremos). Puede ser interesante para contrastar posibles variaciones por efecto de un agente anómalo (principalmente contaminaciones).

- Calcio, magnesio y sodio: permiten obtener el índice (RAS), que hace referencia a la proporción relativa que se encuentran el ión sodio con respecto al calcio y magnesio. El sodio puede causar efectos perjudiciales en la estructura del suelo al provocar la dispersión de las arcillas y materia orgánica, además de poder provocar efectos negativos en la planta al sustituir al potasio o efectos en el balance de agua (Jeschke, 1977), en el aumento de la superficie foliar (Lawlor et al., 1973) y sobre la actuación de los enzimas (Hawker, 1974).

- Potasio: interviene en el movimiento del agua en la planta (presión osmótica de las células), formación de azúcares y grasa en los frutos. Su carencia puede provocar sensibilidad al frío, sequía y hongos, bajo contenido graso y reducción del desarrollo (Pastor, 2005).

- Cloruros: los síntomas de fitotoxicidad en plantas fue estudiado por Eaton en 1966. En el olivar un exceso de cloruros en el suelo provoca el amarilleamiento de las hojas, aunque es un cultivo que parece mostrar una cierta tolerancia (Vega y Pastor, 2005).

- Boro: hay poca diferencia entre los niveles en planta del microelemento considerados adecuados para la planta y aquellos que se consideran como tóxicos (Benlloch et al., 1991). Según la clasificación realizada en 1972 por Lucas y Knezek, el olivo es medianamente sensible a la deficiencia de boro; por el contrario también es un cultivo sensible al exceso de este elemento.

- Bicarbonatos y Carbonatos: para calcular el SAR corregido, pues los riesgos de sodicidad no solamente dependen de la relación entre las concentraciones de Na y los cationes divalentes sino que interviene también el contenido de los cationes bicarbonato y carbonato cuya actividad puede dar lugar a la precipitación de los iones calcio y magnesio. También son importantes para la determinación de la precipitación de determinadas sales que pueden obturar los emisores de riego.

- Nitratos: a altas concentraciones pueden favorecer un desarrollo indeseable de algas en balsas. También resulta interesante valorar el aporte de nitrógeno en forma de nitrato en el agua de riego para una fertilización adecuada del cultivo. En aguas subterráneas puede ser frecuente la existencia de concentraciones elevadas de este ión.

- Fósforo: puede ser indicativo de contaminación de las aguas, aunque en este caso en muestras de agua superficial y principalmente en las de carácter residual. Al igual que ocurre con las aguas ricas en formas nitrogenadas su presencia podría favorecer el desarrollo de algas en balsas.

1.2.6.1.Salinidad

Se define la salinización como “el resultado de procesos naturales y/o antrópicos presentes en todos los suelos que conducen en menor o mayor grado a una acumulación de sales, que pueden afectar la fertilidad del suelo” (Flores et al, 1996). Amezketa et al., (2010), define la salinidad como “la acumulación de las sales solubles en la zona de raíces de los cultivos que produce un descenso de su rendimiento”.

El sistema de riego tiene mucha influencia en la producción del cultivo y en la acumulación y distribución de las sales en el perfil del suelo. Así, los riegos localizados de alta frecuencia, que mantienen una continua y elevada humedad en el suelo, son muy aconsejables cuando se manejan aguas de mala calidad. En estos sistemas, las sales se van concentrando en la periferia de los bulbos húmedos.

Los suelos con excesos de sales solubles reducen el rendimiento de los cultivos. Se han enunciado diversas teorías para explicar las causas del daño salino:

- Teoría de la asimilabilidad del agua: enunciada ya en 1898 por Schimper's, presupone que el exceso de sales en la solución del suelo reduce la disponibilidad externa de agua para la planta. La reacción de las plantas, incluidas las halofitas (Flowers et al., 1977) ante ésta "sequia fisiológica" sería la pérdida de turgencia.
- Teoría de la inhibición osmótica: supone que el crecimiento de las plantas resulta inhibido por la reducción del potencial osmótico el agua intercelular (Bernstein et al., 1964), que en gran medida es una estrategia para adaptarse al bajo potencial osmótico en el agua del suelo como consecuencia de las sales disueltas.
- Teoría de los efectos específicos: el daño sería causado por los iones presentes en el medio salino, bien porque estos fuesen tóxicos "per se", bien porque produjeran desequilibrios nutritivos (Bernstein et al., 1964. Greenway, 1980).
- Teoría hormonal: propone que al menos una parte de los daños originados por la salinidad se deben a una alteración entre raíz y parte aérea, que se debe a una reducción en el aporte de citoquininas y/o ácido giberélico (Bejaoui, 1985).

Por lo tanto, los efectos de las sales del suelo se pueden reunir en los tres grupos siguientes:

- Efecto osmótico de las sales disueltas en la solución del suelo: la absorción de agua del suelo por las raíces de las plantas depende de un potencial hídrico decreciente: es más bajo en la raíz que en el suelo. Las sales disueltas en el agua de riego disminuyen el potencial osmótico (aumentan la presión osmótica) del agua del suelo disminuyendo su potencial hídrico. Para mantener la absorción de agua cuando la concentración de sal disuelta del agua del suelo es muy alta, las plantas deben hacer un ajuste osmótico, acumulando solutos en sus células lo que baja el potencial osmótico y permite mantener el flujo de agua desde el suelo. Esto tiene un gran coste energético y, afecta obviamente al rendimiento.

- Efectos del sodio absorbido: los altos porcentajes de sodio en el complejo de cambio, tienen un efecto importantísimo sobre la estructura del suelo. Además, la presencia de sodio puede crear problemas de toxicidad. Una de las principales características de los suelos sódicos es su tendencia a dispersarse, es decir, a perder la estructura, con toda su secuela de propiedades negativas: disminución de la permeabilidad, encharcamiento, falta de aireación, dificultad física de penetración de las raíces, etc.

- Toxicidad de algunos iones (toxicidad iónica específica): ciertos iones producen efectos tóxicos en las plantas. La toxicidad no suele ser debida al efecto directo de los iones que la ocasionan, sino a que éstos inducen alteraciones en el metabolismo, ocasionando la acumulación de productos tóxicos. La presencia de iones en los tejidos de las plantas a concentraciones superiores a las toleradas, puede originar lesiones características en ellas.

Los efectos de la salinidad se manifiestan principalmente en el olivo con la reducción del crecimiento y el rendimiento. Los daños están causados por alguno o la suma de factores como: mayor dificultad para el olivo de tomar agua (Chartzoulakis, 2005; Letey et al., 2011; Bader et al., 2015) y los solutos del suelo, una elevada concentración de algunos iones potencialmente fitotóxicos en los tejidos de la planta (Na y Cl principalmente) (Klein et al., 1994; Tattini et al., 1992; Kchaou et al., 2010), y una deficiencia nutricional causada porque iones no útiles para el olivo, que ocupan espacios en los tejidos del árbol desplazando a los iones útiles, que repercuten en reducción en la elongación de tallo, área foliar total y área final de la hoja, peso seco, longitud de la raíz y número de hojas y tallos (Tattini et al., 1992, 1995; Marín et al., 1995; Chartzoulakis et al., 2002; Melgar et al., 2007, Levy 2012; Keren, 2012).

Respecto a los mecanismos de tolerancia al estrés salino en el olivo, la respuesta a la salinidad dependerá no solamente del contenido de sales del agua de riego o del extracto de saturación del suelo donde se implante el olivo sino también del tipo de suelo, climatología de la zona, manejo del agua de riego y de las labores del cultivo de olivar, variedad de olivo, estado vegetativo del árbol, la edad de plantación, etc, (Melgar et al., 2007, 2009; Pastor, 2005).

Diversos autores clasifican el olivo como una especie medianamente tolerante a la salinidad (Aragüés et al, 2005; Benlloch et al., 1994; FAO, 1985; Hartman et al., 1966; Maas y Hoffman, 1977; Rugini y Fedeli, 1990, Tattini et al., 1992; Tattini, 1994). La gran ventaja del olivo frente a otras plantas es que el olivo tiene mecanismos de defensa para las altas concentraciones de sal en el suelo, produciendo un descenso en la concentración de sodio y cloro desde la raíz hasta la parte aérea. Este mecanismo de defensa consiste básicamente en acumular los iones tóxicos en zonas de la planta que no afectan a su desarrollo (vacuolas de las hojas adultas) (Tattini et al., 1994; Chartzoulakis, 2005; Kchaou et al., 2010). Reacciona al estrés salino reduciendo el contenido y grado de insaturación de los lípidos de las membranas de la hoja y la raíz. Esto tiene por efecto modificar la permeabilidad de las membranas celulares a los iones. Cuanta más rica es una membrana en ácidos grasos y saturados, más permeable es a los iones Na^+ y K. Por tanto, al disminuir el grado de insaturación de los lípidos y sus membranas, el olivo reduce la absorción y el transporte de sodio hacia las hojas, evitando así una intoxicación por acumulación celular de este elemento y resistiendo finalmente a la salinidad (Tattini et al., 1992; Aragüés et al., 2005).

Los efectos de la salinidad en la calidad del aceite incluyen la alteración en la composición de ácidos grasos, disminución de la relación ácidos grasos insaturados/saturados e incremento en el contenido de fenoles (Wiesman et al., 2004).

En definitiva, el manejo de agua de riego con alto contenido en sales es una práctica que debe estar acompañada de continuos controles y manejo adecuado para evitar dañar al cultivo o salinizar el suelo.

1.2.6.2. Sodificación

Los cationes de calcio (Ca^{2+}) y magnesio (Mg^{2+}) intercambiables, sobre todo el primero, promueven la floculacionón de las partículas de arcilla del suelo, favoreciendo con ello la creación de una estructura estable. Con la sustitución de los cationes por sodio (Na^{+}) intercambiable (sodificación o sodización) se produce una degradación de la estructura del suelo, dispersándose los agregados de éste y disminuyendo los espacios porosos, lo que provoca la disminución de la velocidad de infiltración del agua y de la permeabilidad del suelo, una mala aireación y un mayor peligro de erosión asociado a la escorrentía.

El agua de riego puede contribuir de manera progresiva a la sodización del suelo si la relación de Na^{+} respecto a la de Ca^{2+} y Mg^{2+} en la propia del agua es alta, puesto que ello facilita el intercambio de calcio y magnesio del complejo del cambio del suelo por el sodio del agua.

Para cuantificar el riesgo de sodización del agua de riego se han utilizado distintos índices que comparan la concentración de Na^{+} frente a la de Ca^{2+} y Mg^{2+}, siendo los más ampliamente aceptados la Relación de Adsorción de Sodio (SAR) y la Relación de Adsorción de Sodio Ajustada ($SAR_{Ajustada}$). Para una correcta evaluación del agua de riego, cualquiera de ambos índices debe ser considerado conjuntamente con la conductividad eléctrica (ECw) ya que, para un mismo valor de la SAR o de la $SAR_{Ajustada}$, el peligro de sodización aumenta al aumentar la ECw. Ello es debido a que el intercambio de Ca^{2+} y Mg^{2+} del suelo por el Na^{+} del agua se produce tanto más rápidamente cuanto mayor sea la concentración de sales en la disolución del suelo (Fernández-Escobar et al., 2009). El Carbonato Sódico Residual (RSC), es un indicador del peligro de sodización provocado por un exceso de carbonatos (CO_3^{2-}) y bicarbonatos (HCO_3^{-}) en el agua de riego. Un alto contenido de CO_3^{2-}y HCO_3^{-}aumenta en la práctica el índice de SAR. Los iones de carbonato y bicarbonato precipitan con calcio y magnesio en forma de carbonato cálcico ($CaCO_3$) o carbonato magnésico ($MgCO_3$) cuando la solución del suelo se concentra bajo condiciones secas. La concentración de Ca y Mg decrece en relación al sodio y el índice SAR es mayor. Esto provoca la alcalinización y aumento del pH. Entonces, cuando el análisis del agua indica un nivel alto de pH, esto es una señal de que los valores de carbonatos y bicarbonatos son altos. La dureza del agua, es otro factor a tener en cuenta. En química, se denomina dureza del agua a la concentración de compuestos minerales de cationes polivalentes (principalmente divalentes y específicamente los alcalinotérreos) que hay en el agua, en particular magnesio y calcio. Estas son las causantes de la dureza del agua y el grado de dureza es directamente proporcional a la concentración de sales de esos metales alcalinotérreos. Además, la posibilidad de la obturación en los sistemas emisores de riego, principalmente por la precipitación de carbonatos de Ca y derivados, pueden ser evaluados por grado de dureza del agua, el carbonato sódico residual (RSC), la relación Ca/Mg y con el índice de Langelier (Ayers y Wescot, 1985).

1.2.6.3.Fitotoxicidad

Cuando algún elemento químico supera en las plantas un determinado umbral de concentración, se produce un daño o alteración fisiológica por toxicidad. El uso de un agua de riego con altos contenidos de un determinado elemento puede ser la causa de la fitotoxicidad, al provocar aumentos de su concentración en la disolución del suelo. Los problemas de fitotoxicidad van asociados al uso de las aguas de riego con elevada salinidad, aunque aún con valores bajos de conductividad eléctrica pueden ser provocados por un exceso de cloro, boro o sodio. El criterio de toxicidad estudia los problemas que pueden crear determinados iones. A diferencia de la salinidad, que es un problema externo de la planta y que dificulta la absorción de agua, la toxicidad es un problema interno que se produce cuando determinados iones, absorbidos principalmente por las raíces, se acumulan en las hojas mediante la transpiración, llegando a alcanzar concentraciones nocivas. Los iones tóxicos más frecuentes y, por tanto, con los que más cuidado hay de tener son el cloro, sodio y boro (Bauder et al., 2007). Los iones predominantes en el agua de riego son el calcio (Ca^{2+}), magnesio (Mg^{2+}), sodio (Na^{+}), cloruro (Cl^{-}), bicarbonato (HCO_3^{-}), carbonato (CO_3^{2-}), sulfato (SO_4^{-}), nitrato (NO_3^{-}), amonio (NH_4^{+}), fosfato (PO_4^{3-}), potasio (K^{+}) y boro (B). Es importante conocer sus concentraciones para estimar el riesgo de fitotoxicidad. También es conveniente para estimar el aporte de nutriente (N, P, K, B) que puede hacer el agua de riego y que se debería descontar de la dosis de fertilizante a aplicar.

1.3. Marco legislativo y normativo

En el desarrollo de la presente Tesis Doctoral se ha tenido en cuenta principalmente las siguientes normas:

- Directiva 2007/2/CE del Parlamento Europeo y del Consejo de 14 de marzo de 2007 por la que se establece una infraestructura de información espacial en la Comunidad Europea (INSPIRE), y su transposición a la normativa nacional en la Ley 14/2010, de 5 de julio, sobre las infraestructuras y los servicios de información geográfica en España.
- Ley 37/2007, de 16 de noviembre, sobre reutilización de la información del Sector Público.
- Ley 5/2011, de 6 de octubre, del olivar de Andalucía.
- Ley 31/1995, de 8 de Noviembre, de Prevención de Riesgos Laborales, y específicamente el Manual de buenas prácticas en trabajos en el cultivo del olivar.
- Ley de Aguas, aprobado por Real Decreto Legislativo 1/2001, de 20 de julio, por la que se incorpora al derecho español la Directiva 2000/60/CE, estableciendo un marco comunitario de actuación en el ámbito de la política de aguas.
- Directiva 2006/118/CE del Parlamento Europeo y del Consejo, de 12 de diciembre de 2006, relativa a la protección de las aguas subterráneas contra la contaminación y el deterioro.
- Directiva del Consejo, de 12 de diciembre de 1991, relativa a la protección de las aguas contra la contaminación producida por nitratos utilizados en la agricultura.
- Ley 7/2007, de 9 de julio de Gestión Integrada de la Calidad Ambiental

- UNE-EN ISO 14001:2015 Sistema de Gestión Medioambiental, así como la Guía para la aplicación de la misma, y la mplementación de IRAM-ISO 14001 y el uso de IRAM-ISO 14004 – Estandares de Sistemas de Manejo Ambiental por parte de explotaciones agrícolas.
- UNE-EN 15097:2007 Técnicas de riego. Riego localizado. Evaluación hidraúlica.
- UNE-EN ISO 9261 Equipos de riego. Emisores y tuberías emisoras. Especificaciones y métodos de ensayo.

1.4. Marco conceptual

La descripción de los procesos en la presente Tesis Doctoral, en base a la aplicación, sistemática y lógica, de los conceptos y fundamentos expuestos anteriormente, se estructura en las siguientes fases:

A. Definición del área de estudio, provincia de Jaén, con una extensión 1.348.900 has, distribuidas superficialmente en subcuencas con 585.517 has de olivar, donde los olivares de regadío ocupan 290.297 has (MAPAMA, 2016). La superficie total de masas de aguas subterráneas es de 803.000 has, en las que el olivar de riego ocupa una superficie de 141.900 has. Para ellos se seguirá un procedimiento de:

   - Recopilación, obtención, gestión, manipulación y análisis de información alfanumérica de datos climáticos, de calidad de agua superficial y subterránea, tipos de suelo, orografía y zonas de riego de olivar. La información agroclimática fue obtenida de 35 estaciones, del periodo 1976-2013 (n=459) e incluye lluvia diaria, temperaturas máximas, mínimas y medias, y la evapotranspiración (Junta de Andalucía, 2014). La información hidroquímica fue proporcionada por la autoridad del agua de la cuenca del Guadalquivir (Confederación Hidrográfica del Guadalquivir, 2014). Esta información se obtuvo de 66 estaciones de agua superficial, y la subterránea, de las 136 estaciones de suministro de riego, entre los años 1994-2013 (n=240). Las estaciones subterráneas se corresponden a 26 unidades hidrogeológicas, según el Instituto Nacional de Geología y Minería de España (IGME, 1997, 2010). La propiedades del agua incluyen pH, conductividad eléctrica, y la concentración de Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, PO_4^{3-}, NH_4^+, B, Ca^{2+}, K^+, y Na^+. La precipitación efectiva se estimó según el método de "Bureau of Reclamation" propuesto por Stamm (1967). La SARadj, el RSC, la dureza del agua (en ºfH), relación Ca/Mg y el índice de Langelier, se calcularon como índices hidroquímicos (Ayers y Wescot 1987). El número de datos mensuales por estación y variable/estadístico han sido 111720 (9310 anuales), y las hidroquímicas 285120 (23760 anuales).

- Tratamiento geoestadístico de los datos obtenidos y realización de estadísticos propios procedente de la información recopilada con determinación de la distribución espacial de las variables a partir de herramientas estadísticas para el análisis de datos considerando las características de variabilidad y correlación espacial de datos.

- Creación de capas de información espacial georrefenciadas representada por un shape o archivo donde se almacena la información geométrica de las variables analizadas con el área de interés.

- Implementación del GIS, base de datos espacial que almacena las características atributivas (tabla con los valores de cada variable) y la información espacial (shape), que ha de servir para alcanzar el conocimiento de la situación actual en las diferentes zonas de olivar de riego de la provincia de Jaén.

- Interacción del GIS con herramientas de análisis espacial multicriterio (EMC): con las capas de información creadas se hace necesario establecer un sistema de estandarización dado que las variables originales se expresan en unidades de medida diferentes (Eastman, 1999), con una amplia gama de posibilidades de interpretación en función a las normas de clasificación. Por ello, con independencia de la unidades de medida iniciales y del recorrido de cada variable, se generan mapas en los que las variables son sustituidas por un determinado valor, de acuerdo con la clasificación (1, 2 o 3 para riesgos altos, medianos y bajos, respectivamente). Tras la clasificación se desarrolla un sistema de ponderación de las variables que actúan como factor en función a la gradación estimando los objetivos. La evaluación multiobjetivo (EMO) trata de identificar las mejores soluciones considerando múltiples objetivos simultáneamente. Los mapas resultado obtenidos son la interpretación y reclasificación de los resultados derivados de la evaluación multicriterio. En función de los objetivos específicos, ofrecen la posibilidad de zonificar la provincia de Jaén en zonas con mayor riesgo de utilización en el riego de aguas de mala calidad clasificándose de acuerdo con los posibles efectos: (i) promoción de desórdenes nutricionales, (ii) degradación del suelo por la acumulación de sales solubles, (iii) obstrucción en los sistemas de riego, y (iv) s problemas en los embalses y reservas de agua.

- Marco conceptual: GIS-EMC-EMO. La versatilidad del GIS en la integración y análisis de información espacial goerreferenciada junto a la EMC (conjunto de operaciones espaciales para lograr un objetivo teniendo en consideración simultáneamente todas las variables que intervienen), sirve de base para la diversidad de objetivos (EMO) frecuentemente relacionados con la toma de decisiones espaciales.

En los siguientes pasos se ha procedido a retroalimentar el conjunto GIS-EMC-EMO, implementando:

B. Estimación de la tipología de riego de olivar teniendo en cuenta el marco normativo y estadístico (INE, 2016).

C. Determinación de los requerimientos de lixiviación y cantidades de riego resultantes.

D. Planteamiento y representación de la posibilidad de la mezcla de aguas (superficial y subterránea), para la mejora de calidad del agua de riego.

E. Detección de las zonas con riesgos potenciales de obturación de sistemas emisores en riego localizado, así como cantidades de ácido a inyectar en los sistemas para paliar estos efectos y evitar los depósitos de carbonato cálcico en los sistemas de riego.

F. Planificación y gestión de las soluciones complejas en el manejo sostenible de los recursos hídricos disponibles. Una vez identificadas las zonas, el manejo del agua de las mismas, las necesidades y las características del cultivo, se definen estrategias y realizan propuestas para evitar los efectos potenciales negativos debidos al riego en los cultivos y suelos, así como en términos de ahorro de agua, eficiencia y equilibrio económico en el olivar de la provincia de Jaén.

1.5. Objetivos

El principal objetivo de la presente Tesis Doctoral es establecer un marco conceptual para el manejo sostenible de los recursos hídricos en el cultivo del olivar. Para ello se pretende desarrollar un Sistema de Información Geográfico capaz de actualizarse de manera inmediata e integrarse con herramientas de análisis multicriterio-multiobjetivo, y de proporcionar un análisis de alternativas que permitan ayudar en los procesos de toma de decisión y planificación. Para lograr este objetivo general, se definieron diferentes objetivos específicos:

(1) La identificación de los factores de riesgos relacionados con el uso del agua de riego clasificado por: la degradación del suelo, los trastornos nutricionales de las plantas, la obstrucción de los sistemas de riego y la proliferación de micro y macro organismos en los embalses (Capítulo II).

(2) Desarrollar estrategias de control de problemas de salinidad, mediante dos alternativas: (i) el empleo de fracciones de lavado a aplicar en función del rendimiento relativo del cultivo del olivo, y (ii) empleo conjunto de aguas superficiales y subterráneas para diluir la salinidad y reducir la necesidad de fracciones de lavado elevadas para evitar la acumulación de sales en el suelo (Capítulo III).

(3) El análisis de las posibles causas de obturaciones de emisores en el riego localizado con estrategias integradas de riegos y fertilización paliar los riesgos potenciales de obturación (Capítulo IV). Se determinarán las cantidades de ácido a añadir y los tiempos de inyección, así como las cantidades de nitrógeno aplicado con el agua y el ácido.

(4) La eficiencia del agua de riego a partir de la definición de una situación óptima (o menos mala; "salinidad umbral en agua"), en función de la procedencia del agua y calidad de la misma (Capítulo V). La viabilidad del empleo conjunto de aguas superficiales y subterráneas, mezcla de aguas, se aplicará como alternativa para evitar la acumulación de sales en el suelo y para minimizar la contaminación de los acuíferos con los retornos de agua.

Capítulo 2. A GIS-based quality assessment model for olive tree irrigation water in southern Spain

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Abstract

The primary aim of this study was to produce maps of various types of risk arising from the use of surface and ground water for irrigation (viz., soil degradation, plant nutritional disorders, clogging of irrigation systems and reservoir problems). The maps were obtained as the additive result of each hydrochemical variable (water properties and indices calculated from them) associated with each risk by using open-source GIS software. The study was conducted in the province of Jaen (southern Spain), which spans a total area of 13489 km2, 5860 of which is occupied by olive tree crops. Irrigated olive orchards in the province span more than 2900 km2.

The potential risk of soil degradation and nutritional disorders at their highest rating by effect of the use of irrigation water spanned an area of 72 km2 with ground water and 874 km2 with surface water. Such a large difference was the result of the typically increased salinity and sodicity of surface water. Both types of water exhibited a very high risk of clogging irrigation systems; however, the risk at its highest rating with surface water spanned a larger area (11781 km2) than that with ground water. Also, surface water posed more severe restrictions on water reservoirs by effect of its high

contents in nutrients. Surface water invariably had a phosphate concentration falling in the medium risk region for reservoir problems.

The proposed information management model is useful for developing water quality maps with a view to assessing the potential risks associated with the use of irrigation water. Such information can be used to optimize irrigation practices in specific agricultural areas.

Key words: irrigation, water quality, GIS, salinization, sodification.

2.1. Introduction

Although irrigation improves crop yields in arid and semi-arid lands, this agricultural practice can raise problems such as salinization of agricultural soil (Corwin et al., 2007; Isidoro and Grattan, 2011). The sustainability of irrigated agriculture relies on an appropriate salt balance in soil (Aragues et al., 2011; Keren, 2012). The achievement of this balance requires considering the quality of irrigation water used and its subsequent leaching in order to avoid salt accumulation around plant roots and the resulting decrease in crop yields and degradation of soil structure (Letey et al., 2011; Skaggs et al., 2012). Irrigation guidelines should therefore include recommendations for assessing irrigation water quality. Such quality is governed by the concentration and composition of solutes present in the water, which can not only enrich soil with soluble salts, but also cause the precipitation of insoluble salts and affect its exchangeable cation composition or even increase sodicity (Levy, 2012; Keren, 2012). Additional factors such as the presence of potentially toxic elements or nitrate contents should also be evaluated in order to avoid plant toxicity problems, an imbalanced N supply to crops or algal development in irrigation reservoirs. These factors are all included in the FAO practical guidelines for assessing irrigation water quality (Ayers and Westcot, 1985).

Irrigated land in many arid and semi-arid areas has increased substantially in response to the need for greater food production for an ever increasing population (Ryan et al., 2012). Expanding irrigated areas increases the risk of salinization when available water has a high salt concentration. In many countries of the World, irrigation-related salinization constitutes a growing concern (Toth et al., 2008; Aragues et al., 2011). In Spain, increasing expanding the area occupied by irrigated olive orchards has required using low-quality water for irrigation in many places, especially in the south, where the

Spanish olive production is basically concentrated (Aragues et al., 2005; Aragues et al., 2010). Accurately assessing water quality is essential to avoid salinization problems in these regions. However, evaluating irrigation water quality at a regional scale is made difficult by the high variety of water sources used. Effective rainfall and evapotranspiration, soil properties and land geomorphology must also be considered as they can all influence the risks associated with the use of low-quality water in agriculture.

Geographical information systems (GIS) provide powerful tools for assessing salinization risks (Mirlas, 2012) and irrigation water quality at a regional scale (Romanelli et al., 2012). To this end, several open-source GIS software have shown their capabilities for managing water resources (Chen et al., 2010) beside other interesting advantages such as: low-cost, independence, security and privacy by always having the source code, adaptability since applications are constantly improving and evolving, quality by continuous improvement by a large number of developers and users, and interoperability, this being a fundamental aspect of public administration, given the large number of computing units with responsibilities.

Various effective GIS-based irrigation water indices derived from a combination of hydrochemical properties of water have to date been proposed (Simsek and Gunduz., 2007; Romanelli et al., 2012). These hydrochemical properties are generally accepted for the assessment of irrigation water quality according to international standards such as those by Ayers and Wescot (1985). The primary aims of this work were to use a GIS based on an open-source software in order to develop water quality indices for various potential risks on the basis of chemical properties of the water and to construct water quality maps with a view to facilitating sustainable irrigation management at a regional scale. Contrasting with some previous studies assessing water suitability for irrigation which provided a general index for irrigation water assessment (e.g. Romanelli et al., 2012), maps of different types of potential risks for soil (degradation by effect of salinity and sodicity), plants (nutritional disorders), irrigation reservoirs (algal accumulation due to nutrients), and irrigation piping and drips (clogging due to precipitates), were constructed. These water quality maps took into account climatic conditions (aridity) affecting potential negative consequences of low-quality water. Little attention has been usually paid in previous studies on the effects on irrigation infrastructure (reservoirs, piping and drips), which should be a key issue when water quality for irrigation is assessed, particularly for drip irrigation. The study was conducted in the province of Jaen (southern Spain), a typical Mediterranean region with a large area of irrigated olive orchards —in fact, the largest in Spain.

2.2. Material and methods

2.2.1. Study area

The study was performed in Jaen (southern Spain). This province spans a total area of 13489 km2, 5860 of which is occupied by olive tree crops. This olive orchard area accounts for 78 % of all agricultural land in Jaén and 23 % of all olive orchard area in Spain (MAGRAMA, 2012). Irrigated olive orchards in the province span more than 2900 km2, with 2000 planted in the past 20 years. Drip irrigation systems are used in 96 % of the irrigated olive cropped land.

The expansion of irrigated olive orchards has relied on an increasing use of water from different sources (wells or rivers) for irrigation with high salt concentration. Also, the low water availability of the study area has led to the adoption of deficit irrigation, with rates clearly below crop evapotranspiration but affords a high crop water productivity. The use of highly efficient systems such as drip irrigation, and the resulting low leaching fractions, has led to an increasing risk of salinization of the soil (Letey et al., 2011). The high economic interest of this crop in the region and the salinization risk warranted the conduct of the present study, aimed at assessing the quality of irrigation water used in the area.

2.2.2. Data set

Climatic data including daily rainfall and temperatures (high, low and mean), effective rainfall, and potential evapotranspiration (PET) between 2000 and 2013 from 35 weather stations in the province were obtained at http://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController?action=Static&url=listadoEstaciones.jsp&c_provincia=23 .

Hydrochemical information was supplied by the water authority of the Guadalquivir basin (Confederación Hidrográfica del Guadalquivir, (http://www.chguadalquivir.es/opencms/portalchg/laDemarcacion/guadalquivir/calidadAguas/). This information was collected from 66 surface water stations and 136 ground water stations used as irrigation supplies. The ground water stations corresponded to 26 hydrogeological units according to Spain's National Institute of Geology and Mining (IGME, 1997). Samples were taken on a monthly basis, between 1994 and 2013. The water properties examined included pH, electrical conductivity (EC), and the concentrations of Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, PO_4^{3-}, NH_4^+, B, Ca^{2+}, K^+, and Na^+. These variables were used to calculate the following hydrochemical indices: sodium adsorption ratio (SAR) and adjusted sodium adsorption ratio (SARadj), residual sodium carbonate (RSC), water hardness (French degrees, ofH) and Langelier index (Ayers and Wescot, 1985). Calculation of these hydrochemical indices is described in supplementary material (Annexed 2).

Hydrochemical properties and the ensuing indices (hydrochemical variables) can be relevant explaining the following adverse effects:

(a) Soil degradation through accumulation of soluble salts and sodicity, and infiltration risks. Accumulation of salts can be evaluated from the EC of water (USDA 1954; Ayers and Wescot, 1985). Sodicity and infiltration risks can be estimated from EC and SARadj (Suarez, 1981; Ayers and Wescot, 1985), as well as from RSC (Romanelli et al., 2012). In Mg-dominated water ($Ca/Mg < 1$), the potential effect of sodium may be slightly but sufficiently increased to result in a higher than normal soil exchangeable Na percentage (ESP) when using water with Ca/Mg < 1 at a given SAR (Rahman and Rowell, 1979; Ayers and Wescot, 1985).

(b) Nutritional disorders. Elements such as B, Na and Cl can be toxic to plants. Also, bicarbonate can cause nutritional disorders such as deficiencies in micronutrients (particularly Fe and Zn) (Ayers and Wescot, 1985; Benítez et al., 2002). Although olive crops are assumed to be insensitive to Fe deficiency, an increasing number of trees of new varieties which are indeed sensitive (e.g. cv. Arbequina; Alcántara et al., 2003) have been planted lately. Also, a Ca/Mg ratio below 1 can reduce Ca uptake via an antagonistic effect (Ayers and Wescot, 1985).

(c) Clogging of irrigation systems. This problem is usually caused by precipitation of Ca and Mg compounds (e.g., from P fertilizers added to the water), which can be evaluated in French degrees (ºfH), and precipitation of Ca carbonates, which can be estimated via the Langelier index (Ayers and Wescot, 1985). RSC can also be an useful index to assess the risk of carbonate precipitation. Ca/Mg ratio will be also considered in the evaluation of this problem, since at similar ºfH or RSC values, increased ratios can boost precipitation of Ca phosphates and carbonates which are less soluble than their Mg counterparts.

(d) Problems in reservoirs as result of excessive algal development by effect of a high nutrient concentration (N and P) in the water, which can be evaluated from three hydrochemical properties: (i) NO_3^- and NH_4^+ concentration for N, and PO_4^{3-} concentration for P (Ayers and Wescot, 1985).

2.2.3. Model

Climatic and hydrochemical information was included in a GIS implemented for this study in order to integrate data for their management and spatial analysis by using the free GIS software gvSIG (www.gvsig.org). A data model was designed (Figure 2.1) for georeferencing all climatic and hydrochemical variables which allows storing and manipulating data while maintaining their spatial relationships. This model links a relational database to geometrical features, with the association of an alphanumeric table with graphical entities which provides a precise location in the space and an easy maintenance and upgrade. With this model, performance of different types of layers, graphics and alphanumeric consultation with different types of filters and geometric transformation can be easily achieved by using different mathematical algorithms available in one of the modules of gvSIG software called “Sextante”.

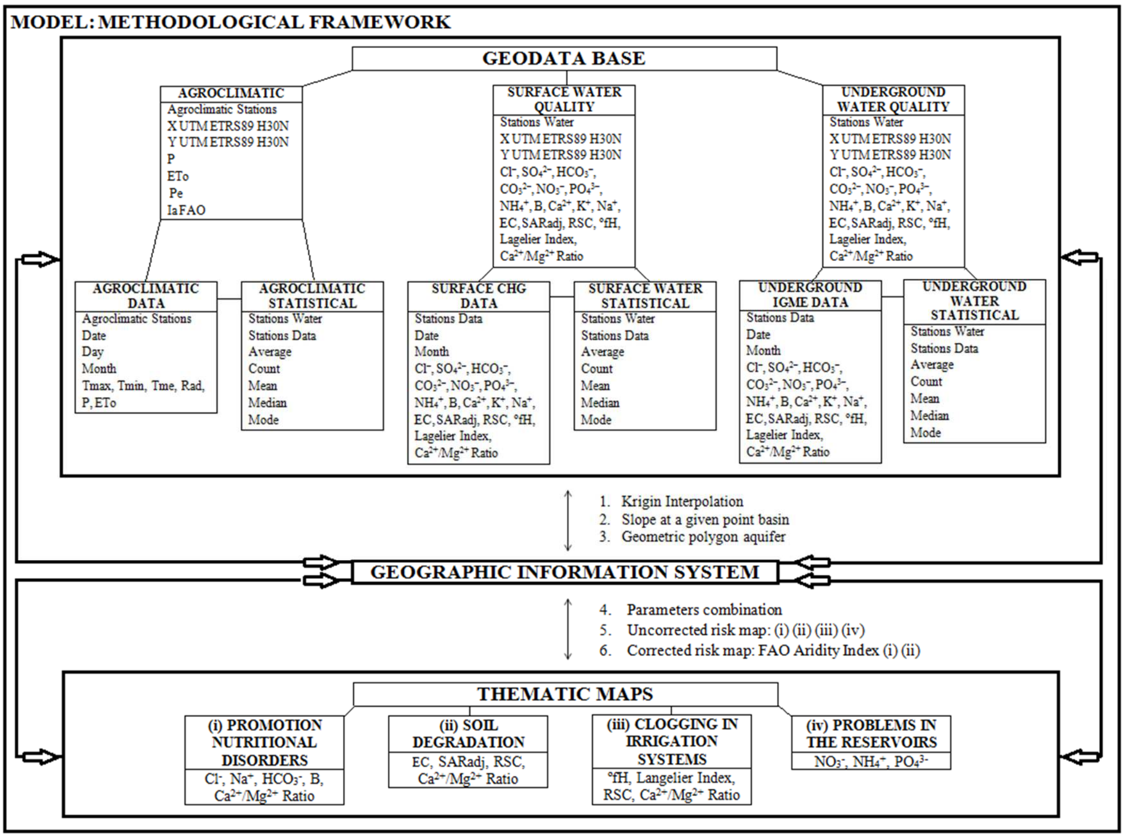

Figure 13. Methodological framework for GIS-based methodology proposed structure

A thematic map for each hydrochemical variable used in the model was prepared. Firstly, surface and ground waters were georeferenced, assuming the surface water used to come from the sub-basins where the pumping station was located, and defining polygons corresponding to each aquifer to assign each ground water source to a specific area. Sub-basins were defined by using the algorithm "slope at a given point basin", and ground water polygons using the algorithm "geometric polygon aquifer". After that, each map was constructed by kriging interpolation. Kriging creates a surface of estimated values from a series of point values. The method is based on a preliminary analysis of the spatial autocorrelation of the variable through the theoretical variogram. From the values of the variogram, a vector of weights multiplied by the vector of values of the points gives the estimated value. Transformation of each map into raster format (using the spatial analysis module of gvSIG) was done considering a spatial cell resolution of 100 x 100 m.

Available information for each thematic map was classified into three categories according to rating (1, 2 or 3 for high, medium and low risks, respectively) specifically created in order to define zones of different irrigation water quality (Table 2.1). Ratings were based on the limitations to irrigation water use defined by USDA (1954), Suarez (1981), and Ayers and Wescot (1985). That is, they were based on hydrochemical properties and the ensuing indices described above to explain the negative effect of low-quality water. Regarding nutritional disorders risk, which can be different depending on each specific crop, it has been taken into account that olive has an intermediate tolerance to Cl, Na, and B (Chartzoulakis, 2005), and that new varieties planted in the province have an intermediate tolerance to Fe-deficiency chlorosis (Benítez et al., 2002) potentially induced by bicarbonate in water. Thus, ratings for this risk have been based on general limitations defined by Ayers and Wescot (1985) regarding nutritional disorders.

Table 1. Interpretation of irrigation water quality according to risk gradation rating of the hydrochemical variables which can be relevant on different processes and rating for FAO aridity index used in additive corrections of nutritional disorder and soil degradation maps

Hydrochemical variable	Risk-Gradation		
	3	2	1
	Low	Medium	High
Soil degradation			
EC[a] ($\mu S\ cm^{-1}$)	< 700	700 - 3000	> 3000
SAR adj[b]	EC ($\mu S\ cm^{-1}$)		
0 - 3	> 700	700 - 2.000	< 200
3 – 6	> 1200	1200 - 300	< 300
6 - 12	> 1900	1900 - 500	< 500
12 - 20	> 2900	2900 - 1300	< 1300
20 - 40	> 5000	5000 - 2900	< 2900
RSC ($mmol_c\ L^{-1}$)[c]	< 1.25	1.25 - 2,5	> 2.5
Ca^{2+}/Mg^{2+} ratio	> 1		< 1
Nutritional disorders			
Cl^- ($mg\ L^{-1}$)	< 140	140 - 350	350
Na^+ (SAR)	< 3	3 - 9	> 9
HCO_3^- ($mg\ L^{-1}$)	< 91.5	91.5 – 457.5	> 457.5
B ($mg\ L^{-1}$)	< 0,7	0,7 - 3	> 3
Ca^{2+}/Mg^{2+} ratio	> 1		< 1
Clogging irrigation systems			
French Degrees (ºfH)	< 1.7	1.7 - 12	≥ 12
RSC ($mmol_c\ L^{-1}$)	< 1.25	1.25 – 2.5	> 2.5
Langelier Index	< 0	0	> 0
Ca^{2+}/Mg^{2+} ratio	> 1		< 1
Problems in reservoirs			
NO_3^- ($mg\ L^{-1}$)	< 5	5.0 - 30	> 30
NH_4^+ ($mg\ L^{-1}$)	< 0.5	0.5 - 3	> 3
PO_4^{3-} ($mg\ L^{-1}$)	0 – 0.15	0.15 – 0.3	> 0.3
FAO Aridity Index			
Classification	Dry-Subhumid	Semiarid	Arid
P[d] (mm)	600-800 (winter) or 500-700 (summer)	400-600 (winter) or 200-500 (summer)	< 400 (winter) or < 200 (summer)
P/ETP[e]	0,50 - 0,65	0,20 - 0,50	0,05 - 0,20

[a] CE, electrical conductivity of water; [b] SARadj, adjusted Na adsorption ratio of water corrected according to Ayers and Westcot (1985); [c] RSC, residual Na carbonate; [d] P, precipitation; [e] ETP, potential evapotranspiration. Rating (1, 2 or 3 for high, medium and low risks, respectively) was specifically created in order to define zones of different irrigation water quality (Table 1). Ratings were based on the limitations to irrigation water use stated by USDA (1954), Suarez (1981), and Ayers and Wescot (1985).
Different intensity of grey colour is used to represent each risk-gradation in each map.

Thematic maps defined in this way were grouped for surface and ground waters according to potential adverse effects on (a) soils, (b) plants, (c) irrigation systems and (d) reservoirs. A general water quality index for each effect was obtained by additive rating in each zone of the map, using a "combination of parameters algorithm" which allows algebraic operations with alphanumeric attributes arranged in vector layers, and provides results as new layers of geographic data. This provided four risk maps for each type of water (surface or ground) as the additive result of each individual hydrogeochemical variable considered for each risk, namely: soil degradation, plant nutritional disorders, clogging of irrigation systems, and problems in irrigation reservoirs.

The potential effect of rainfall and evapotranspiration on the water and salt balance of soil was considered via the aridity index (Ia) proposed by FAO (1993, equation described in supplementary material, annexed 2) as estimated for each surface water sub-basin, and each ground water polygon. A map for Ia was constructed by kriging interpolation. A rating for aridity index ranging from 1 to 3 was specifically created with decreased values assigned to increased aridity (Table 2.1). The risk maps for plant nutritional disorders and soil degradation potentially caused by surface and ground water were additively corrected for the climatic index as calculated from the aridity index on the assumption that a decreased aridity reduces the risk of plant nutritional disorders or soil degradation. Additive correction was performed by an "adding value algorithm" which adds assigned values for one layer to those assigned to other providing results in a new raster layer.

All the mathematical algorithms used in the model, namely: kriging interpolation, slope at a given point basin, geometric polygon aquifer, combination of parameters, and additive corrections, are included in the geoprocessing tools of the Sextante module of gvSIG (www.gvsig.org) by creating scripting in Jython programming language (www.jython.org; commands used are shown in Table 2.2).

Table 2. Mathematical algorithms (gvSIG scripting) in the framework methodology using the jython programming language

Kriging Interpolation	Slope at a given point basin	Parameters combination	Correction by adding
runalg("kriging", LAYER[Vector Layer], FIELD[Table Field from LAYER], DIST[Numerical Value], MINPOINTS[Numerical Value], MAXPOINTS[Numerical Value], MODEL[Selection], NUGGET[Numerical Value], SILL[Numerical Value], RANGE[Numerical Value], RESULT[output raster layer], CROSSVALIDATION[output table], VARIANCE[output raster layer],);	runalg("upslopeareafrompoint", DEM[Raster Layer], OUTLET[Point], RESULT[output raster layer],);	runalg("vectorfieldcalculator", LAYER[Vector Layer], FORMULA[String], RESULT[output vector layer],);	runalg("plus", LAYER[Raster Layer], LAYER2[Raster Layer], RESULT[output raster layer],);

2.3. Results

2.3.1. Soil degradation

The surface water-irrigated area under a high risk of salinization exceeded 1000 km^2 and accounted for nearly 8 % of the province area (Table 2.3), whereas that under a high risk of infiltration problems due to sodicity (measured as SAR_{adj}) was 790 km^2 (5.9 % of the province surface) (see Table 2.3). By contrast, more than 80 % of the area potentially irrigated with ground water had a medium risk of salinization, and more than 56 % an also medium risk of sodification (Table 2.3). The sodicity risk, estimated as RSC, peaked in 15 % of the area potentially irrigated with ground water (Table 2.3). The soil degradation risk map and areas spanned by each risk rating were identical with those under a risk of nutritional disorders whether they were irrigated with surface or ground water (Figures 2.2 and 2.3; Table 2.4).

Table 3. Parameters involved in the definition of the different risks related to irrigation water, surface affected, and % of the surface of the province affected for surface and underground waters

Risk	Parameters	Risk-Gradation	Affected area for surface water		Affected area for underground water	
			Provincial Area (km²)	% Provincial Area	Provincial Area (km²)	% Provincial Area
Soil degradation	EC	1 2 3	1064 7716 4709	7.9 57.2 34.9	- 6473 1557	- 80.6 19.4
	SARadj	1 2 3	790 5587 7112	5.9 41.4 52.7	- 4561 3469	- 56.8 43.2
	RSC	1 2 3	- - 13489	- - 100	1228 - 6802	15.3 - 84.7
	Ca^{2+}/Mg^{2+} ratio	3	13489	100	8030	100
Nutritional disorders	Cl^{-}	1 2 3	2238 2656 8595	16.6 19.7 63.7	958 - 7072	11.9 - 88.1
	Na^{+}	1 2 3	790 5424 7275	5.9 40.2 53.9	- 4561 3469	- 56.8 43.2
	HCO_3^{-}	1 2 3	- 11756 1733	- 87.2 12.8	1744 6286 -	21.7 78.3 -
	B	3	13489	100	8030	100
	Ca^{2+}/Mg^{2+} ratio	3	13489	100	8030	100
Clogging irrigation systems	French Degrees (ºfH)	1 2 3	12916 233 340	95.8 1.7 2.5	7851 179 -	97.8 2.2 -
	Langelier Index	1 2 3	13172 109 208	97.7 0.8 1.5	4029 3822 179	50.2 47.6 2.2
	RSC	1 2 3	- - 13489	- - 100	1228 - 6802	15.3 - 84.7
	Ca^{2+}/Mg^{2+} ratio	3	13489	100	8030	100
Problems in reservoirs	NO_3^{-}	1 2 3	68 9381 4040	0.5 69.5 30.0	1539 4795 1696	19.2 59.7 21.1
	NH_4^{+}	1 2 3	553 4397 8539	4.1 32.6 63.3	- 1173 6857	- 14.6 85.4
	PO_4^{3-}	2 3	13489 -	100 -	3215 4815	40.0 60.0
FAO Aridity index	Arid Semiarid Dry-Subhumid	1 2 3	115 12742 632	0.9 94.5 4.6	114 7475 441	1.4 93.1 5.5

CE, electrical conductivity of water; SARadj, adjusted Na adsorption ratio of water corrected according to Ayers and Westcot (1985); RSC, residual Na carbonate

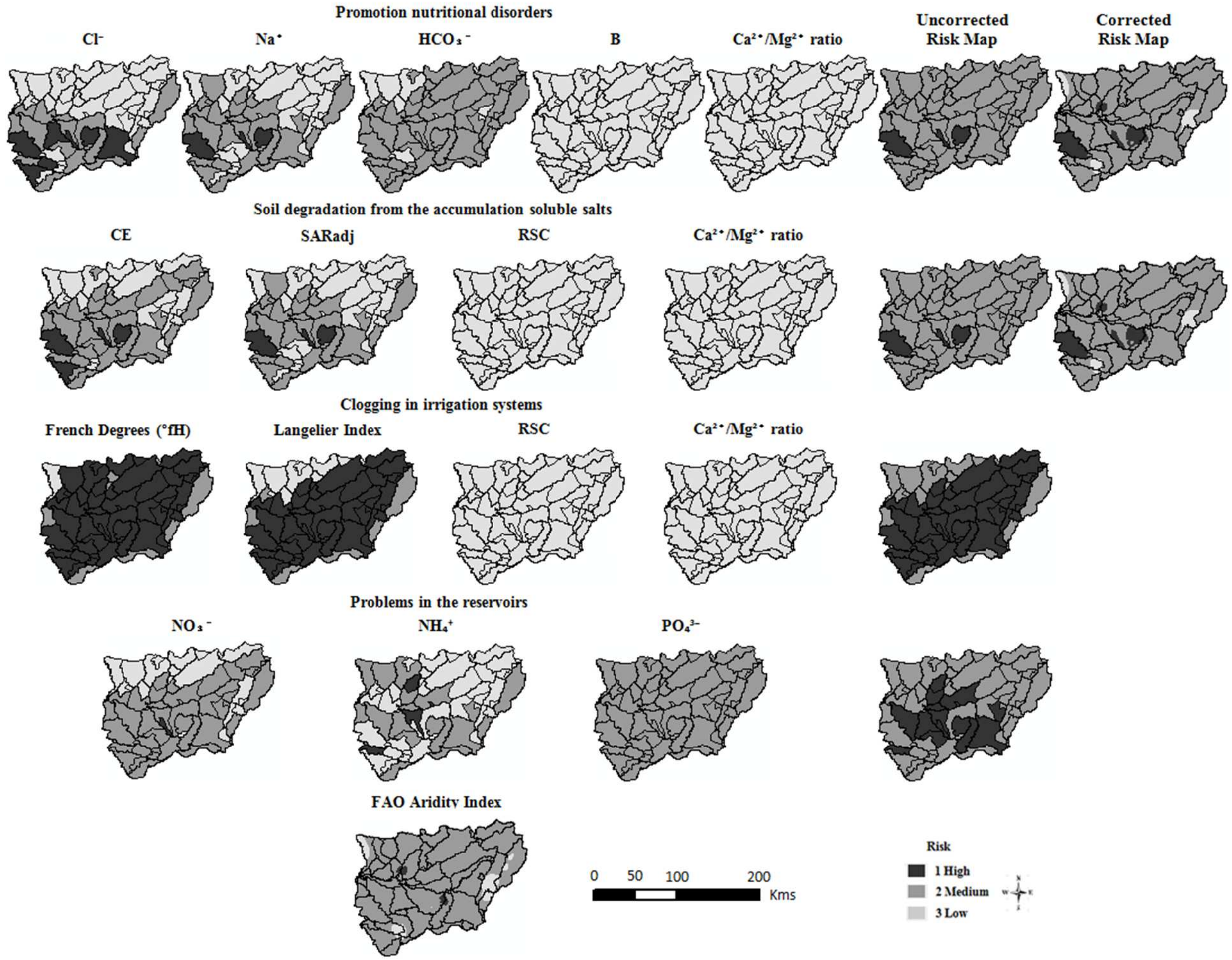

Figure 14. Thematic map for each hydrochemical variable defined for each risk and risk maps as obtained by additive rating of each zone on the map with the Sextante module of gvSIG (http://www.gvsig.org) for surface water. Uncorrected maps are those obtained for each risk without correction by climatic variables, and corrected ones are those corrected with aridity index by additive correction

2.3.2. Nutritional disorders risk

The main risks potentially derived from the use of surface water were posed by Na and Cl at their highest ratings, which were found to span 6 and 17 %, respectively, of the total area of Jaen (790 and 2238 km^2, respectively; Figure 2.2, Table 2.3). The risk posed by bicarbonate at a medium rating spanned 87 % of the area (viz., 11756 km^2). On the other hand, the main risk derived from the use of ground water was posed by its bicarbonate concentration; at its highest rating, the risk for bicarbonate spanned nearly 22 % of the area potentially irrigated with ground water (1744 km^2, Figure 2.3, Table 2.3). No special problems were seemingly derived from the B concentration or Ca/Mg ratio in surface or ground water (Table 2.3, Figure 2.2 and 2.3).

Table 4. Surface affected and % of the surface of the province affected by different risks related to the irrigation water quality for surface and underground waters

Risk	Risk-Gradation	Uncorrected by FAO Aridity Index				Corrected by FAO Aridity Index			
		Surface Water		Undergraund Water		Surface Water		Undergraund Water	
		Prov. Area (km²)	% Prov. Area	Prov. Area (km²)	% Prov. Area	Prov. Area (km²)	% Prov. Area	Prov. Area (km²)	% Prov. Area
Soil degradation	1	791	5.9	-	-	874	6.5	72	0.9
	2	12698	94.1	4295	53.5	12199	90.4	7566	94.2
	3	-	-	3735	46.5	416	3.1	392	4.9
Promotion nutritional disorders	1	791	5.9	-	-	874	6.5	72	0.9
	2	12698	94.1	6063	75.5	12199	90.4	7566	94.2
	3	-	-	1967	24.5	416	3.1	392	4.9
Clogging irrigation systems	1	11781	87.3	2420	30.1	-	-	-	-
	2	1708	12.7	5610	69.9	-	-	-	-
	3	-	-	-	-	-	-	-	-
Problems in reservoirs	1	5029	37.3	-	-	-	-	-	-
	2	8460	62.7	5967	74.3	-	-	-	-
	3	-	-	2063	25.7	-	-	-	-

Prov.: Provincial; For each one of these effects, risk gradation calculated by additive rating in each zone of the map using the Sextante module of the gvSIG software.

The map of nutritional disorder risk obtained as the additive result of each hydrochemical variable considered (Figures 2.2 and 2.3) revealed that near 6 % of the area irrigated with surface water (791 km^2) was at a high risk. Correction for the FAO aridity index slightly increased the area under maximal risk of nutritional disorders (874 km^2) and decreased that under a medium risk; in any case, high and medium risk spanned more than 90 % of the studied area (over 13000 km^2, Table 2.4). By contrast, the ground water-irrigated area potentially affected by nutritional disorders at their highest rating after correction for Ia was only 72 km^2; also, the area under a medium risk of such disorders accounted for more than 94 % of the total area potentially irrigated with this type of water.

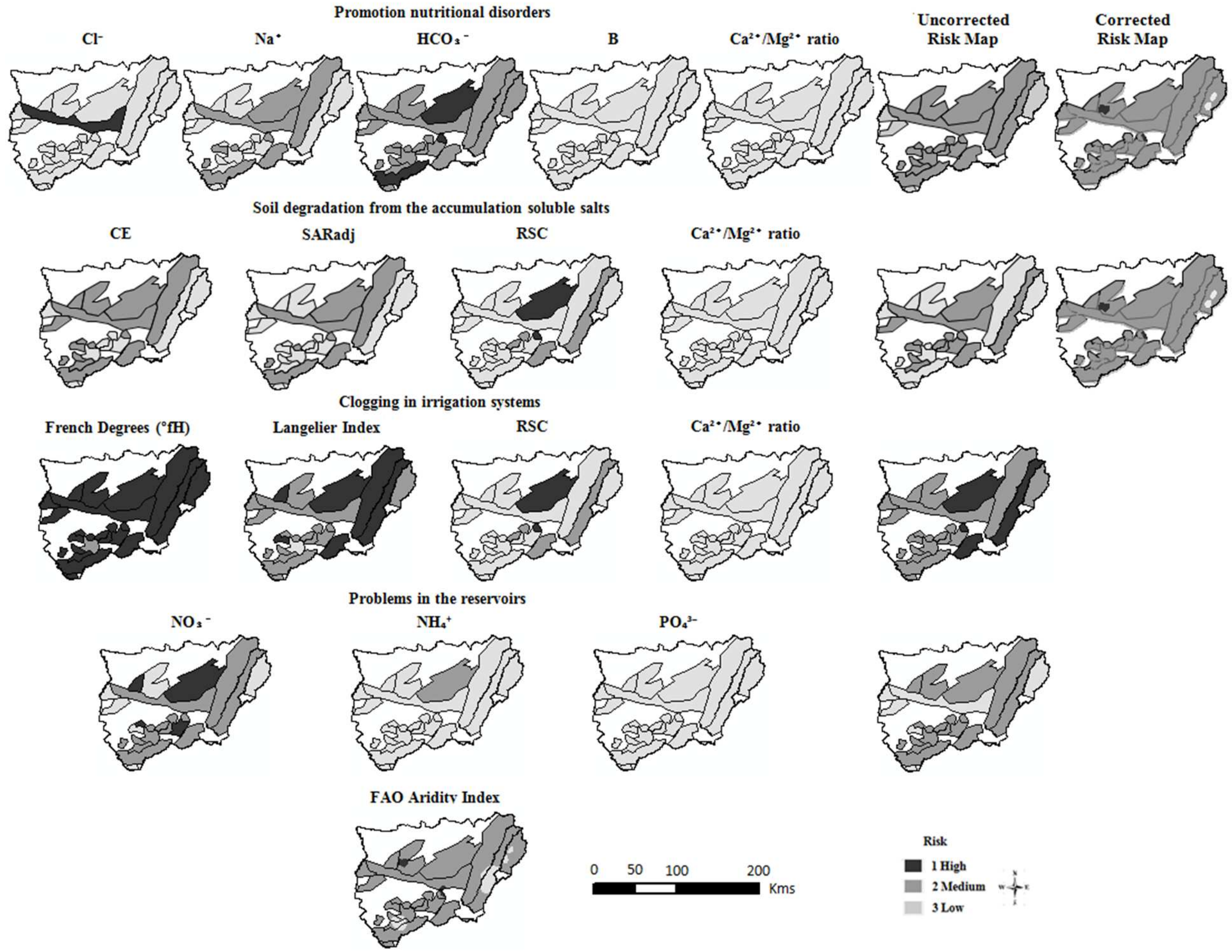

Figure 15. Thematic map for each hydrochemical variable defined for each risk and risk maps as obtained by additive rating of each zone on the map with the Sextante module of gvSIG (http://www.gvsig.org) for ground water. Uncorrected maps are those obtained for each risk without correction by climatic variables, and corrected ones are those corrected with aridity index by additive correction

2.3.3. Effects on the irrigation network: piping and reservoirs

More than 95 % of the surface- and ground water-irrigated land exhibited the highest risk rating for French degrees, and thus a high risk of precipitation of Ca and Mg compounds. Regarding the precipitation of carbonates, the area with the highest Langelier index was greater than 95 % for surface water, but only 50 % for ground water (Table 2.3). The risk maps of irrigation system clogging revealed that using surface water resulted in a higher risk (87 % of the province area was potentially under the highest risk) than using ground water for irrigation (30 % of the area potentially irrigated with this type of water; Figures 2.2 and 2.3, Table 2.4). Regarding reservoirs, the relative area potentially irrigated with waters with the highest rating in algal bloom risk in reservoirs due to nutrient richness was greater for surface water than for ground water (Table 2.3). The map of reservoir risks revealed that the surface water-irrigated area under the highest risk (Figure 2.2) accounted for more than 37% of the total area of the province (Table 2.4); on the other hand, none of the ground water-irrigated land was under the highest risk of reservoir problems (Figure 2.3, Table 2.4).

2.4. Discussion

Based on our results, using the proposed model in combination with open-source GIS software is effective towards managing hydrochemical and climatic information in order to construct water quality maps for assessing risks derived from the use of irrigation water. More complex models and GIS-based tools were previously used to assess quality in ground water (e.g. Moratalla et al., 2011) and irrigation water (Romanelli et al., 2012). However, the proposed model allows one to obtain maps for specific risks with a view to defining measures tailored to each risk and area, and also for different water sources (surface and ground).

In fact, the model provided four maps defining the main risks to be expected from the use of the two types of water; also, it allowed us to identify the locations at risk and estimate their surface areas, thereby confirming the potential capabilities of the open-source software gvSIG for managing water resources in agreement with Chen et al. (2010). The information thus obtained can be useful towards selecting optimal irrigation practices for reducing the potential risks identified in the irrigation water used in a given area. Further research into the management of risk-related information with the aid of GIS will be required with a view to select and handle best management practices to avoid problems derived from the use of low-quality water for each specific location.

In general, the potential risks of using irrigation water differ with the origin of the water. Salinity and sodicity were more frequently encountered with surface water than with ground water (Table 2.3). Especially saline and sodic water should be avoided for irrigation unless the leaching requirements of the target soil are previously assessed to avoid deleterious salt accumulation and the use of water amendments (e.g. gypsum, Ca-containing fertilizers for fertigation) to lower the risk of infiltration. These practices can also help reduce the risk of nutritional disorders posed by irrigation water.

For both sources of water, soil degradation and nutritional disorders risks maps corrected by Ia were coincident (Figures 2.2 and 2.3). With ground water, the highest risk rating for both soil degradation and nutritional disorders affected the same area of only 72 km^2, whereas surface water increased the potentially affected area by each risk at their highest rating to 874 km^2 (Table 2.4). Potential plant disorders arising from the use of irrigation water were found to be derived mainly from the contents in Cl and Na of surface water, and those in Cl and bicarbonate of ground water (Table 2.3). Values of Cl, SAR, and B in the nutritional disorders risk category within the medium rating risk can promote increasing problems of toxicity in olive; severe problems of toxicity in olive can be only expected with Na, Cl, and B concentrations above 1.2 g L^{-1}, 1.8 g L^{-1}, and 2 mg L^{-1}, respectively (Chartzoulakis, 2005). If one considers the tolerance of olive trees to nutritional disorders potentially caused by irrigation water, particularly their intermediate to relatively high tolerance to micronutrient deficiencies induced by a high concentration of bicarbonate (Benítez et al., 2002), using surface water for irrigation is seemingly more restrictive in physiological terms. The correlations of EC with the Cl and Na concentrations, and that between the Na concentration and SARadj, are consistent with the coincidence of nutritional disorder and soil degradation risk maps for surface water; for ground water these both maps are coincident after correction by Ia (Figures 2.2 and 2.3).

Overall, there was a high risk of clogging irrigation systems through precipitation of Ca and Mg compounds by using either type of water; as can be seen from the clogging risk maps (Figures 2.2, 2.3) and Table 2.4; the risk, judging by the span of the potentially affected area, was more marked with surface water than with ground water. Clogging of drip irrigation systems is a serious concern as it can detract from irrigation efficiency and uniformity. This problem can be avoided by using acidified irrigation water —e.g. by applying with fertigation part of the N and/or P requirements as nitric and/or phosphoric acid, respectively.

Surface water posed a more serious constraint on water reservoirs than did ground water (Table 2.4) owing to the more widespread high nutrient concentrations in the former (Table 2.3). This was a result of surface water being enriched with nutrients by effect of run-off and leaching from agricultural land. All surface water sources examined had a phosphate concentration falling in the medium risk interval previously defined for problems in reservoirs; this should allow aquatic organisms not depending on a nitrogen supply (cyanobacteria) to proliferate (Delgado and Scalenghe, 2008). An adequate algaecide supply should be considered to avoid problems in reservoirs.

Overall, the use of surface water for irrigation was subject to greater restrictions than that of ground water. For example, ground water was potentially less prone to cause nutritional disorders and soil degradation. As regards reservoir problems, ground water usually had lower nutrient concentrations than surface water. One potentially effective way of avoiding nutritional, soil, and reservoir problems ascribed to the use of surface water would be therefore to combine water from both origins where possible to decrease salt and nutrient concentration in irrigation water. This solution could also be effective to avoid clogging of irrigation systems, which was more likely with surface water than with ground water. Water mixing may be feasible at the irrigation community level. At the farm level, however, water amendment and fertigation with acids may be more effective towards reducing the risks for soil and irrigation systems, probably with little economic impact —a point which requires further analysis, however.

The proposed model, which uses the software gvSIG, can help stakeholders improve water resource management in the study area by supplying useful information about the type and location of potential risks relating to irrigation water quality. Our model, which could be easily transferred to other regions and crops, can be used as the basis to develop educated water management policies leading to the adoption of optimal management practices for each site in a region, and also to extract useful information with a view to optimizing the use of water and irrigation systems at the farm level.

2.5. Conclusions

The proposed model, developed with the aid of gvSIG, allows one to readily identify and locate potential risks relating to irrigation water quality at a regional scale with a view to taking preventive and corrective measures at the irrigation community or individual farm scale. Overall, clogging of drip irrigation systems accounted for the most extended risk at the highest rating in the province, particularly with surface water, which requires careful management of the systems at the farm scale.

2.6. Acknowledgments

The authors wish to thank Juan Carlos Rubio of Spain's National Institute of Geology and Mining (IGME) for providing access to ground water information. This work was co-funded by Spain's former Ministry of Education and Science, and Ministry of Science and Innovation, as well as by the European Regional Development Fund of the European Union through the National Research, Development and Innovation Programme (Plan Nacional I+d+i, Project AGL2011-29893).

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Capítulo 3. A GIS-based decision tool for reducing salinization risks in olive orchards

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Abstract

This work was aimed at implementing a GIS based on an open-source software able to help in decision making in irrigation water management with a view of avoiding the excessive accumulation of salts in soils for olive tree production in South Spain (province of Jaen). The proposed model provides graphical and geostatistical analysis that can be easily performed by using different mathematical algorithms available in the gvSIG software. Leaching and mixing of water from different origin were taken into account in the model as strategies to decrease salinization risk in soil.

Overall, electrical conductivity, and consequently leaching requirements, were higher for surface water than for groundwater. A relative crop yield of 90% can be achieved in 23% of the area irrigated with surface water, meanwhile with groundwater a 90 % of relative yield can be achieved in 36.7 % of the irrigated area with leaching fraction (LF) above 10 %. The implemented GIS-tool based on open source gvSIG software was able to assess water leaching requirements in order to prevent the salinization risk of soils in olive orchards in the province of Jaen. Where LF was so high to be feasible, the GIS-based tool can recommend different mixing ratios for surface and underground water in order to decrease recommended LF thus making irrigation sustainable. The model was able to facilitate data analysis and processing, allowing the visualization of the spatial distribution and offering all the functionality of handling geographic data, which will be used in the planning and decision making. The proposed GIS-based tool is also able to provide fast map recalculation after an update of database, thus allowing one to adapt decisions to fast changes in water properties.

Key words: leaching requirements, water mixing, salinization, olive, GIS.

3.1. Introduction

Agricultural productivity is enhanced by irrigation in many arid and semi-arid lands of the World, where irrigated surface has expanded significantly in the last decades in response to the needs of a growing population (Peragón et al. 2015). However, this expansion has frequently relied on the use of low-quality water, such as in a number of Mediterranean countries, which increases the risks of irrigation-related salinization of soils (Toth et al. 2008; Aragues et al. 2011). Avoiding land degradation ascribed to soil salinization is a crucial issue for sustainability of irrigated agricultural production and for ensuring food security in many areas of the World (Peragón et al. 2015).

Irrigation-related salinization is the consequence of an unsuitable salt balance in soil (Corwin et al. 2007; Aragues et al. 2011; Keren 2012) and can be prevented by accurate leaching recommendations (Letey et al. 2011; Skaggs et al. 2012). To this end, management tools are required for assessing risk ascribed to irrigation and to take decisions based on water quality, climate data, and irrigation schemes. Although estimation of leaching requirement is the first tool to be considered, the joint use of water sources with different salt concentration is a strategy that may lead to an improved quality of irrigation water through dilution (Qureshi et al. 2004). Therefore, another possible strategy to decrease these potential risks could be the mix of surface and underground water when they both are available and have different salt concentration (Mahfuzur et al. 2014; Prendergast et al. 1994). This water mixing can also contribute to reduce the consequences of the long-term use of underground water in arid and semiarid regions when irrigation is based on the use of underground water and where abstraction rates exceeds recharge rates. This can be particularly relevant in regions with a large pressure in the use of ground water bodies and where irrigation with underground water is usually more profitable than irrigation with surface water such as in south Spain (Hernández-Mora et al. 2001; Vives, 2003; MMA 2006). In any case, a rational management of underground water in arid and semiarid lands should be encourage by using tools such as geographic information systems (GIS) able to process large spatial information in order to recommend different water mixing rates depending on changes in availability and salinity of the different sources of water for irrigation. Assessment of long-term evolution of levels in underground water bodies is also required to guarantee the sustainability of irrigation. All this will contribute to avoid overexploitation of underground water bodies.

Assessment of these methods to avoid salinization at regional scales is made difficult by the high variety of water sources used (Peragón et al. 2015). This difficulty can be overcome with the use of GIS, which facilitates the integration and handling of large spatial data from different sources, and the prediction of consequences of management decisions (Melh et al. 1997). GIS can be applied to the management of irrigation systems (Shahbaz et al. 2007) and have proved effective in the evaluation of irrigation water quality and salinization risks at regional scales (Mirlas 2012; Romanelli et al. 2012). Recently, Peragón et al. (2015) proposed an information management model based on GIS which was useful to assess the risks associated with the use of irrigation water for olive tree orchards in South Spain (Jaen Province). However, farmers and stakeholders need tools not only providing risk scales, but also able to assess optimal management practices to decrease risks related to irrigation water quality. Since water quality can change quickly with time, e.g. after storm events, a GIS-based tool should be able to precisely adapt solutions to these changes. In this regard, the aim of this work is the implementation of a GIS based on an open-source software in order to manage water quality and climatic information to assess leaching requirements or mixing of water from different origin (i.e. surface or underground water) with a view of preventing the excessive accumulation of soluble salts in soils. This would evidence that not only descriptive information can be managed by GIS, but also that GIS-based tools can be effective in providing solutions for irrigation through management of large databases at regional scale. The study was conducted using the same software (gvSIG), in the same area (province of Jaen, South Spain), and for the same crop (olive tree) that Peragón et al. (2015). The economic relevance of this crop and the increased salinization risk in this area ascribed to poor-quality water and deficit irrigation warranted the conduct of the present study.

3.2. Material and methods

3.2.1. Study area

The study was performed the province of Jaen (Southern Spain), which accounts for 586000 ha of olive orchards which represents 43.4 % of the total area of the province, and 23 % of the total olive orchard area in Spain (MAGRAMA, 2012). Irrigated olive orchards extend on more than 290000 ha, most of them (70 %) planted during the past 20 years. Deficit drip irrigation is used in 96 % of the irrigated olive cropped land. In spite of applying irrigation rates clearly below crop evapotranspiration, this management affords high crop water productivity (Peragón et al. 2015).

3.2.2. Irrigation systems

Water was supplied in most of the orchards (around 90 %) with a drip irrigation system with 2 self-compensating dropper per tree allowing a water flow of 8 L h^{-1} each one (Peragón et al. 2015). Droppers were connected to irrigation branches by polyethylene tubes. A reservoir allowed water storage and irrigation regulation in each farm, enabling the irrigation in several (usually three) sectors. Water used for irrigation was surface water in 73% of the irrigated area, underground water in 22%, wastewater in 4%, and combined surface and groundwater in 1%, according to the regional government (Junta de Andalucía, 2008).

3.2.3. Water and climatic data

Electrical conductivity of irrigation water was supplied by the water authority of the Guadalquivir basin (Confederación Hidrográfica del Guadalquivir, 2014). Average water data for each month between 1994 and 2013 were collected from 66 surface water stations and 136 ground water stations used as irrigation supplies each month. Climatic data including daily rainfall and temperatures (high, low and mean), effective rainfall, and potential evapotranspiration (PET) between 2000 and 2013 were obtained from the 35 agroclimatic stations from the Andalusian network (Junta de Andalucia, 2014). Effective rainfall was estimated according to Stamm (1967).

3.2.4. Estimation of leaching requirements

Relative yield (RY) was related to the electrical conductivity (EC) of saturated extract of soil using the equation of Mass and Hoffman (1977):

$$RY = 100 - b\,(ECs - ECc) \qquad (3.1)$$

RY being the relative crop yield expressed as a percentage of maximum expectable yield unlimited by salt content of soil, ECs the electrical conductivity of soil saturation extract, and b the decrease in % of relative yield per unit increase in EC in the soil saturation extract above the threshold value (ECc) below which there is not decrease in crop yield ascribed to soil salinity. An ECc value of 6 dS m^{-1}, and a slope (b) of 7.7 were selected for olive varieties resistant to salinity (Mass and Hoffman 1977; Benlloch et al. 1994). For relative yields of 50, 75, and 90%, ECs was considered 12.5, 9.2, and 7.3 dS m^{-1}, respectively.

Salt leaching requirements (LR) were estimated according to the model of Rhoades (1982) for high frequency irrigation:

$$LR = 0.1794\ CF^{-3.0417} \qquad (3.2)$$

LR is expressed as the fraction of applied irrigation water that must pass through the root zone to maintain salts concentration in soil (measured as EC in the saturation extract) below a certain level. Its values depends on the salinity of the water, crop tolerance to salts and irrigation system used; CF is the concentration factor, which is the ratio at which salt in irrigation water is concentrated in soil, and can be affected by weathering or precipitation of salts; CF is estimated as:

$$CF = ECs/ECw \quad (3.3)$$

ECw being the electrical conductivity in irrigation water.

With the highly efficient irrigation system described above and the common practice of deficit irrigation, losses of applied irrigation water can be considered low, and mainly ascribed to preferential flow in soil. These losses can be considered lower than 15 % of applied water (Stewart and Nielsen, 1990), and thus the minimal water application efficiency (Howell, 2003) can be estimated as 85%. Since preferential flow is poorly efficient for leaching salts (Hurtado et al. 2011), the Leaching Fraction (LF) need to avoid an accumulation of salts that may affect crop production can be estimated as:

$$LF = LR/0.85 \quad (3.4)$$

3.2.5. Estimation of water mixture ratio

The salt concentration in the final mixture can be estimated as a weighted average between the concentrations of the mixed water:

$$ECf = [ECa\ (Qa/Qt)] + [ECb\ (Qb/Qt)] \quad (3.5)$$

where ECf is the final electrical conductivity in the mixture, ECa and ECb are the electrical conductivity of water "a" and "b" expressed in dS m^{-1}, respectively, Qa and Qb the volume of water "a" and "b", respectively, and Qt the total volume of water (Qa + Qb).

3.2.6. Model

The data of climate, effective rainfall, ECw, and leaching fraction for different RY were handled with a GIS implemented as described by Peragón et al. (2015) using the free GIS software gvSIG (www.gvsig.org). Each data was associated with a geographical reference according to the model described in Figure 3.1. This model provides an association of an alphanumeric table with graphical entities which provides a precise location in the space and an easy maintenance and upgrade. With this model, graphical and geostatistical analysis can be easily performed by using different mathematical algorithms available in a module called "Sextante" of the gvSIG software.

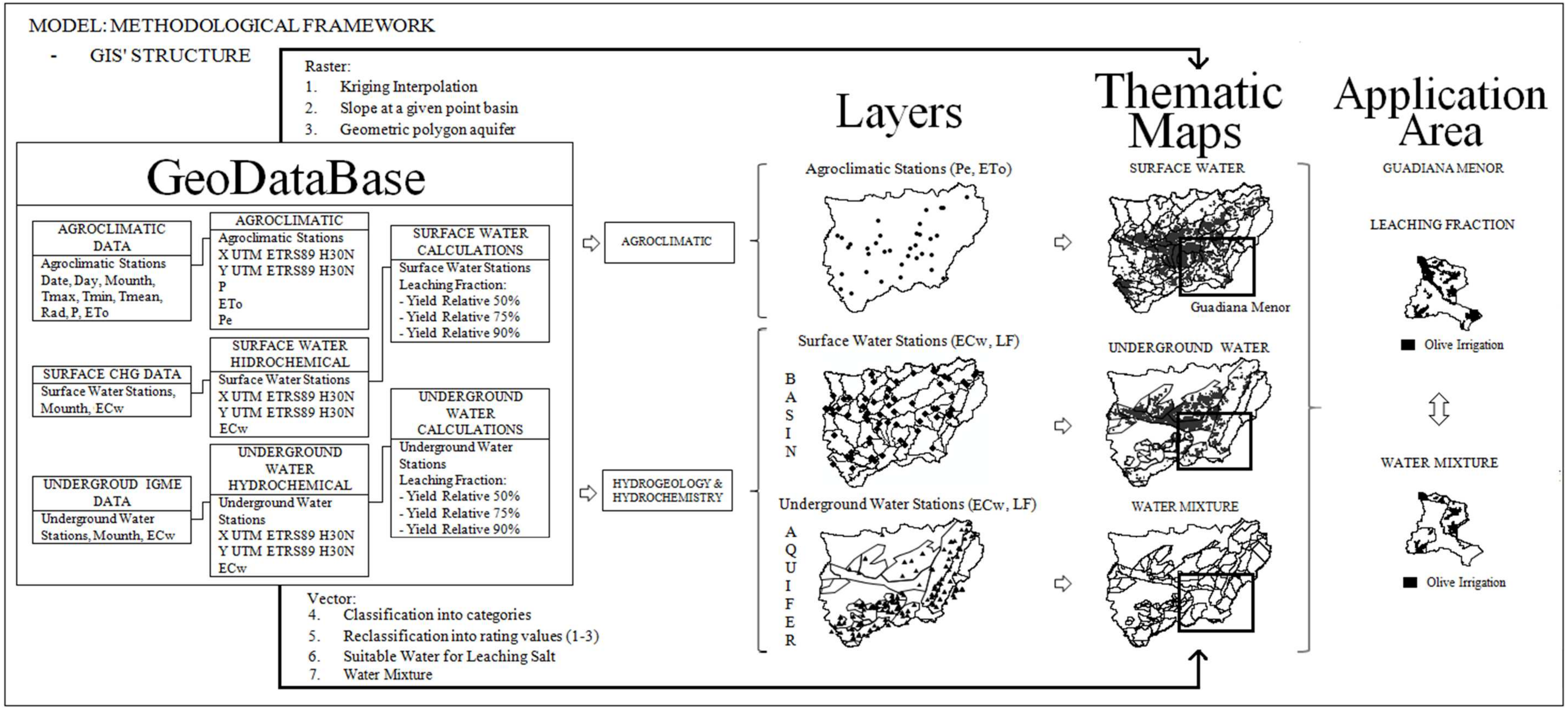

Figure 16. Methodological framework for GIS-based methodology

Surface and ground waters were georeferenced, assuming the surface water used to come from the sub-basins where the pumping station was located, and defining polygons corresponding to each aquifer to assign each ground water source to a specific area. Sub-basins were defined by using the algorithm "slope at a given point basin", and ground water polygons using the algorithm "geometric polygon aquifer" available in the module Sextante of gvSIG. After that, for each type of data (climate, effective rainfall, and ECw) a map was constructed by kriging interpolation, which creates a surface of estimated values from a series of point values (Peragón et al. 2015). Kriging has been selected because it is a complex interpolation technique that considers both the distance and the degree of variation between known data points when estimating values in unknown areas. Also, it takes into account directional influences, which could be a relevant factor in hydrologic studies, and it the most recommended technique for climatic data interpolation (Naoum and Tsanis 2004; Hofstra et al. 2008). Transformation of each map into raster format with a spatial cell resolution of 100 x 100 m was done using the spatial analysis module of gvSIG.

Available information was classified into three risk categories: 1, 2 or 3 for high, medium and low risks, respectively, based on climate, effective rainfall, and irrigation water salinity according to Peragón et al. (2015). Based on these maps and on the LF estimation method defined above, maps of LF for different relative yields (we have considered 50, 75, and 90 %) can be released as result of vector geoprocessing using the "Sextante" module of gvSIG software. As described by Peragón et al. (2015), all the mathematical algorithms used in the model are included in the geoprocessing tools of the Sextante module of gvSIG (www.gvsig.org) by creating scripting in Jython programming language (www.jython.org). More information about the use of the tools of Sextante module of gvSIG and Jython language use can be found in Peragón et al. (2015).

Average ECw values from 1994 to 2003 were used for classification in risk categories, LF estimation and LF maps. To assess the effect of the changes in salt concentration of surface water with time on recommended LF, maps of LF for 90 % yield were performed from April to September for 2006 and 2010 in the Guadiana Menor basin. This basin was selected since ECw values ranged more than in other basins, and these years were selected because they differed widely in rainfall and, consequently, in ECw of surface water.

For water mixing, the GIS thematic map for ECw for surface water should be overlapped with that of the area occupied by the groundwater bodies. This was done using the mathematical algorithms rasterization ("rasterized vector layer" and "cut raster layer with polygon layer"), and subsequent vectorization ("vectorize raster layer") available in the Sextant module of gvSIG. Two solutions can be provided. The first one is the mixing ratio of water from different origin to achieve a given EC, e.g. 0.7 dS m^{-1} for a minimum leaching fraction requirement. The second possibility is to provide the final ECw and leaching fraction for given mixing ratios. In both cases, the algorithm "calculator maps" was applied. The methodological framework for both solutions is described in Figure 2, and the process using gvSIG described in supplementary material (Annexed 3). Both possible solutions were applied to the Guadiana Menor Basin as an example of the potentiality of the model using average water data from 1994 to 2013.

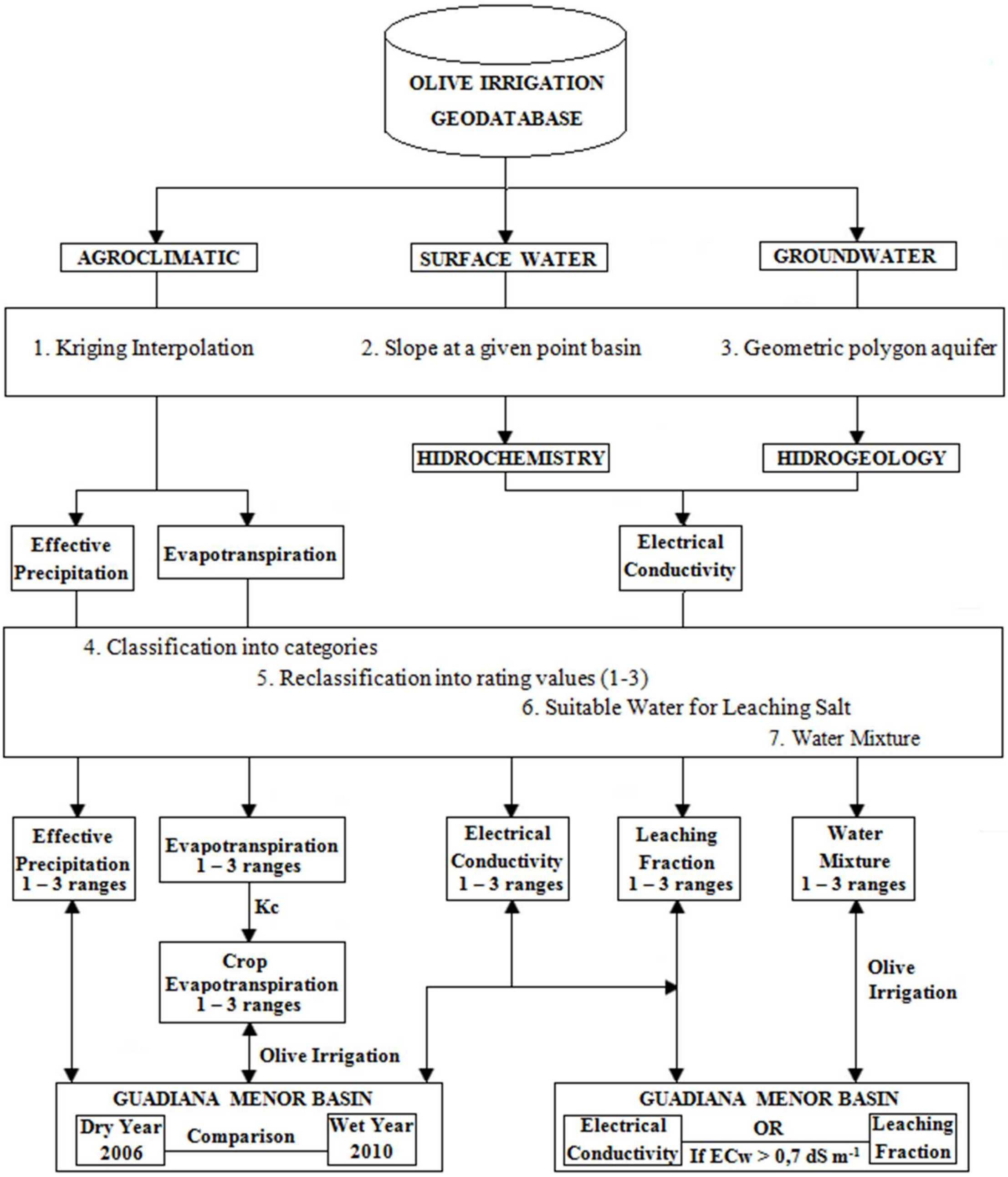

Figure 17. Implementation of the methodological framework for assessing water mixture depending on results in the previous estimation of leaching fraction, and new estimation of leaching fractions with mixed waters when ECw > 0.7 dS m^{-1} to achieve minimum leaching requirements

3.3. Results

In the study area, annual rainfall was lower than potential evapotranspiration with less than 500 mm of effective rainfall in 84 and 86.6 % of the area supplied by surface and groundwater, respectively (Table 3.1, Figure 3.3). Potential evapotranspiration exceeded 900 mm in 100% of the olive orchard area irrigated for both types of water (2903 and 1419 km^2 for surface water and groundwater, respectively).

Table 5. Parameters involved in the definition of the different risks related to hidrochemical and climatic parameters, surface affected, and % of the olive surface irrigation in the province affected for surface and underground waters

Parameters	Risk-Gradation	Annual	Surface Water		Underground Water	
			Olive Area Irrigation (km²)	% Olive Area Irrigation	Olive Area Irrigation (km²)	% Olive Area Irrigation
EP (mm)	1-High	< 500	2440	84,0	1229	86,6
	2-Medium	500 - 700	384	13,2	153	10,8
	3-Low	> 700	79	2,8	37	2,6
ETo (mm)	1-High	> 700	2903	100	1419	100
	2-Medium	500 - 700	-	-	-	-
	3-Low	< 500	-	-	-	-
ECw (dS m^{-1})	1-High	> 3	342	10,8	-	-
	2-Medium	0,7 - 3	2248	77,4	1259	88,7
	3-Low	<0,7	313	11,8	160	11,3

ECw, electrical conductivity of water according to Ayers and Westcot (1985)

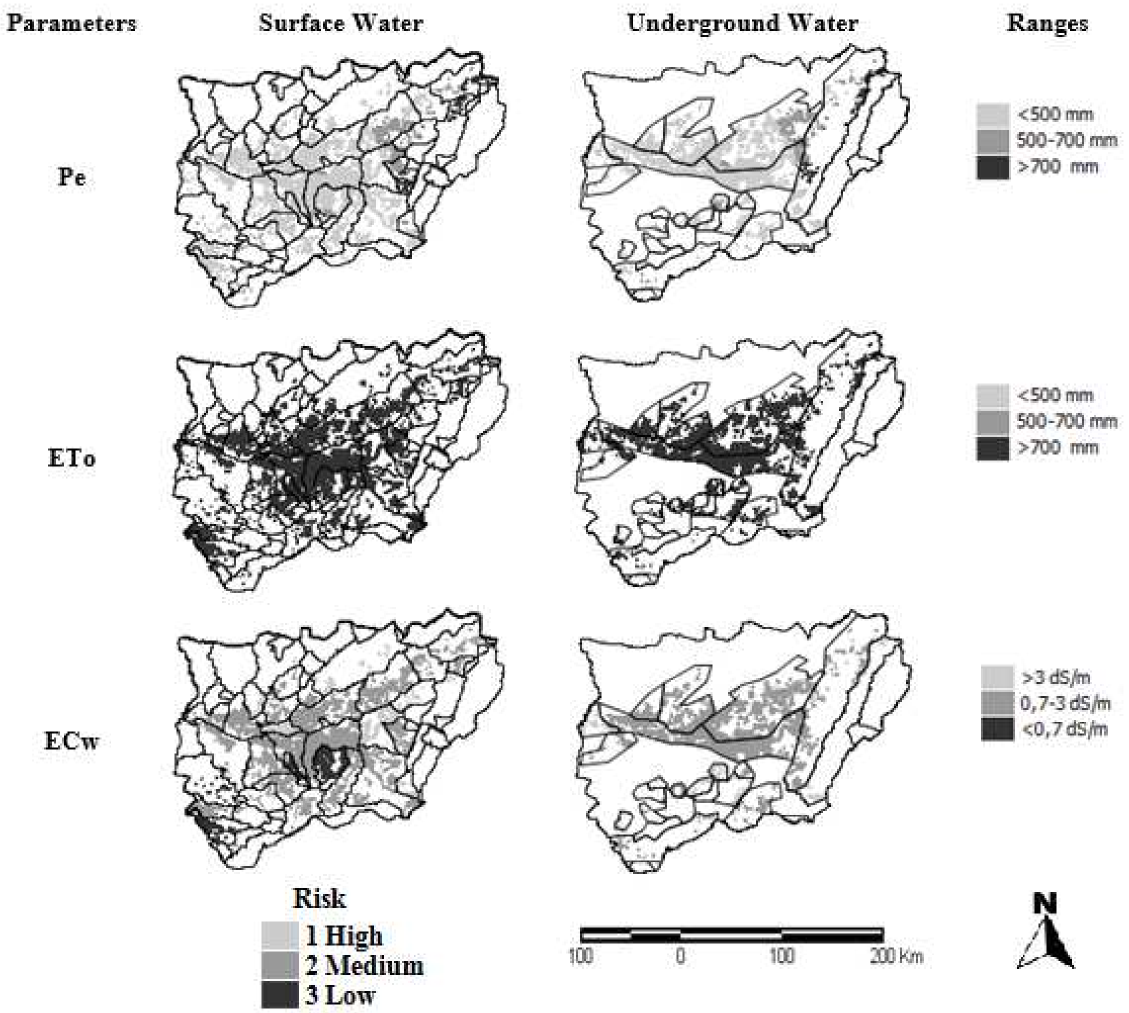

Figure 18. Thematic map for each climatic and hydrochemical property used to estimate salinization risks porformed by geostatistical analysis for both surface and groundwater

Considering average data in the period of study (1994-2013), ECw was higher than 3 dS m^{-1}, in 335 km^2 of the olive orchard area irrigated with surface water, which amounted to 11 % of the surface irrigated with this water source. This is the area with the highest salinization risk according to Peragón et al. (2015). An intermediate salinization risk, consequence of irrigation with water with mean ECw between 0.7 and 3 dS m^{-}1, was expected in 77.4% and 88% of the area irrigated with surface water and ground water, respectively (Table 3.2, Figure 3.3).

Table 6. Leaching fraction (in %) for obtain an optimal yield relative of olive cultivar, surface affected, and % of the olive surface irrigation in the province affected for surface and underground waters

	Gradation-Risk	Leaching Fraction	Yield Relative 50%		Yield Relative 75%		Yield Relative 90%	
			Olive Area Irrigation (km²)	% Olive Area Irrigation	Olive Area Irrigation (km²)	% Olive Area Irrigation	Olive Area Irrigation (km²)	% Olive Area Irrigation
Surface Water	1-High	> 30 %	43	1,5	43	1,5	335	11,6
	2-Medium	10 - 30 %	-	-	184	6,3	332	11,4
	3-Low	< 10%	2860	98,5	2676	92,2	2236	77,0
Underground Water	1-High	> 30 %	-	-	-	-	-	-
	2-Medium	10 - 30 %	-	-	-	-	520	36,7
	3-Low	< 10%	1419	100	1419	100	899	63,3

Leaching Fraction of water according to Rhoades (1982)

To achieve relative crop yield of 90%, LF higher than 10% was required in 667 km^2 (23%) of the area irrigated with surface water (Table 3.2; Figure 3.4). In the area with the highest salinization risk (335 km^2), more than 30 % of LF was required to achieve a 90 % of relative yield; this LF being insufficient to maintain more than a 50 % of potential yield in 43 km^2 (1.5 %) of the area irrigated with surface water. With this water source, LF of 10 % or less was required for relative yields of 90 % in 77 % of the irrigated area, this leaching fraction being enough to achieve more than 50 % of relative yield in 98.5 % of the area irrigated with surface water (2860 km^2; Table 3.2; Figure 3.4). On the other hand, with groundwater, a 90 % of relative yield was expectable in 36.7 % of the irrigated area with LF above 10 %; with this water source, a 75 % of the relative yield could be achieved in 100 % of the irrigated area with LF of 10 % or less (Table 3.2; Figure 3.4).

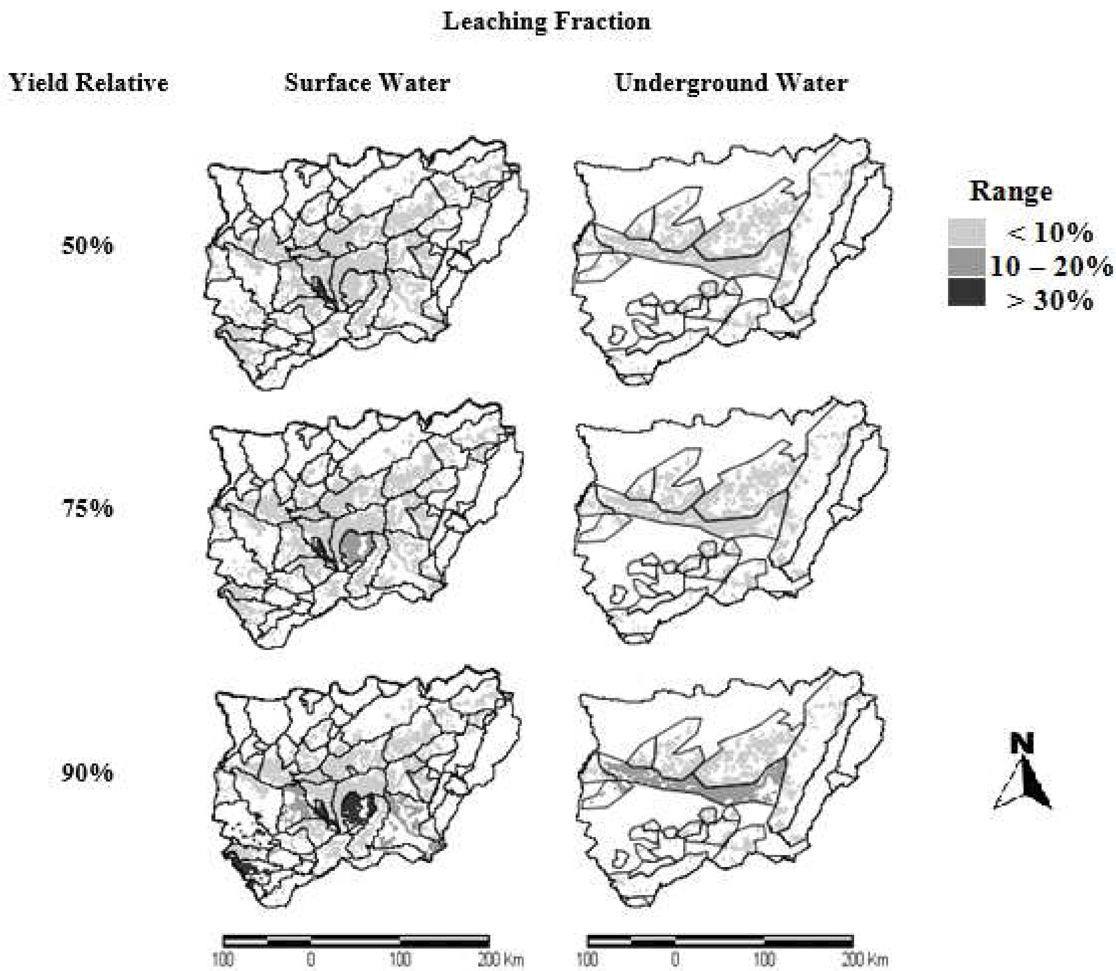

Figure 19. Maps of leaching fractions needed to achieve different percentages of relative yields of olives for both surface water and groundwater

Recommended LF for a given relative yield changed depending on the water composition; change in ECw was more evident in surface water as a result of runoff process after storms or by dilution/concentration of water in reservoirs. Overall, ECw in surface water tended to increase in dry years. Taking the Guadiana Menor basin (south east of the study area, Figure 3.5) as an example, ECw of surface water was overall higher, and consequently LF required for avoiding salinization risks, in 2006 than in 2010 (Table 3.3). In this basin, mean leaching fractions required to achieve a 90 % of relative yield changed month to month as a consequence of the changes in water quality. This was particularly evident from August to September 2006, with LF increasing from 0.25 to 26.75 to maintain relative yields of 90 % (Table 3.3; Figure 3.5).

Table 7. Application of the results obtained in the basin of the Guadiana Menor (with 139,53 km^2 olive irrigation), by comparison with the dry and wet years, 2006 and 2010, obtaining the Leaching fraction (in %) for obtain an optimal yield relative (90%) of olive cultivar

	Years									
	2006					2010				
Month	Pe (mm)	ETo (mm)	ETc (mm)	ECw (dS m^{-1})	LF (%)	Pe (mm)	ETo (mm)	ETc (mm)	ECw (dS m^{-1})	LF (%)
April	31,79	139,89	83,93	3,81	2,92	22,52	124,93	74,96	1,37	0,13
May	11,00	191,98	105,59	3,37	2,01	21,41	162,79	89,53	1,38	0,13
June	12,35	235,40	129,47	1,79	0,29	35,34	181,09	99,60	1,40	0,14
July	1,20	263,95	131,98	1,81	0,30	0,00	247,25	123,63	1,88	0,34
August	4,96	230,16	115,08	1,69	0,25	25,65	214,77	107,39	3,68	2,64
September	9,45	161,51	88,83	7,89	26,75	24,55	141,82	78,00	2,12	0,49

LF: Leaching Fraction of water according to Rhoades (1982)

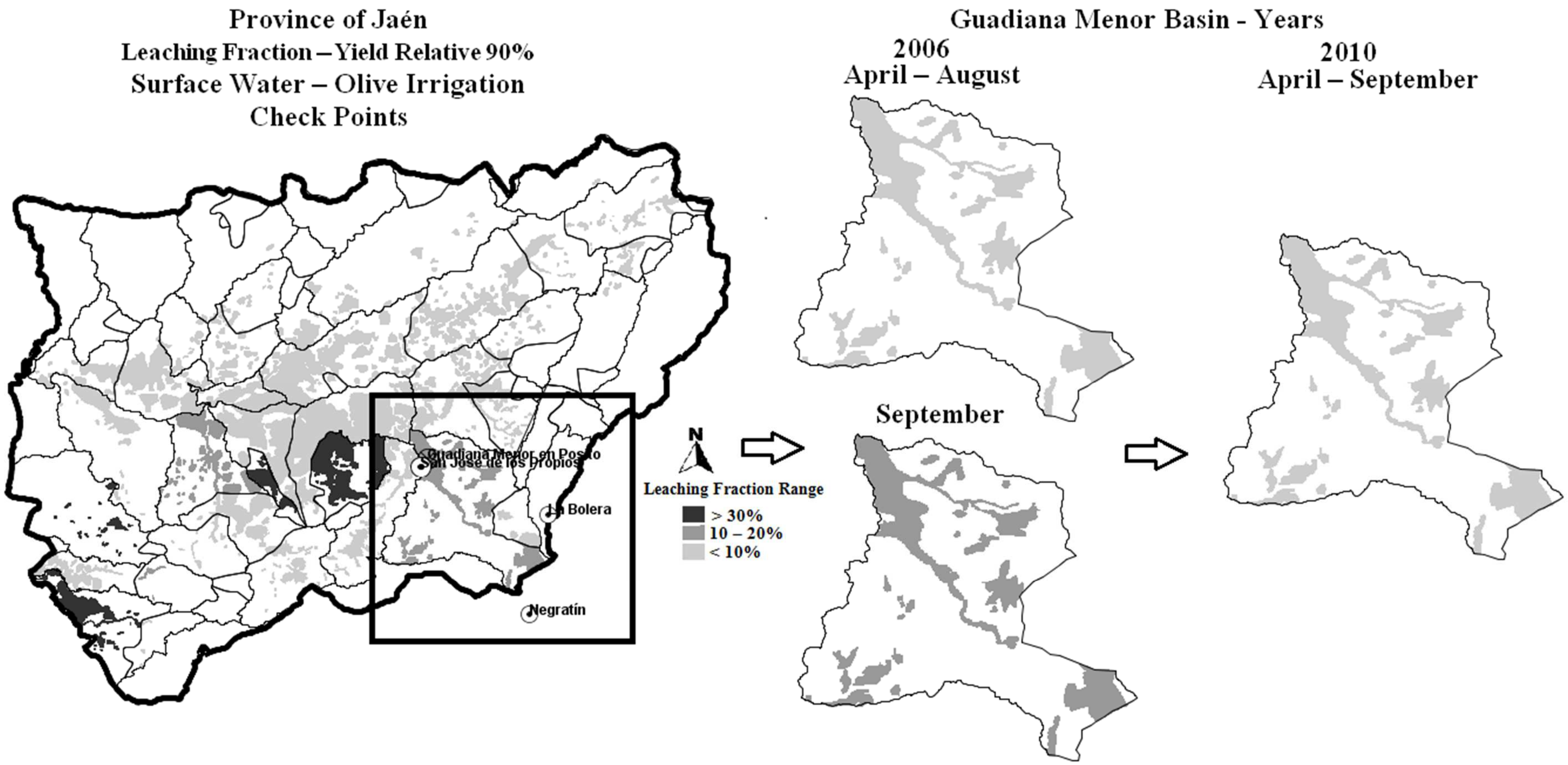

Figure 20. Application of the model for the estimation of leaching fractions at three different dates in the Guadiana Menor Basin

In the Guadiana Menor basin it was possible to mix water in four sub-basins, with a total surface of 58.9 km^2 (Table 3.4). On average, from 1994 to 2013, ground water was a source of less saline water in a greater area than surface water. ECw in ground water was lower than 0.9 dS m^{-1} in 43.65 km^2. On the other hand, ECw in surface water was 2.68 dS m^{-1} in 58.5 km^2 (Table 3.4). This means the underground water can be considered the source of quality water to dilute the more saline surface waters. Irrigation water within the lowest salinization risk interval can be achieved by using between 61 and 100 % of underground water in the mixture (Table 3.5; Figure 3.6). For given ratios of surface to underground water used in irrigation, ECw in the resulting irrigation water, LF, and surface affected were also estimated as an alternative solution (Table 3.6; Figure 3.6). Increasing the proportion of underground water from 10 to 50 % implies that LF could be decreased by more than 80 %. The distribution of different ECw resulting from water mixing and new leaching fractions in the basin is described in Figure 3.6 for the different mixing ratios proposed.

Table 8. Electrical conductivity (dS m^{-1}) in the areas of irrigation olive grove where it is possible to perform the mixing of waters in the basin of the Guadiana Menor, and% affected area (km^2)

Surface Water		Underground Water	
ECw (dS m^{-1})	Area (Km^2)	ECw (dS m^{-1})	Area (Km^2)
0,60	0,13	0,43	0,25
1,36	0,10	0,74	16,55
1,75	0,14	0,89	26,85
2,68	58,51	2,74	15,23

ECw, Electrical conductivity of irrigation water according to Ayers y Westcot (1985)

Table 9. Solution 1: Application of the results obtained in the basin of the Guadiana Menor (with 58,88 km^2 olive irrigation), fixing the final concentration 0,7 dS m^{-1}, to apply a low salinity water, for obtain an optimal yield relative (90%) of olive cultivar

Proportion (%)		Area (Km^2)
Surface Water	Underground Water	
38,7	61,3	15,09
1,5	98,5	0,10
2,1	97,9	0,04
0,7	99,3	0,13
0,1	99,9	0,35
*0	*100	43,17

* Final Concentration: 0,9 dS m^{-1} to apply only underground water

Table 10. Solution 2: Application of the results obtained in the basin of the Guadiana Menor (with 58,88 km^2 olive irrigation), get final concentration from de concentrations of each type of water used, obtaining the Electrical conductivity (in dS m^{-1}) and Leaching fraction (in %s) for obtain an optimal yield relative (90%) of olive cultivar

Concentrations (% SW + % UW)	ECw (dS m^{-1})	LF (%)	Area (Km^2)
90 + 10	0,47	0	0,08
	0,54	0,01	1,03
	2,41	0,73	57,77
80 + 20	0,42	0	0,08
	0,48	0,01	1,03
	2,15	0,51	57,77
70 + 30	0,36	0	0,08
	0,42	0	1,03
	1,88	0,34	57,77
60 + 40	0,31	0	0,08
	0,36	0	1,03
	1,61	0,21	57,77
50 + 50	0,26	0	0,08
	0,30	0	1,03
	1,34	0,12	57,77

ECw, Electrical conductivity of irrigation water according to Ayers y Westcot (1985).
LF, Leaching fraction for 90 % yield relative according to Rhoades (1982), Stewart and Nielsen (1990), and Howell (2003).
(% surface water + % underground water).

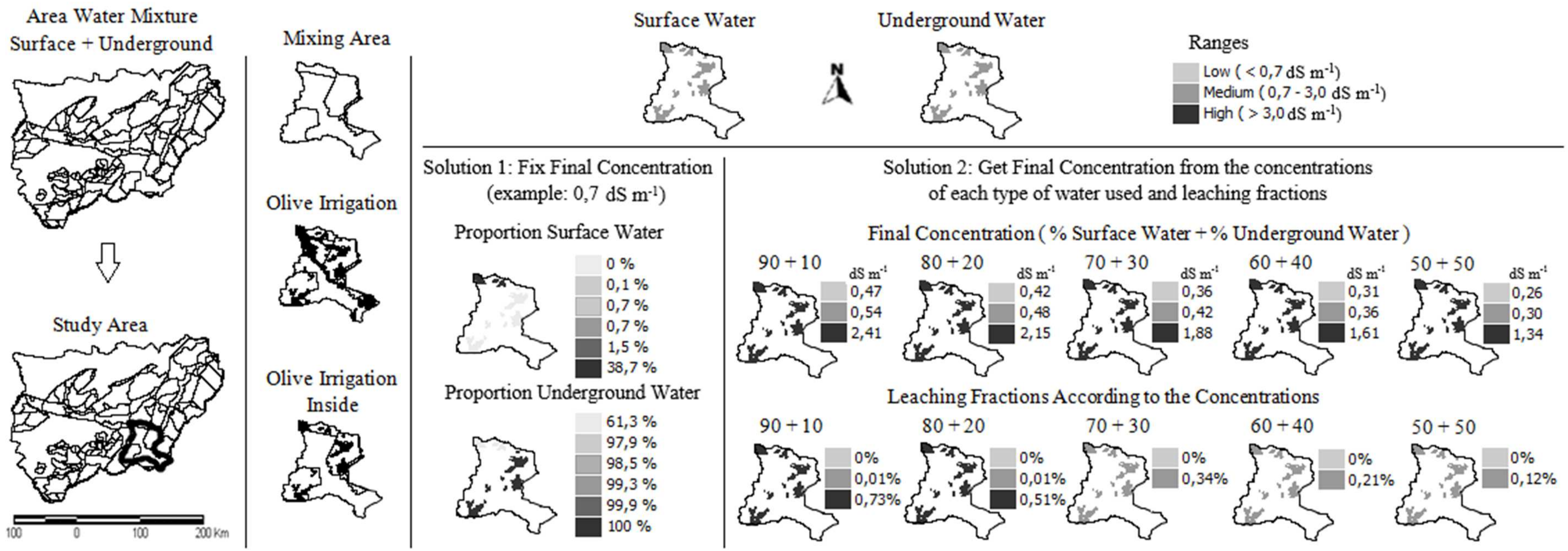

Figure 21. Application of the model for the estimation of water mixture ratios (surface:underground) to achieve irrigation water with a given ECw (0.7 dS m^{-1}) (Solution 1), and estimation of leaching fractions for different mixture ratios (Solution 2)

3.4. Discussion

Overall, leaching requirements were higher with surface water than with groundwater (Table 3.2; Figure 3.4). Also, recommended LF changed more with time for surface water than for groundwater as consequence of a more variable water composition and salt concentration as result of weather differences between months and years (e.g. those showed for the Guadiana Menor basin, Table 3.3; Figure 3.5).

Annual irrigation water assignation for olive growers is 1500 m^3 ha^{-1} per year in the province of Jaen. This means a deficit irrigation for olive in the area since an optimal irrigation supply requires average rates above 3000 m^3 ha^{-1} (Pastor et al. 2002). Which such low water availability, LF of 30 % or above implies an unsustainable management of irrigated orchards. The highest leaching fractions was required in 335 km^2 irrigated with surface water with mean ECw above 3 dS m^{-1}, which means above 1.6·107 m^3 of leaching water, a very high requirement for sustainable water management. The olive cultivar usually cropped is “Picual”, which is fairly tolerant to salinity (Benlloch et al. 1994). Thus, the selection of other more tolerant cultivars cannot be an option to avoid risks ascribed to poor quality water. In 43 km^2 of the area irrigated with surface water where LF > 30 % only guarantee a 50 % of relative yield, alternative land use should be considered. However, when overlap of surface and underground sources is possible, water mixing can be a solution to achieve lower LF. In the Guadiana Menor Basin, mixture of water from different origin can contribute to achieve much lower LF (Table 3.5; Figure 3.6). This is an example which can be applied to the whole study area. Regarding this option, the only limitation is the infrastructure cost. However, in many cases the present infrastructure allows to adapt this solution at a reasonable cost.

The main concern derived from water mixing is how it can contribute to an overexploitation of ground water bodies. This risk is is high in Spain (around 23 % of ground water bodies are affected) and particularly in the province of Jaen where approximately half of the area is affected by ground water overexploitation (MMA 2006). However, the proposed GIS-based decision tool can be integrated in a joint sustainable management of surface and ground water bodies which allows for decreasing the proportion of groundwater used in irrigation when the quality of surface water improves. All this is focused on avoiding land degradation by salinization and ensuring sustainability of irrigation agricultura which not only depends on water availability but also on non-degraded soils. Furthermore, the tool can contribute to save water independently of the origin by decreasing LF. In any case, the implementation of water mixing strategies should be monitored on the long-term to assess how affect to underground water bodies. To this end, the use of GIS-based tools can be also of interest.

Results revealed that implemented GIS-tool based on open source gvSIG software was able to assess water leaching requirements in order to prevent the salinization risk of soils in olive orchards from the province of Jaen. This complements previous studies using GIS based models, such as that performed by Peragón et al. (2015) in the same geographic area, to assess water irrigation quality and to estimate risks related to the use of poor-quality irrigation water. Although only three ranges of LF were considered for each relative yield in the model, this can be considered as a demonstration of potential capabilities; it can be easily implemented for more accurate assessing of LF in each zone. The GIS-based tool is also able to adapt decisions to fast changes in water composition, as revealed by the LF estimates in the Guadiana Menor basin for different months and for two different years (Figure 3.5). Using this basin as an example, the proposed model was also able to handle spatial data to provide an additional solution based on the mixing of water from different origins; this solution provided a significant decrease in LF and thus in water consumption for irrigation. The developed model was suitable, not only to provide information to help stakeholder to take decisions, but also to facilitate data analysis and processing. In this regard, it can provide a range of alternative or complementary technical solutions for irrigation management at a regional scale. In this case, the model was tested for two solutions (LF estimation and water mixing) for reducing salinization risks. Beside this, it also allows visualize the geographic information and provides all the functionality of handling geographic data, which will be used in the planning and decisión making. The model can be easily extrapolated to other regions and crops and can be an useful tool for helping stakeholders to take decisions on irrigation management at regional scales.

3.5. Acknowledgments

The authors wish to thank Juan Carlos Rubio of Spain's National Institute of Geology and Mining (IGME) for providing access to ground water information. This work was co-funded by Spain's former Ministry of Education and Science, and Ministry of Science and Innovation, as well as by the European Regional Development Fund of the European Union through the National Research, Development and Innovation Programme (Plan Nacional I+d+i, Project AGL2011-29893).

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Capítulo 4. A GIS-based tool for integrated management of clogging risk and nitrogen fertilization in drip irrigation

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Abstract

Precipitation of insoluble compounds poses a relevant concern in the management of drip irrigation. This risk is controlled by acidification of irrigation water. The main objective of this work was the development of a GIS-based tool to control drip clogging risk in drip irrigation by nitric acid injection in irrigation water. The study was performed in the province of Jaen (south Spain) focused on the irrigation of olive orchards. The GIS-based model was developed incorporating climate and water data in order to identify zones with different risks of drip clogging which require different rates of acid injection in the irrigation water. Volume of nitric acid injected increased with irrigation frequency and acid injection time, e.g. with 30 min injection time in daily irrigations more than 10 kg N ha^{-1} were applied in 47 % of land potentially irrigated with surface water, meanwhile this percentage was around 60 % of that potentially irrigated with underground water. This means that N supply with acid injections to reduce clogging risk may account for a relevant portion of N fertilization requirements in olive orchards. Consequently, this supply should be integrated in fertilization programs to avoid agronomic and

environmental constraints. The GIS-based tool proposed was able to provide complementary technical solutions to the clogging problem in drip irrigation. For each alternative released, a precise estimation of N supply to be considered in accurate N fertilizer management was also provided. The tool also supplied graphical visualization of information and functionality of handling geographic data, with an easy update. All this is necessary in planning and decision making at regional scale with changing properties in irrigation water.

Keywords: irrigation water quality, GIS, water hardness, Langelier index, chemical precipitation, nitrogen.

4.1. Introduction

Aridity poses a major constraint for land productivity and consequently for food production in approximately one third of agricultural land in the World (Simmers, 2003). The need of increasing food production to meet the requirements of a growing population is particularly relevant in many arid lands, such as the West Asia and North Africa region (WANA, Ryan et al. 2012). This demographic pressure will be reflected in increasing water consumption for agricultural production which may account for a serious concern for environment and also for the sustainable use of water resources (Smakhtin et al., 2004). Thus, efficient use of water in agriculture is mandatory in arid lands to achieve the sustainability of irrigation agriculture. To this end, the use of drip irrigation has been usually recommended (Fernández et al., 2004).

Olive tree is one of the most relevant crops in many arid and semi-arid lands in the World, such as many areas of south Europe and WANA region. In these areas, its yield is significantly increased by irrigation. Restricted water availability is frequent in these areas, thus making only possible deficit irrigation. In spite of limited irrigation rates, high water use efficiency by crop and high profitability in the use of water are achieved with this deficit irrigation (Peragón et al. 2016). This response to irrigation justifies that currently 22 % of the 10.5 mill ha of total olive orchard surface in the World is being irrigated (Morales-Sillero et al., 2013). In particular, irrigated olive orchard surface has been significantly increased in south Spain during the last decades, mostly with drip irrigation systems (Palomo et al., 2002). A paradigmatic case is the province of Jaen in south Spain, with more than 580000 ha of olive orchards accounting for 23 % of the total olive orchard area in Spain (MAGRAMA, 2012). Drip irrigated olive orchards extend on 47 % of this surface, most of them planted during the last 20 years (Peragón et al., 2015).

In drip irrigated land, most of the cost in preserving irrigation networks is related to emitters (drip) clogging, which can be due to different reasons: (i) physical, by suspended particles in water, (ii) chemical, by precipitation of dissolved compounds, or (iii) biological, by waterborne organic matter mainly related to the growth of aquatic organisms (Vega et al., 2011). Physical clogging by suspended particles can be easily prevented by filtering. Filtering can be also effective in preventing clogging by algae or other biological-derived matter along with the use of biocides; this control has been widely studied (Gerba et al., 2009; Pachepsky et al., 2011). One of the biggest problems of biological origin is the formation of biofilms in the surface of irrigation pipes (Sadovski et al., 1978; Dehghanisanij et al., 2004; Li et al., 2012). Algae proliferation is mainly related to the concentration of N and P in irrigation water. In the case of the province of Jaen, this is a relevant issue in the maintenance of irrigation networks, and treatment for algae development is usually recommended in water reservoirs for drip irrigation (Junta de Andalucía, 2009). In addition, an assessment of N concentration in irrigation water is necessary to prevent imbalanced N supply to crops (Peragón et al., 2015). All these issues are taken into account in the usual recommendations in assessing water quality for irrigation, such as the widely use and recommended FAO report (Ayers y Westcot, 1985) for arid lands.

Physical and biological constrains in drip irrigation can be overcame by filtering and algicide application. However, the precipitation of insoluble compounds in emitters is more difficult to control, making necessary a control of water quality parameters and the application of acids, if necessary, to avoid precipitation of insoluble compounds. Precipitation leading to drip clogging can be the result of carbonate precipitation when hard waters are used for irrigation and also the result of incorrect management of fertilizers in fertigation (e.g. precipitation of poorly soluble P compounds). Carbonate solubility is affected by temperature and pressure, it decreasing with decreasing pressure in the pipes (Marín-Cruz et al., 2004). In this regard, the effect of pressure is relevant in drip irrigation because these systems function at pressures (usually 100–400 kPa) lower than that in pipes of distribution network and with negligible pressure at the exit of the dropper. A decreased pressure implies volatilization of dissolved CO_2 which promotes an increased pH leading to the formation of crust on pipes and emitters walls by carbonate precipitation. This precipitation is also affected by the salt concentration of irrigation water. On the other hand, solubility of CaCO3 increases with decreased temperature and with increased acidity.

It can be concluded that an assessment on preventing measures that should rely on the study of water quality is required to avoid the precipitation of insoluble compounds in drip irrigation networks. In addition, an evaluation of the irrigation network system is necessary in order to stablish how it can contribute to drip clogging and how the network can be negatively affected by this clogging. In this regard, in the province of Jaen, pressure in networks ranges widely, and self-compensating droppers are usually installed to enhance irrigation uniformity (Mesa-Jurado et al., 2010). This means that the precipitation risk is non-uniform in the orchards. On the other hand, the main risk affecting irrigation efficiency and uniformity is drip clogging. In addition, irrigation rates are clearly deficient (Peragón et al., 2016), which means that decreased water supply by dripper clogging may have a very high negative impact on yields.

Measures to control drip clogging can be difficult to apply for most farmers, and information required is not usually available for them. Precise assessment on sustainable agricultural practices should rely on effective management tools available to farmers, e.g.

those called "navigator" (e.g. the soil navigator proposed in http://www.ulster.ac.uk/es/h2020-landmark-project/), able to provide the best management options. These tools should handle climatic, water quality, and management information on a geographical basis able to provide solutions for each specific site depending on the parameters processed for each site. GIS-based tools are able to adapt solutions to specific information in each site at a regional scale, as proposed by Peragón et al. (2016) for decreasing salinization risks. In this regard, this work was aimed at developing a GIS-based tool to control drip clogging risk in drip irrigation which should also encompass other related agricultural practices such as fertigation. Since the control of drip clogging by chemical precipitation of insoluble salts usually involves the application of acids containing nutrients, the chemical control of clogging should be integrated with fertigation taking into account the amount of applied nutrients with acids. The study will only consider the application of nitric acid, since nutrients applied with other acids potentially usable for avoiding clogging (e.g. P in phosphoric acid, or S in sulphuric acid) are required in much less amounts by olive. In addition, the inherent N concentration in water should be also taken into account as an additional supply to crops to achieve a more sustainable fertigation and to decrease environmental risks related to excessive N fertilization to crop. The study was performed in the province of Jaen (South Spain) focused on the irrigation of olive orchards. In this area, Peragón et al. (2015) showed using GIS-based tools that irrigation water quality may pose a relevant constraint for future sustainability of this crop.

4.2. Material and methods

4.2.1. Study area

The study was performed in the province of Jaen in south Spain where olive is the most relevant crop in planted surface and economical value and thus fundamental support to the economy of the province. More detailed information on the olive production and irrigation management in the area can be found elsewhere (Mesa-Jurado et al., 2010; Peragón et al., 2015; 2016). Irrigation installations mostly involve the use of self-compensating drippers of 8 L h^{-1} connected to 16 mm-diameter polyethylene pipes and with water reservoir for regulation in the own farm. Olive orchards irrigated with surface water accounts for 73% of the irrigated olive land, meanwhile underground water is used in 22% of the irrigated surface, and combination of these both sources in only 1 % of the surface; residual water is also used for irrigation, but only in 4 % of the olive irrigated surface (Junta de Andalucía, 2008; Peragón et al., 2016). Water availability for irrigation season is 1500 m^3 ha^{-1}. This rate means a deficitary irrigation since this supply is clearly below the crop water demand (Peragón et al., 2016). Irrigation is applied between April and September, with usual weekly rates of 64 m^3 ha^{-1} (6.4 mm) (Fernández et al., 2006).

4.2.2. Data set

Climatic data were obtained from 35 stations (Junta de Andalucía, 2014; http://www.juntadeandalucia.es/agriculturaypesca/ifapa/ria/servlet/FrontController?action=Static&url=listadoEstaciones.jsp&c_provincia=23). This information included: daily rainfall, maximum, minimum, and mean temperature, and potential evapotranspiration (ETo) for the period 1976-2014 (total number of monthly data n=459). Effective rainfall was estimated according to Stamm (1967).

Hydrochemical data, including ions concentration, electrical conductivity, and pH of irrigation water were provided by the water authority of the Guadalquivir basin (Confederación Hidrográfica del Guadalquivir, 2014; http://www.chguadalquivir.es/opencms/portalchg/laDemarcacion/guadalquivir/calidadAguas/) for the 1994-2013 term (monthly data, n = 240). Data were obtained from 66 surface water stations and 136 ground water stations used as sources of irrigation water. Ground water stations corresponded to 26 different hydrogeologic units defined by the Spanish National Institute of Geology and Minery (IGME, 1997).

The water properties studied were: pH, electrical conductivity (EC), and the concentrations of Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, PO_4^{3-}, NH_4^+, B, Ca^{2+}, K^+, and Na^+. These variables were used to calculate the residual sodium carbonate (RSC), water hardness (French degrees, ofH), and Langelier index (Ayers and Wescot, 1985). Detailed description of these calculations is available in Peragón et al. (2015) and in supplementary material (Annexed 4). The risk of precipitation of Ca and Mg compounds can be assessed by the French degrees (ºfH), and precipitation of Ca carbonates by the Langelier index (Ayers and Wescot, 1985). RSC can be also useful to estimate the risk of carbonate precipitation. Ca/Mg ratio will be also considered in the evaluation of this problem; at similar ºfH or RSC values, increased Ca/Mg ratios can boost precipitation of Ca phosphates and carbonates which are less soluble than their Mg counterparts.

4.2.3. Estimation of acid requirements

Acid should be injected into the irrigation water at the end of the irrigation time in order to leave all the emitters at the end of the irrigation full with acidified water to achieve a low risk of precipitation of insoluble Ca or Mg compounds. Different methods can be used to calculate the concentration of acid required, the most usual is the one based on the Langelier Index (Is), which is defined according to the following equation:

$$Is = pHw - pHs \qquad (4.1)$$

where, pHw is the value of pH in irrigation water used, and pHs is the pH value at which water with a given alkalinity and Ca concentration is in equilibrium. Calculation steps are:

Calculation of the maximum concentration of carbonate and bicarbonate in water at which they both do not precipitate, usually referred to as Alkc, which is related to the actual concentration of both anions (Alk) and Is through the equation:

$$p(Alkc) = p(Alk) + Is \qquad (4.2)$$

p being the minus decimal logarithm.

Calculation of the concentration of carbonates to eliminate (Alke):

$$Alke = Alk - Alkc \qquad (4.3)$$

The concentration of acid (expressed in mmolc L^{-1}) to avoid precipitation is equivalent to the concentration of carbonates to eliminate. More details on calculations are provided in supplementary material (Annexed 4, Table B.1).

The time required for injecting acid at the end of the irrigation was estimated on the basis of the volume of water contained in the irrigation network. It was assumed that this volume is replaced several times in order to ensure that the network remains completely full with acidified water at the end of the irrigation. The water volume contained in the irrigation network was estimated on an hectare basis taking into account the usual type of installation and orchards, with 100 olive trees per ha and 2 self-compensating droppers of 8 L h^{-1} per tree. On average, this amounts to 1000 m of 16 mm-polyethylene tubes with droppers and 100 m of main pipes to which the former pipes are connected per hectare. The total volume of water which can be accumulated in this installation is 0.17 m^3. On the basis of the type of emitter, the water flow in the installation is 4.44 · 10-4 m^3 s^{-1}. Taking into account this water flow and the volume of the installation, the time required to completely full the installation can be estimated. In order to guarantee that all the installation is completely full with acidified water, it was assumed that the volume of acidified water that should circulate in the installation should range from 2 to 4 times the estimated volume of the installation. The circulation of this water volume corresponded, taking into account usual water flow, to 15 to 30 min of injection time for acid in the irrigation network (Supplementary material (Annexed 4), Table B.1). It could be assumed increased injection times with increased surface of orchards, where the main pipes could contain a relevant volume of water that should be acidified, and with increased precipitation risk according to Langelier Index. An additional strategy may be the acidification of all the irrigation water since typically the injection of N fertilizers for fertigation is done at farmers community scale, not in each farm. Although this complete acidification of irrigation water involves a greater consumption of acid, it can provide a complete reduction of precipitation risk when the farmer does not have the possibility of injecting fertilizers in the farm.

The nitric acid was selected to avoid precipitation. N supplied with this acid should cover part of the N fertilization requirements of the crop. Fertilizer rates are usually in the range 0–1 kg N $tree^{-1}$ per year for fully productive orchards depending on the nutritional status of the crop. The use of nitric acid is recommended when compared with other acids because the injections with this acid can be better adapted to crop fertigation. In the case of null N requirement of crop according to nutritional status, phosphoric or sulphuric acid may be applied. A nitric acid with 50 % richness has been considered since it is one of the most usual commercial products for fertigation. Calculation of volumes with nitric acid at other concentrations or with other acids can be easily performed (an example is shown in supplementary material (Annexed 4), Table B.2; Figure C.1).

On the basis of the N concentration of acid and injection time required to avoid clogging, total amounts of N applied with acid to crop were calculated. In addition, the concentration of nitrogen in water before nitric acid injection was also taken into account. This allows one to estimate the total amount of N supplied with irrigation. The difference between estimated crop requirement and that supplied with water can be deemed the estimated N fertilizer rate for crop (basis for calculation is shown in supplementary material (Annexed 4)). The study had to reflect also the wide range of irrigation frequency in the area. To this end, it was supposed that injections were done at the end of all the irrigation events; this means, on average: (i) 120 cleaning nitric acid injections with daily irrigation during the irrigation season (April-September), (ii) 60 with irrigation each two days, and (iii) 20 with weekly irrigations. Thus, the total required amount of acid depended on the injection time selected and on the irrigation frequency. Calculations were also done for the complete acidification of the whole irrigation water volume (1500 $m^3\ ha^{-1}$).

4.2.4. Model

A GIS-based model was developed for irrigated olive areas of the province of Jaen. The model incorporated data of climate and chemical variables of water related to studied problems. This information was used to identify zones with different risks of dropper clogging and thus requiring different solutions which will imply the supply of different amounts of N to crops. In the model, as described in Figure 4.1, a geographic database was incorporated. In this database, spatial and geometric values were assigned to each climatic and water variable included in the model (Simsek et al., 2007; Peragón et al., 2015). Assigned values were the monthly averages for each variable in the period considered. The definition of different risk levels was done on the basis of: French degrees (ºfH), Langelier index, residual Na carbonate (RSC), and Ca/Mg ratio (Peragón et al., 2015). For each of the climatic data, water property, and indices mentioned above for assessing clogging risk, a geographical reference was assigned with the objective of integrating and handling all the information for a geostatistical analysis using the open source software gvSIG (www.gvsig.org). Thus, with this model, an alphanumeric table was linked to graphical entities ensuring an accurate location in the space with the possibility of an easy upgrade, which is a crucial issue due to changing properties of water along irrigation seasons (Peragón et al., 2016). Graphical and geostatistical analysis can be easily performed with the model by using different mathematical algorithms available in a module called "Sextante" of the gvSIG software (Peragón et al., 2015; 2016). Advantages in the use of open source GIS software, particularly gvSIG, are discussed elsewhere (Peragón et al., 2016).

Georeferencing of water data was performed according to Peragón et al. (2016) with the following assumptions: (i) the geographical reference of each source of surface water was that of the sub-basins where irrigation pumping station was situated, and (ii) the geographical reference of each source of ground water was done by defining polygons corresponding to each aquifer which were assigned to a specific area. Sub-basins were defined by using the algorithm "slope at a given point basin", and ground water polygons using the algorithm "geometric polygon aquifer" available in the module Sextante of gvSIG.

Geostatistical analysis was done by kriging interpolation, which creates a surface with the spatial distribution of estimated values from a series of point values, thus creating a map for each one of the variables analyzed (Raziei y Pereira, 2013; Mello et al., 2013; Peragón et al., 2015). Kriging was used because it takes into account: (i) the distance and the degree of variation between known data points when estimating values for unknown areas, (ii) the spatial autocorrelation of the variable through theoretical variogram, and (iii) directional influences, which is a crucial factor in hydrologic studies. In addition, it has been considered as the most suitable interpolation method for climatic data (Naoum and Tsanis 2004; Hofstra et al. 2008). Each defined map was transformed into raster format. Due to the extension of the studied surface (13489 km^2), a spatial cell resolution of 100 x 100 m was selected for the spatial analysis module of gvSIG.

Based on the indices used to assess clogging risk, a risk map with 3 risk categories (1, 2, and 3, corresponding to high, medium, and low, respectively; previously described in Peragón et al., 2015) was performed based on the recommendations by FAO (Ayers and Wescot, 1985). Briefly, this was achieved by additive rating of each individual index of clogging risk considered using a "combination of parameters algorithm" which allows algebraic operations with alphanumeric attributes arranged in vector layers. This provides results as new layers of geographic data using the module Sextante in software gvSIG (Peragón et al., 2015).

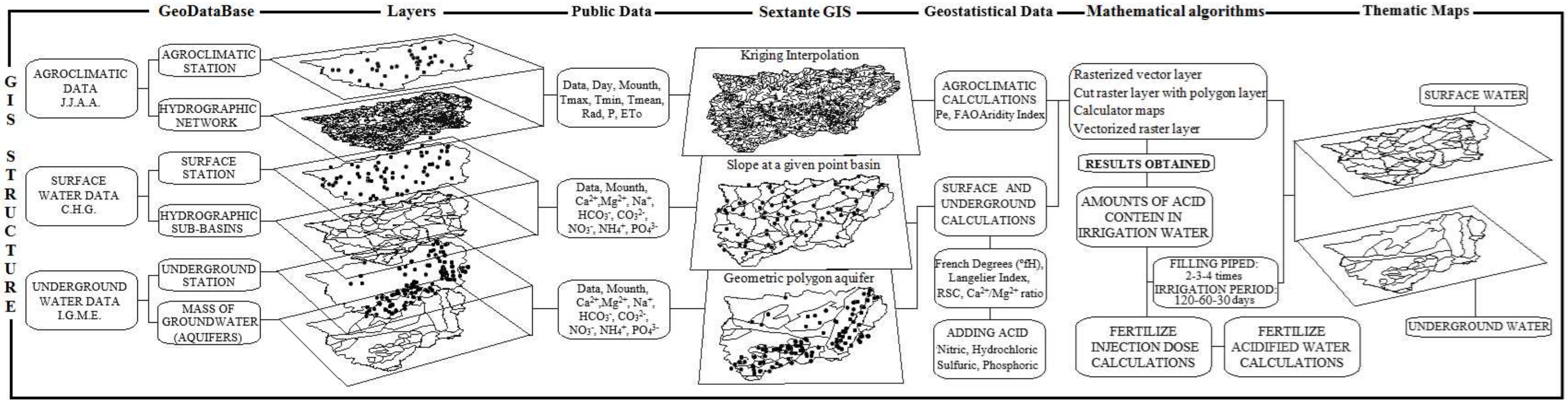

Figure 22. Model: Methodological Framework

Maps of different volumes of acid in irrigation water for a given injection time and frequency of irrigation were released using the estimation method described above with the vector geoprocessing available in the "Sextante" module of gvSIG software. The tool can be easily updated for the use of other acids if required. A spatial link was created between parameters which define the volume of acid to be injected at the end of fertigation. In addition, for each location, concentration of inorganic N (nitrate, ammonium, and nitrite) in irrigation water before acid injection was also taken into account. As described by Peragón et al. (2015), all the mathematical algorithms used in the model are included in the geoprocessing tools of the Sextante module of gvSIG (www.gvsig.org). Scripts Jython programming language were created to this end (www.jython.org). More information about the use of the tools of Sextante module of gvSIG and Jython language use can be found in Peragón et al. (2015).

4.3. Results

4.3.1. Risk of clogging

According to the French degrees (ºfH), the highest risk of precipitation of Ca and Mg compounds was expected in more than 95 % of the land which can be irrigated with both surface and underground waters. The carbonate precipitation risk assessed by the Langelier index affected a greater portion of the land potentially irrigated with surface water (95 %) than that potentially irrigated with underground water (50 %) (Peragón et al., 2015). Clogging risk maps, on the basis of the four indeces used to assess it, revealed that this risk affected more the land which can be irrigated with surface water (87 % of the surface), than that which can be irrigated with underground water (30 % of the surface) (Peragón et al., 2015).

4.3.2. Volumes of nitric acid to be injeted

Depending on the irrigation frequency, from daily to weekly as described above, and on the injection time, which ranged from 15 to 30 min, volume of nitric acid to be injected varied widely (Tables 4.1 and 4.2). Injected volumes increased with increased times of injections and irrigation frequency. Around 70 % of the area where surface water can be used required more than 30 L ha_{-1} of commercial nitric acid when it is injected with daily irrigation during 30 min. On the other hand, this volume of acid was required in around 40 % of the area if injection time is decreased to 22.5 min (Table 4.1, Figure 4.2). Less than 10 L ha^{-1} were required in the area where surface water can be used with the shortest injection time and weekly irrigation (Table 4.1, Figure 4.2). With underground water, more than 30 L ha^{-1} of commercial nitric acid was required in 59 %

of the area potentially irrigated with this water source for daily irrigation with 30 min of acid injection time (Table 4.2; Figure 4.3).

Table 11. Surface where different rates of commercial nitric acid (50%) per hectare should be applied to surface water in order to avoid drip clogging. The volume depends on water quality, irrigation frequency, and injection time. % Area is referred to the area potentially irrigated with this water source

Irrigation frequency (number of irrigation events between brackets)	Nitric acid injected (L ha^{-1})	Injection times (min)					
		15		22.5		30	
		Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
Daily (120)	< 10	3220	23.9	2449	18.2	2449	18.2
	10 – 20	4643	34.4	1441	10.7	771	5.7
	20 – 30	5453	40.4	3973	29.4	826	6.1
	30 – 40	174	1.3	4294	31.8	3817	28.3
	40 – 50	-	-	1170	8.7	3761	27.9
	> 50	-	-	163	1.2	1865	13.8
Each two days (60)	< 10	7862	58.3	3890	28.8	3220	23.9
	10 – 20	5627	41.7	8267	61.3	4643	34.4
	20 – 30	-	-	1333	9.9	5453	40.4
	30 – 40	-	-	-	-	174	1.3
	40 – 50	-	-	-	-	-	-
	> 50	-	-	-	-	-	-
Weekly (20)	< 10	13489	100	13326	98.8	11624	86.2
	10 – 20	-	-	163	1.2	1865	13.8
	20 – 30	-	-	-	-	-	-
	30 – 40	-	-	-	-	-	-
	40 – 50	-	-	-	-	-	-
	> 50	-	-	-	-	-	-

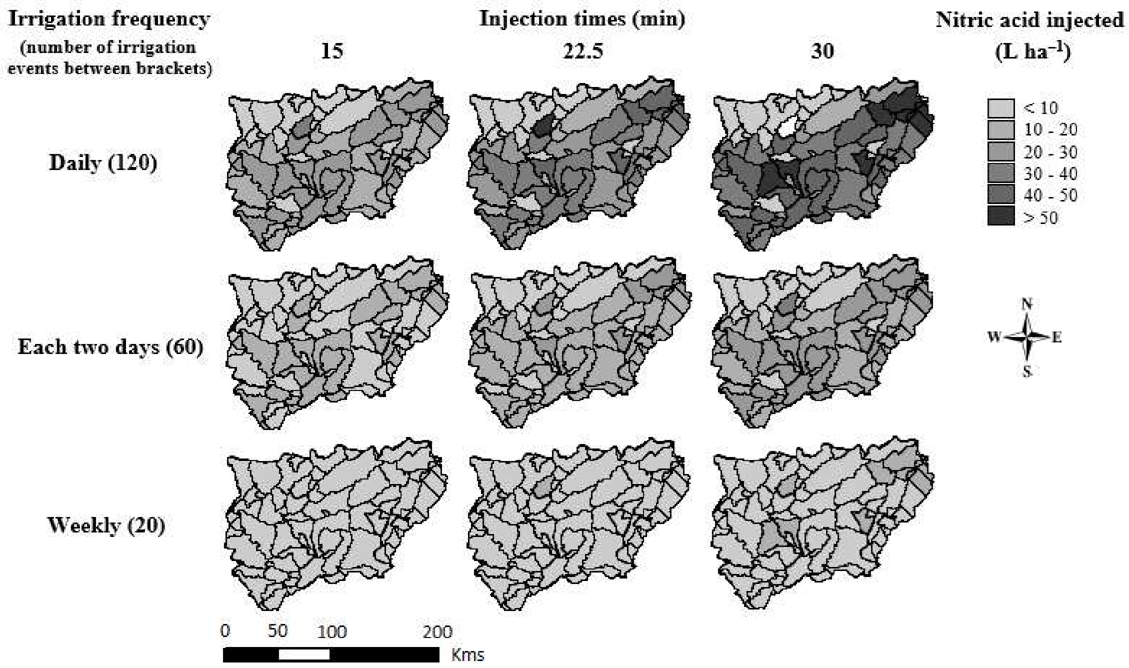

Figure 23. Recommended rates of commercial nitric acid (50%) that should be applied to surface water to avoid clogging. The volume depend on water quality, irrigation frequency, and injection time

Table 12. Surface where different rates of commercial nitric acid (50%) per hectare should be applied to underground water in order to avoid drip clogging. The volume depends on water quality, irrigation frequency, and injection time. % Area is referred to the area potentially irrigated with this water source

Irrigation frequency (number of irrigation events between brackets)	Nitric acid injected (L ha^{-1})	Injection time (min)					
		15		22.5		30	
		Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
Daily (120)	< 10	2955	36.8	2859	35.6	2859	35.6
	10 – 20	498	6.2	375	4.7	96	1.2
	20 – 30	2482	30.9	218	2.7	397	4.9
	30 – 40	353	4.4	1569	19.5	100	1.3
	40 – 50	1688	21	913	11.4	1569	19.5
	> 50	55	0.7	2096	26.1	3009	37.5
Each two days (60)	< 10	3452	43	3234	40.3	2955	36.8
	10 – 20	2834	35.3	1787	22.2	498	6.2
	20 – 30	1743	21.7	1265	15.8	2482	30.9
	30 – 40	-	-	1743	21.7	353	4.4
	40 – 50	-	-	-	-	1688	21
	> 50	-	-	-	-	55	0.7
Weekly (20)	< 10	7975	99.3	5934	73.9	5021	62.5
	10 – 20	55	0.7	2096	26.1	2953	36.8
	20 – 30	-	-	-	-	55	0.7
	30 – 40	-	-	-	-	-	-
	40 – 50	-	-	-	-	-	-
	> 50	-	-	-	-	-	-

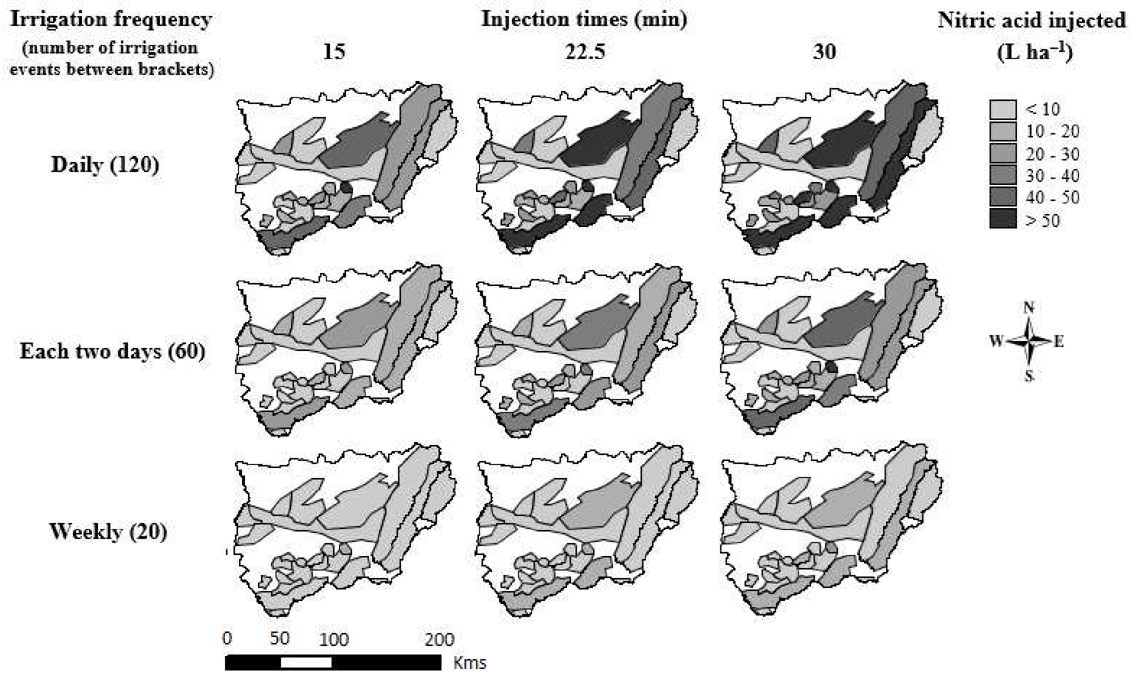

Figure 24. Recommended rates of commercial nitric acid (50%) that should be applied to underground water to avoid clogging. The volume depend on water quality, irrigation frequency, and injection time

Overall, with surface water, less than 5 kg N ha^{-1} are required in virtually the entire irrigated area for all the fertigation frequencies when 15 min of acid injection is assumed to avoid clogging (Table 4.3). Amounts of N applied with acid increased with injection time and with increased irrigation frequencies, in such a way that for 30 min injection time and daily irrigation, estimated N supply with acid ranged between 5 and 10 kg ha^{-1} in 9270 km^2, and between 10 and 15 kg N ha^{-1} in 174 km^2 of the land which can be irrigated with surface water (Table 4.3; Figure 4.4). For underground water, estimated N supply with acid amounted to 10–15 kg ha^{-1} in 2096 km^2 with daily irrigation and longest injection time (Table 4.4; Figure 4.5). Overall, for surface and underground water irrigation frequency is more relevant in determining injected volumes of acid and resultant N supply than injection times.

Table 13. Surface where different amounts of nitrogen per hectare are supplied with injected acid in surface water depending on irrigation frequency and injection times. % Area is referred to the area potentially irrigated with this water source

Irrigation frequency (number of irrigation events between brackets)	Nitrogen supplied (kg ha^{-1})	Injection time (min)					
		15		22.5		30	
		Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
Daily (120)	0 – 5	12987	96.3	7862	58.3	4045	30
	5 – 10	502	3.7	5627	41.7	9270	68.7
	10 – 15	-	-	-	-	174	1.3
Each two days (60)	0 – 5	13489	100	13489	100	13315	98.7
	5 – 10	-	-	-	-	174	1.3
	10 – 15	-	-	-	-	-	-
Weekly (20)	0 – 5	13489	100	13489	100	13489	100
	5 – 10	-	-	-	-	-	-
	10 – 15	-	-	-	-	-	-

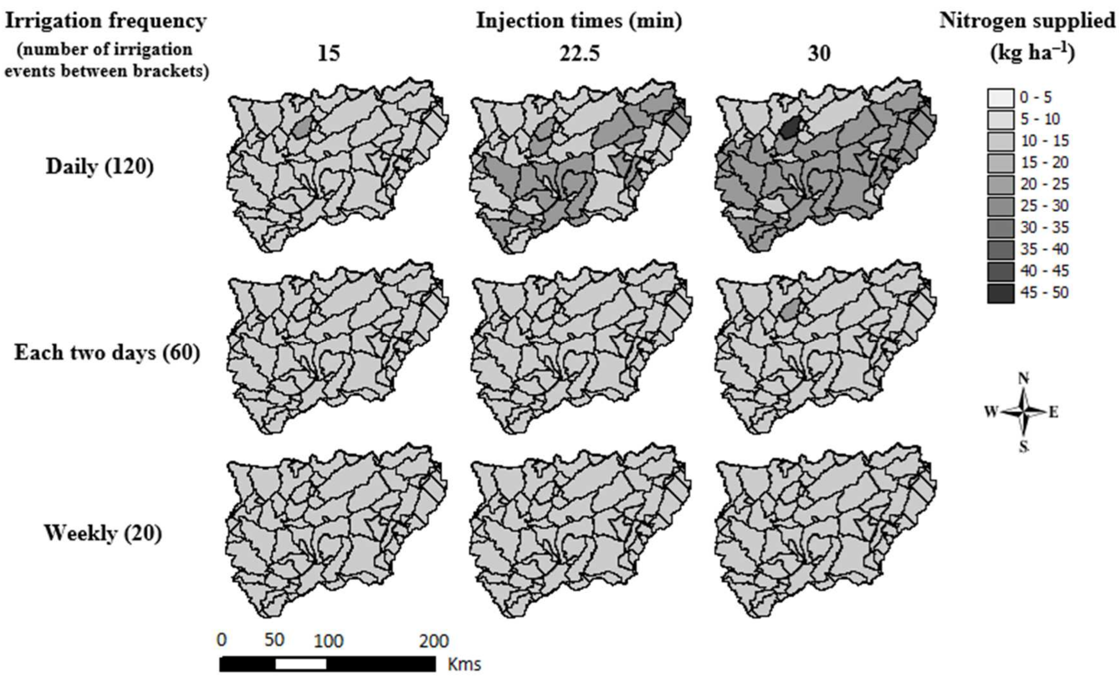

Figure 25. Amounts of nitrogen per hectare supplied with injected acid in surface water depending on irrigation frequency and injection times

Table 14. Surface where different amounts of nitrogen per hectare are supplied with injected acid in underground water depending on irrigation frequency and injection times. % Area is referred to the area potentially irrigated with this water source

Irrigation frequency (irrigation events between brackets)	Nitrogen supplied (kg ha^{-1})	Injection time (min)					
		15		22.5		30	
		Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
Daily (120)	0 – 5	5934	73.9	3452	43	3234	40.3
	5 – 10	2096	26.1	2834	35.3	2700	33.6
	10 – 15	-	-	1743	21.7	2096	26.1
Each two days (60)	0 – 5	8030	100	6287	78.3	5934	73.9
	5 – 10	-	-	1743	21.7	2096	26.1
	10 – 15	-	-	-	-	-	-
Weekly (20)	0 – 5	8030	100	8030	100	8030	100
	5 – 10	-	-	-	-	-	-
	10 – 15	-	-	-	-	-	-

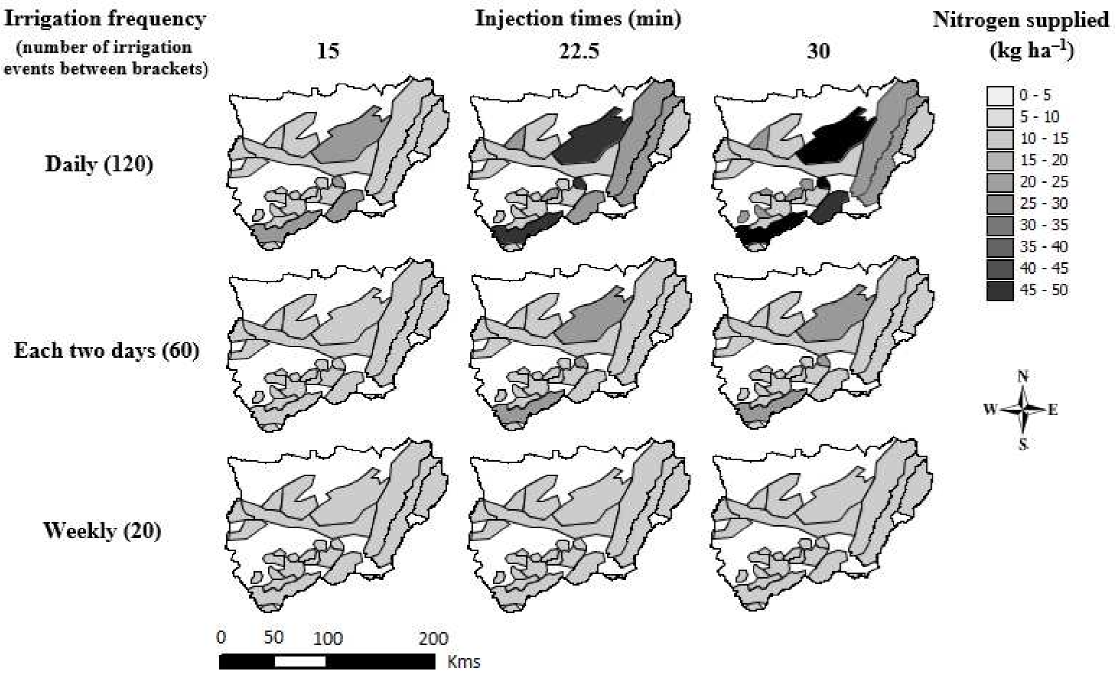

Figure 26. Amounts of nitrogen per hectare supplied with injected acid in underground water depending on irrigation frequency and injection times

4.3.3. N supply with irrigation water

Surface waters contain appreciable amounts of ammonium and nitrite; on the other hand, only nitrate is detected in appreciable concentration in underground water (Tables B.3 and B.4 supplementary material (Annexed 4)). Overall, in around 30 % of the land which can be irrigated with surface water, 5 to 20 kg N ha^{-1} were applied with water, meanwhile this supply was observed in only 17 % of the land which can be irrigated with underground water. However, in 14.6 % of the area potentially irrigated with ground water, N supply with irrigation water ranged from 20 to 25 kg ha^{-1} and this supply increased above 40 kg ha^{-1} in one of the hydrogeological units (Table B.4, Figure C.2 in supplementary material (Annexed 4).

4.3.4. Total N supply with irrigation

In addition to inherent N content of irrigation water, supply was increased when injections with nitric acid to avoid clogging was done (Tables 4.5 and 4.6; Tables B.5 and B.6, and Figures C3 and C4 in supplementary material (Annexed 4)). With 30 min injection time in daily irrigations, more than 10 kg N ha^{-1} were expectable to be applied in 47 % of the land which can be irrigated with surface water (Table 4.5, Figure 4.6), meanwhile this percentage was around 60 % with underground water (Table 4.6, Figure 4.6). If all the irrigation water was acidified, considering a management at farmers community scale, a supply greater than 10 kg N ha^{-1} were expected in 70 % of the land which can be irrigated with surface water, and in 60 % of that potentially irrigated with underground water (Tables 4.5 and 4.6, Figure 4.6). When N supply greater than 20 kg ha^{-1} was taken into account, the percentage of surface which can be irrigated with underground water where this supply was expectable was much greater than that potentially irrigated with surface water. In this regard, with the total acidification of irrigation water, this N supply was expectable in 37.5 and 13.8 % of the surface which can be irrigated with underground and surface water, respectively (Table 4.5 and 4.6, Figure 4.6).

Table 15. Surface where different amounts of nitrogen per hectare are supplied taking into account soluble nitrogen in surface irrigation water and nitrogen supplied with the injection of nitric acid depending on the injection time for daily irrigation (120 irrigation events). The acidification of the whole irrigation rate assigned (1500 m^3 ha^{-1}) is also considered as an alternative to avoid clogging. % Area is referred to the area potentially irrigated with this water source

Nitrogen supplied (kg ha^{-1})	30 min		22.5 min		15 min		Acidification of the whole irrigation rate	
	Area (km^2)	% Area	Area (km^2)	% Area	Area (km^2)	% Area	Area (km^2)	% Area
< 5	3042	22.6	3442	25.5	5390	40.0	2449.0	18.2
5 – 10	4105	30.4	5197	38.5	5471	40.6	1440.9	10.7
10 - 15	3720	27.6	2476	18.4	948	7.0	3692.5	27.4
15 - 20	950	7.0	1032	7.7	822	6.1	4041.3	30.0
20 - 25	832	6.2	987	7.3	511	3.8	1702.3	12.6
25 - 30	489	3.6	167	1.2	156	1.2	163.0	1.2
30 - 35	161	1.2	1	0.0	5	0.0	-	-
35 - 40	1	0.0	188	1.4	186	1.4	-	-
40 - 45	188	1.4	-	-	-	-	-	-
45 - 50	-	-	-	-	-	-	-	-

Table 16. Surface where different amounts of nitrogen per hectare are supplied taking into account soluble nitrogen in underground irrigation water and nitrogen supplied with the injection of nitric acid depending on the injection time for daily irrigation (120 irrigation events). The acidification of the whole irrigation rate assigned (1500 m^3 ha^{-1}) is also considered as an alternative to avoid clogging. % Area is referred to the area potentially irrigated with this water source

Nitrogen supplied (kg ha^{-1})	30 min		22.5 min		15 min		Acidification of the whole irrigation rate	
	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
< 5	2954	36.8	2954	36.8	2954	36.8	2858.9	35.6
5 – 10	220	2.7	2477	30.8	2551	31.8	375.4	4.7
10 - 15	2394	29.8	352	4.4	1146	14.3	218	2.7
15 - 20	568	7.1	868	10.8	55	0.7	1569.1	19.5
20 - 25	515	6.4	55	0.7	-	-	912.8	11.4
25 - 30	55	0.7	-	-	1173	14.6	352.5	4.4
30 - 35	-	-	1173	14.6	-	-	-	-
35 - 40	1172.71	14.6	-	-	-	-	1688.1	21.04
40 - 45	-	-	-	-	151	1.9	55.2	0.7
45 - 50	150.72	1.9	151	1.9	-	-	-	-

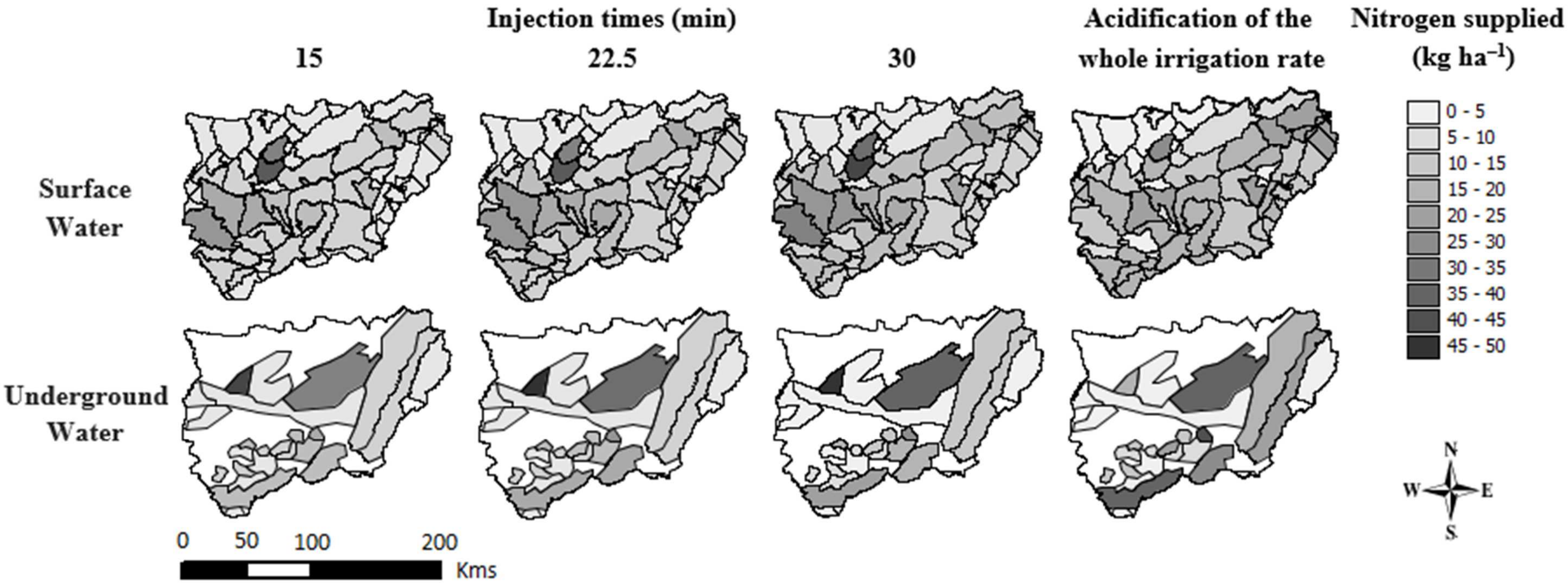

Figure 27. Amounts of nitrogen per hectare supplied taking into account soluble nitrogen in surface and underground irrigation water and nitrogen supplied with the injection of nitric acid to avoid drip depending on the injection time for daily irrigation (120 irrigation events). The acidification of the whole irrigation rate assigned (1500 m^3 ha^{-1}) is also considered as an alternative to avoid clogging

4.4. Discussion

Overall, there was an extended clogging risk in drip irrigation with surface and underground waters. The risk was greater for surface water than for subsurface water. In practice, this means that greater acid volumes should be injected in the area which can be irrigated with surface water than in that with subsurface water. On the contrary, the N supply ascribed to the inherent N concentration of irrigation water was higher in underground than in surface water. This can be ascribed to soluble N accumulation in aquifers leading in some cases to noticeable N pollution of underground water. This explains that, despite the greater volumes of nitric acids that should be more widely applied with surface water irrigation, N supply with irrigation water after nitric injection was usually greater with underground water than with surface water.

With N concentration in leaves below 15 g kg^{-1}, which is the threshold values for fertilizer response in the area (Fernández-Escobar et al., 2009), olive N requirements can be taken as N exported in fruits and pruning material under non-restricted N status in plants. Overall, N uptake around 50 kg ha^{-1} can be supposed for the usual orchards in the area, with 100 tree ha^{-1} and with an average production (“on and “off” years) of 6000 kg ha^{-1} under irrigation (Fernández-Escobar et al., 2012; 2015). With the most efficient fertigation scheme (daily) and the most secure acid injection (30 min), N supply with acidulated water was equivalent to the expected mean N uptake by crop in near 2 % of the area which can be irrigated with underground water; with this irrigation scheme, N supplied with acidulated irrigation water may account for 70 to 80 % of crop N uptake in 14.6 % of the area potentially irrigated with ground water. With the acidification of all the volume of irrigation water, N supplied amounted to 80 to 90 % of crop N uptake in 21 % of the land which can be irrigated with underground water. This latter strategy for controlling clogging risks should be considered since in most of the area N fertilizers are applied by fertigation at farmer community scale, without possibility of precise injections of acid at farm scale.

All these evidences reveal that N supply with irrigation water management to reduce clogging risk may cover a relevant portion of crop N requirements. Consequently, this water management should be integrated in fertilization practices to avoid agronomic (e.g. decreased oil concentration; Fernández-Escobar et al., 2006) and environmental risks, i.e. water pollution, ascribed to excessive N fertilization in olive orchards. Taking into account N in acidulated water and fertilizer as the main inputs and considering efficiencies in N use (NUE) in fertigation with the usual irrigation schemes around 0.7 (Singandhupe et al. 2003; Thompson et al., 2003), N rates can be easily estimated (Table B.7; Figure C.5, supplementary material (Annexed 4)). However, information required for accurate management of clogging risk in drip irrigation and its integrated management within fertigation practices cannot be easily managed by farmers. Our results reveal that assessment of acid injection and N supplied with optimal management of drip irrigation can be easily assessed by using the GIS-tool defined in the present research. Although only the most frequent irrigation schedules and injection times has been considered, results demonstrate potential capabilities of the GIS-based tool for integrated management of clogging risk in drip irrigation and fertigation. Also, it can be readily updated for more precise integrated management of drip irrigation maintenance and fertilization. In this regard, as previously demonstrated by Peragón et al. (2016) in the same area for managing salinization risks, this type of tool is able to adapt decisions to fast changes in water composition. In addition, it has a high capability of data analysis and processing. Thus, it can be considered appropriate to provide detailed information to help stakeholder to take decisions on irrigation and fertilization. Different alternative or complementary technical solutions can be given; e.g., it provides different alternatives for acid injection, and on the basis of a selected acid injection time and irrigation schedule, it can provide a precise estimation of N supply as a basis of an accurate N fertilizer requirement estimation. If additional information is included, such as nutritional status of orchards, a model update able to recommend N fertilization rates can be easily performed. Graphical visualization of information and functionality of handling geographic data, which is necessary in planning and decision making at regional scale, can be also yielded by the model. As another advantage, the model can be readily adapted to other geographical areas and crops in order to help in decision-making process on drip irrigation and fertilization management at regional scales.

4.5. Conclusions

Assessment of acid injection and N supplied with optimal management of drip irrigation to avoid drip clogging can be easily assessed by using the GIS-tool defined in the present research. This tool can be readily updated for more precise integrated management of drip irrigation maintenance and fertilization. Different alternative or complementary technical solutions can be given at regional scale, and for each alternative, precise estimation of N supply as a basis of an accurate N fertilizer requirement estimation is provided.

4.6. Acknowledgments

Mr. Juan Manuel Peragón received a grant from the Doctoral School of the University of Jaen. This work has been complementary funded by the National Research, Development and Innovation Plan (Plan Estatal de I+D+i) from the Ministry of Economy and Innovation and by European Regional Development Fund of the European Union through the National Research, Development and Innovation Program (Plan Nacional I+d+i, AGL2014-57835-C2-1-R).

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Capítulo 5. Best management irrigation practices assessed by a GIS-based decision tool for reducing salinization risks in olive orchards

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Abstract

Sustainable irrigation should rely on the efficient use of water while avoiding soil degradation. To this end, decision tools for assessing best management practices are necessary. There is, however, little evidence of efficient tools to assess best irrigation practices at regional scale taking into account water quality to avoid soil degradation and negative impacts on crop yields. The objective of this work was the performance of a GIS-based decision tool to assess best irrigation management practices aimed at reducing the negative effect of salts in irrigation water in olive orchards. The approach in this tool involved first the blending of two sources of available waters, surface and underground, and when necessary, the application of leaching fractions (LF). We tested this tool in the

province of Jaen (south Spain) as representative area of olive cultivation in Mediterranean environments.

In 82.4 % of the study area, the use of one of both water sources with electrical conductivity (ECw) below the defined threshold (1.8 dSm−1) was possible without blending. Water blending for achieving optimal irrigation water quality was possible in 16% of the irrigated land. In other 9.8% of the irrigated land, leaching fraction was required to achieve the defined salinity threshold. In the area where water blending was possible, this strategy resulted in the best irrigation water efficiency (IWE) estimated for the province. With water blending and LF when necessary, the annual gross income in the province can be increased by 80 mill €.

The proposed GIS-base decision tool is easy to update for different crops and regions. It is able to transform and combine geographical data and value judgments for decision making in irrigation at a regional scale with a view of achieving the most efficient irrigation water use while avoiding negative effects on crop and soil due to water salinity.

Keywords: GIS, irrigation water quality, water blending, leaching fraction, olive, benchmarking.

5.1. Introduction

The efficient Water is the most critical resource for sustainable agricultural development worldwide (Chartzoulakis and Bertaki, 2015). Agriculture consumes more water than any other human activity (Pimentel et al., 1997; Hosseinzade et al., 2017), and the efficient and sustainable use of water is nowadays the main challenge of irrigated agriculture (Araus, 2004; Levidow et al., 2014). A sustainable use of water resources in irrigation must take into account not only crop water requirements but also the quality of irrigation water in order to predict and overcome negative impacts mainly ascribed to water salt content (Ghassemi et al., 1995; Paz et al., 2004; Houk et al., 2006). In this regard, soil salinization ascribed to irrigation is the main constraint for irrigation agricultura sustainability in many regions of the World, affecting more than 34 Mha (Letey et al., 2011; Mateo-Sagasta and Burke, 2011; Mora et al., 2017). Only in Europe, around 4 Mha have a moderate to high soil salinization by irrigation, mostly in the Mediterranean countries where this problem affects 25% of irrigated agricultural land (Paz et al., 2004; Daliakopoulos et al., 2016).

The main strategy used to prevent the harmful effects of excessive accumulation of soluble salts in soils due to irrigation is to promote drainage in the root zone in order to leach the excess of soluble salts that could constrain crop yield. The fraction of applied water required to maintain soil salt content below a given threshold is named “leaching fraction” (LF), which increases with increased crop sensitivity to salinity (U.S. Salinity Laboratory Staff, 1954; Rhoades, 1974). This extra volume of water percolates below the root zone displacing at least in part the salts accumulated therein (Pastor et al., 2002; Orgaz and Fereres, 2004; Raine et al., 2007; Mesa-Jurado et al., 2010). In the long term, the amount of salts displaced by leaching must be equal to or higher than the salts applied with the irrigation water to avoid their accumulation at dangerous levels in soil. This salt balance is the crucial issue in achieving sustainability in irrigated agriculture (Corwin et al., 2007; Letey et al., 2011). However, it implies a decreased water application efficiency since a significant fraction of applied water must be lost through drainage. In areas where different source of water with different quality are available, their combined use may allow an improvement in irrigation water quality through dilution (Qureshi et al., 2004). This leads to a decreased LF requirement and consequently an increased efficiency in irrigation water application. In practice, this means more water available for irrigation while maintaining yield and soil quality. This strategy is feasible by combining surface and underground water with different salt concentrations in areas where both water sources coincide (Mahfuzur et al., 2014; Prendergast et al., 1994; Singh, 2014).

In recent decades, irrigated land has increased steadily, frequently involving the use of poor quality irrigation water (Singh, 2016). This consequently increases the area with risk of soil salinization. This occurred particularly in arid regions of the world, where agricultural production is strongly dependent on irrigation (Ashour and Al-Najar, 2012; Hosseinzade et al., 2017). In the Mediterranean basin, many new irrigated olive orchards were planted in the last decades (Fereres, 1998; Fereres and González-Dugo, 2009; Vega et al., 2001; Vega and Pastor, 2005; Wiesman et al., 2004). This is explained because olive is one of the most important crops in this region (10.4 Mha, 98% of the world's olive cultivated area; FAO, 2016), with lower water demand than other crops, and which allows a profitable deficit irrigation with low water availability (Peragón et al., 2015). A representative example of this expanded irrigation land in the Mediterranean basin sometimes relying on poor quality irrigation water is the province of Jaen (south Spain). This is the most representative area of olive cultivation in Spain, with near a quarter of the total national orchard surface, and amounting to 5.5% of the total surface in the world (Peragón et al., 2015, 2016). This area has arid and semi-arid zones (Junta de Andalucía, 2011; AEMET, 2011), with scarcity and irregular distribution of rainfall throughout the agricultural year constraining yields in olive orchards (Melgar et al., 2009). The water authority assigns an irrigation rate of 1.500m^3 ha^{-1} per year, which in practice means deficit irrigation in this crop (Pastor et al., 2002). Therefore, LF to avoid soil salinization may pose in practice a reduction in available water for olives negatively affecting yields in the short-term.

The efficient management of limited water resources for agricultura in Mediterranean basin requires complex decision-making processes at regional scales (Araus, 2004). This implies the management of large datasets and the spatial analysis of the information, which can be achieved with geographic information systems (GIS) (Chowdary et al., 2003; Malczewski, 2006). GIS allows geospatial analysis integrating different sources of information making maps and providing complex outputs of the model results (Singh, 2016; Pereira et al., 2018). GIS have proved practical tools for assessing the quality of irrigation water and the risk of salinization at the regional level by providing maps of water quality and salinization risks in many regions of the world such as west Asia (Simsek and Gunduz, 2007; Arslan, 2012), Argentine Pampas (Romanelli et al., 2012), and Spain (Paz et al., 2004). In the province of Jaen, Peragón et al. (2015) recently described how the use of GIS was useful for providing salinization risk maps. In addition, GIS-based tools were useful in calculating LF and water blending from different sources in the same province (Peragón et al., 2016). However, for developing a GIS-based decision tool for the assessment of best irrigation management practices a next step is required beyond the release of risk maps. This means the definition of targets to be achieved with the use of the decision tool. To this end, the GIS-based tool should be implemented with a model able to combine and process geographical data in order to provide different solutions to achieve the defined target (Chowdary et al., 2003). In this case, the target is a salinity threshold in irrigation water below which no substantial yield decrease or soil salinization can be expected. These solutions involve, first water blending and second, if necessary, LF estimation to compensate the effect of water salinity on soil and crops if the threshold is surpassed. In addition, an analysis of solutions provided is required to assess the efficiency in using irrigation water. This means an assessment of the economic implications of these irrigation management practices for farmers and policy makers. In this regard, the objective of the present work was to study the suitability of a GIS-based decision tool in assessing the best management practices to avoid salinization effects due to irrigation, not only in terms of potential effects on crops and soils, but also in terms of water saving, efficiency, and economical balance at regional scale.

5.2. Material and methods

5.2.1. Study area

The study was carried out in the province of Jaén (southern Spain), which is the most representative area of olive production in Spain. It covers an area of 13489 km^2, which accounts for 15.4% and 2.7% of the Andalusian region and Spanish territory, respectively. The province has a mountainous geography with heights above 900 m in the north, south, and east of the province. The valley formed by the Guadalquivir River and its tributaries, especially the Guadalimar and Guadiana Minor rivers, offers a relatively flat topography in the central zone, with heights lower than 450 meters. Overall, 25% of the province is below 450 m.a.s.l.; 20% is between 450 and 600; 31% between 600 and 900; 20.5% between 900 and 1.500; and 3.51% is above 1500 m.a.s.l. Most of the territory, 97% of the total area of the province, corresponds to the administrative area of the Guadalquivir River Basin, and the rest of the area (3%) to the Segura River Basin. Between both areas, there is a small endorheic basin of only 130 km^2. There are two different sources of ground water aquifers: carbonated aquifers and detrital aquifers. On the one hand, carbonate aquifers from limestone materials poses less salt concentration than detrital aquifers. Aquifers in the province cover around 8030 km^2. These water sources are mostly located in the eastern part of the province, in the areas known as Sierras de Cazorla Segura and the Villas and Quesada-Castril, accounting for 61% of the area covered by aquifers (4900 km^2) (IGME, 2010).

The olive orchard is the main crop in this province, and irrigated orchards amounts to a surface of 2903 km^2, mainly within the basin of the Guadalquivir River (MAGRAMA, 2015). Olive orchards are mainly irrigated by a drip system with deficient water supplies (MAGRAMA, 2012). Even with these water limitations, olive tree has proved to be the best cultivation alternative in the area, it being a key element for the sustainability of irrigated land in the province which provides maximum social and economic profitability per cubic meter of water (Pastor et al., 2002).

In this province, olive orchards are predominantly of the Picual variety (CESPJ, 2011), which is considered one of the most tolerant varieties to salinity (Benlloch et al., 1994). For this variety, salinity in irrigation water may constraint yields at electrical conductivity (EC) higher than 1.8 dSm^{-1}. Above this threshold, yield decrease may be expected. Reduced yields of olive orchard of 10%, 25% and 50% are expectable at EC values of 2.6, 3.7 y 5.6 dSm^{-1}, respectively (Maas and Hoffman, 1977; Fipps, 1996).

5.2.2. Data set

The authority of the Guadalquivir basin (Confederación Hidrográfica del Guadalquivir, 2014) provided the monthly average electrical conductivity data of irrigation water (ECw) for the years 1994 to 2013. This information comes from 66 surface water stations, and 136 groundwater stations. The underground stations corresponded to 26 hydrogeological units delimited territorially according to the National Institute of Geology and Mining of Spain (IGME, 2010). Water quality parameters, in particular salt concentration, are described elsewhere (Peragón et al., 2015). Estimation of the water blending rate and leaching requirement (leaching fraction; LF) were done according to previous results by Peragón et al., (2016).

In the province of Jaén, drip irrigation system is installed in around 90% of irrigated olive orchards (Peragón et al., 2016). For this system, annual fixed irrigation cost was set at 692.74 € ha^{-1} (Alarcón, 2016), based on the average irrigation cost in Spain. This cost includes: average amortization of the investment to install a drip irrigation system, average maintenance of irrigation system, and maintenance costs and average annual cost of installed electrical power (Aquavir, 2005; AEMO, 2010; CESPJ, 2011). Calculation of the irrigation cost was done for an annual water supply of 1500 m^3 ha^{-1}, which is the irrigation rate allowed in the area. The economic data for olive production in the province of Jaén according to the described irrigation typology were estimated according to Alarcon (2016) and COI (2015). Average income for growers were 2197.20 € ha^{-1} based on mean olive fruit production, oil concentration in olive, and oil production (AEMO, 2010; CESPJ, 2011).

5.2.3. Model

A methodological framework was defined for the management of water resources in the province of Jaén (Figure 5.1). This model integrates the required information for a geostatistical analysis involving spatial analysis and management. After that, georeferencing of the different layers of information was performed using the gvSIG program (www.gvsig.org) (Peragón et al., 2015; Peragón et al., 2016). The model includes the definition of a target of EC in irrigation water to avoid negative effects (1.8 dS m^{-1}). On this ground, information was processed, required strategies defined (water blending, or LF), and maps where each strategy should be applied released as a result. Thus, released maps define, for each area considered, the best management option for irrigation water according to premises in the model.

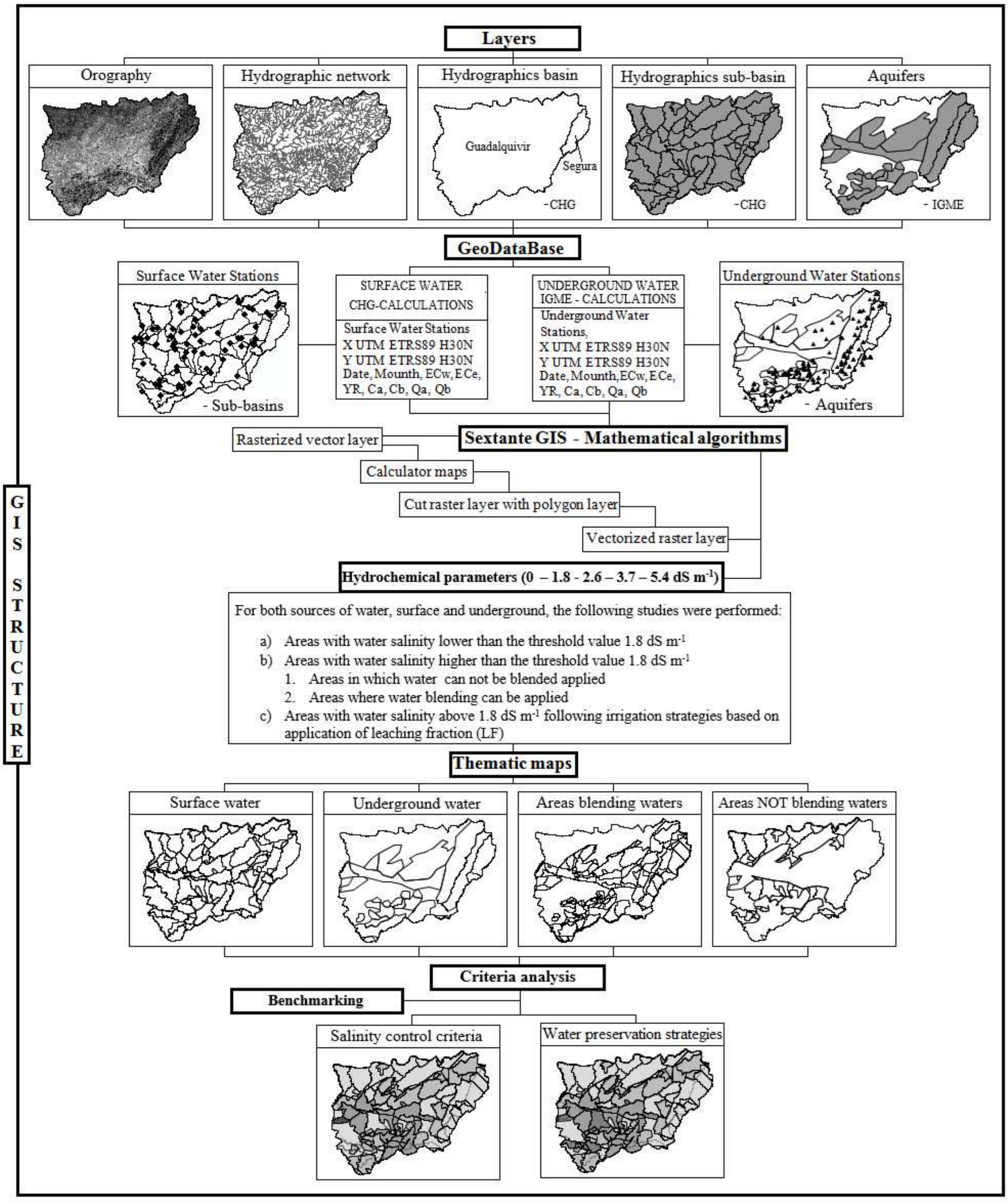

Figure 28. Model: Methodological framework. ECw, electrical conductivity in irrigation water; ECe, electrical conductivity in the saturation extract of the soil; YR, relative yield; Ca, proportion of surface water in the water blending, Cb, proportion of underground water in blending; Qa, amount of surface water; Qb, amount of underground water.

Areas with different salinity range were defined based on the expectable yield decrease for both surface and underground water. Upper limits in the considered ranges were: 1.8, 2.6, 3.7 and 5.6 dS m^{-1}; an additional range above the latter value was also considered. The three later values corresponded to the threshold values for a relative yield reduction in the production of the olive orchard of 10, 25 and 50% respectively (Ayers and Westcot, 1985; Fipps, 1996; Hoffman and Shalhevet, 2007). For both sources of water, surface and underground, the following premises were applied to define alternative solutions in the model:

a) Zones with water salinity lower than the threshold value of 1.8 dS m^{-1}, where it is not necessary any action since there is not any expectable harvest reduction due to salinity in water.

b) Zones with water salinity higher than the threshold value of 1.8 dS m^{-1}, which were divided into two categories: (i) those where both sources of water cannot be blended and consequently yield reduction is expectable; differentiation according to the threshold values of 2.6, 3.7 and 5.6 dS m^{-1} was done in order to predict reductions of the relative yield of the olive orchard of 10, 25 and 50%, respectively, and (ii) areas where water blending is feasible to achieve an ECw of 1.8 dS m^{-1} and consequently LF is not required.

c) Areas with water salinity above 1.8 dS m^{-1} where water blending is not applicable (those defined in point (i) above), and also where the blending can be applied but the result obtained is higher than to the threshold of 1.8 dS m^{-1}. In these cases, leaching fraction (LF) is required to reduce risks. LF requirement was estimated to avoid a yield reduction in olive higher than 10 %.

5.2.4. GIS calculations

The classifications in the limitations for the use of irrigation water in olive and the definition of thresholds for irrigation water are based on data published by Ayers and Wescot (1985), Maas and Hoffman (1977) and Benlloch et al., (1994), Rhoades (1982) and Rhoades and Loveday (1990).

The optimum proportions of both sources of water were calculated where their blending was possible, i.e. in those sub-basins with surface and underground water availability. By mathematical algorithms of rasterization ("rasterize vector layer" and "cut raster layer with polygon layer"), and later vectorization ("vectorize raster layer"), the GIS Sextant module reduces the thematic map of EC in surface water to the region where there is an overlap with aquifers. Then, using the "mapping calculator" algorithm of the GIS, the proportion of each water source in water mixture was calculated. This calculation was done according to the tolerance limit of olive to salinity mentioned above, i.e., for ECw of 1.8 dS m^{-1}. This calculation was applied to areas of surface waters below defined values that coincide with areas of underground water with values higher than the established thresholds or vice versa. After integrating all the variables in the model with their geospatial attributes, through queries involving both thematic and spatial components, we obtained the maps that meet the criteria for efficient use of irrigation water according to the three premises defined above. In practice this means that, where it was not possible to use a source of water with less than 1.8 dS m^{-1}, we applied first water blending; if this alternative was not feasible to achieve the defined threshold, LF was applied.

Finally, to compare the water use strategies described above, we calculated the irrigation water efficiency (IWE) as ratio of the potential olive yield (kg ha^{-1}) to the irrigation rate (m^3 ha^{-1}). In addition, an analysis of the income according to the harvest value and the cost of irrigation was performed according to sources mentioned above in the description of the dataset.

5.3. Results

5.3.1. Irrigated areas without water blending

Approximately in 82% of the land which can be potentially irrigated with surface water (11111 km^2), it can be used water with eléctrical conductivity (ECw) below the threshold of 1.8 dS m^{-1}, meanwhile 85% of the land potentially irrigated with groundwater (6855 km^2) was supplied with water below that limit (Table 5.1; Figure 5.2). A yield reduction of 10 %, i.e., ECw ranging from 1.8 to 2.6 dS m^{-1}, was expectable in 4.6% of the area supplied with surface water (617 km^2), and in 2.7% (218 km^2) of the area supplied with underground water (Table 5.1, Figure 5.2). The land potentially irrigated with water with EC ranging from 2.6 to 3.7 dS m^{-1}, where a yield decrease between 10 and 25% may be expectable as result, amounted to 10.7% (1457 km^2) and 11.9% (957 km^2) of the land with surface and underground water supplies, respectively. The area irrigable with water ranging from 3.7 to 5.6 dS m^{-1} was not accountable, and that irrigated with water with EC higher than 5.6 dS m^{-1} only represented 2.3 % (304 km^2) of the area supplied with surface water. Thus, irrigated areas with EC between 1.8 and 5.6 dS m^{-1}, where yield reduction up to 50% was possible, accounted for ca 15% of the land supplied with surface and underground water supplies (2074 km^2 and 1176 km^2, respectively, Table 5.2).

Table 17. Area irrigated with surface and underground irrigation water according to their electrical conductivity in the province of Jaen. Surface water is divided in two categories: that overlapping with underground water, and that not overlapping with underground water

Electrical Conductivity	Surface Water						Underground Water	
	A		B		C			
dS m^{-1}	km^2					% Area	km^2	% Area
0 - 1.8	11111	=	6900	+	4211	82.4	6855	85.4
1.8 - 2.6	617	=	191	+	426	4.6	218	2.7
2.6 - 3.7	1457	=	751	+	706	10.7	957	11.9
3.7 - 5.6	-	=	-	+	-	-	-	-
> 5.6	304	=	188	+	116	2.3	-	-
Total	13489	=	8030	+	5459	100	8030	100

A, All the surface irrigated with surface water.
B, Area where surface water overlap with underground water.
C, Area where surface water do not overlap with underground.
% Area is referred to that area potentially irrigated with each source of water (over 13489 km^2 in surface water, and 8030 km^2 in underground water).

Table 18. Areas irrigated with different water sources in the province of Jaen with water salinity expressed in electrical conductivity (dS m^{-1}) above and below different threshold values for different effect on olive crop

		< 1,8		≥ 1,8		< 2.6		≥ 2.6		< 3.7		≥ 3.7		< 5.6		≥ 5.6	
		km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
SW	A	11111	82.4	2378	17.7	12181	90.3	1760	13.0	13102	97.1	387	2.9	13176	97.6	304	2.3
	B	6900	51.2	1130	8.4	7543	55.9	939	6.9	7842	58.1	188	1.4	7842	58.1	188	1,4
	C	4211	31.2	1248	9.3	4638	34.4	821	6.1	5260	39.0	199	1.5	5334	39.5	116	0.9
UW		6855	85.4	1176	14.6	7073	88.1	957	11.9	8030	100	-	-	8030	100	-	-

SW, surface water; UW, underground water.
A, All the surface irrigated with surface water; B, Area where surface water overlap with underground water; C, Area where surface water do not overlap with underground.
% Area is referred to that area potentially irrigated with each source of water (13489 km^2 in surface water, and 8030 km^2 in underground water).
Below 1.8 dS m^{-1}, no yield reduction can be expected; above 5.6 dS m^{-1} yield decrease above 50 % can be expected.

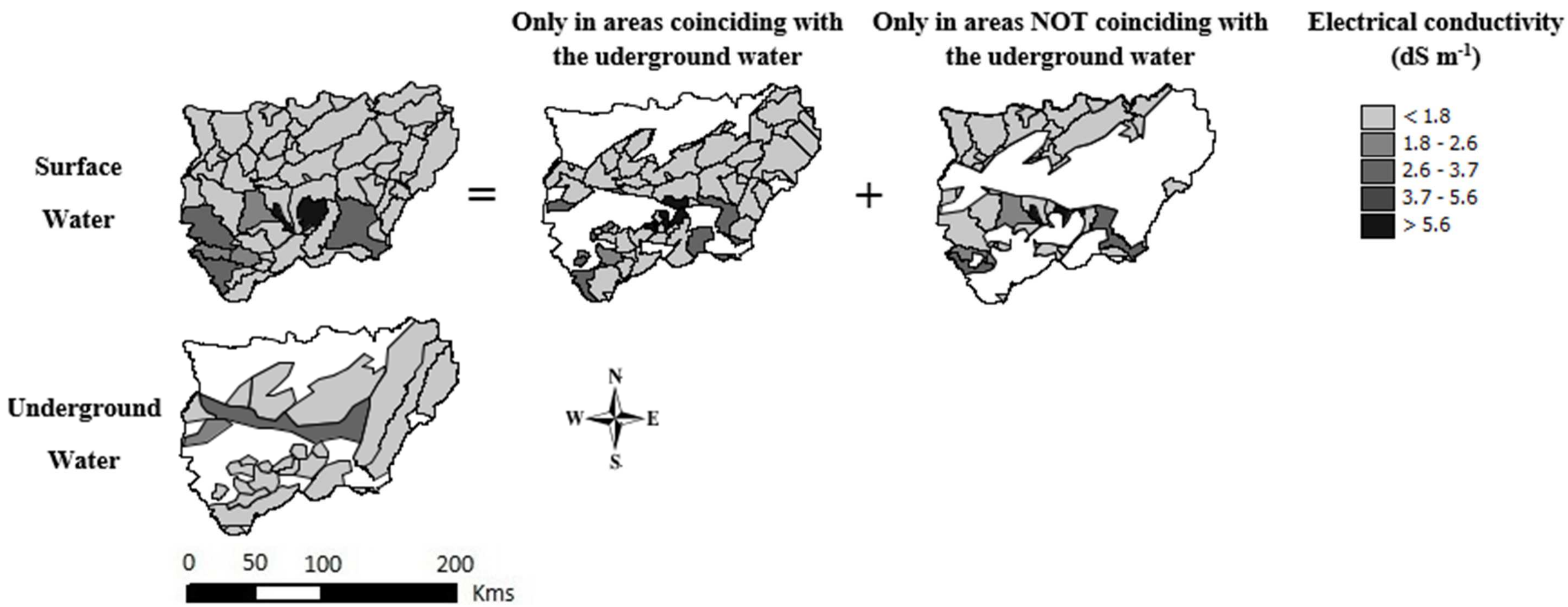

Figure 29. Electrical conductivity in the irrigation water (in dS m^{-1})

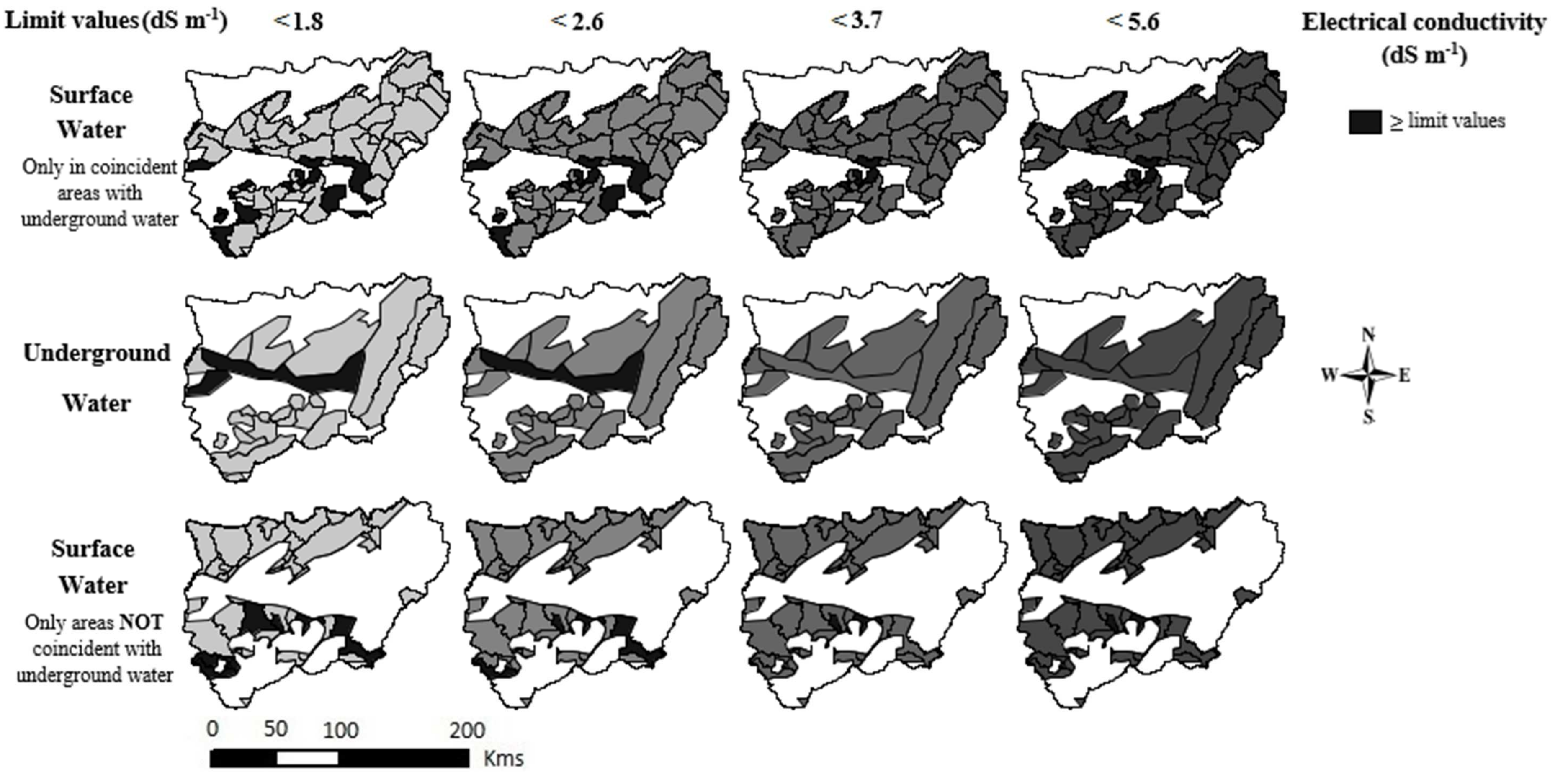

Figure 30. Areas with water salinity lower and higher than the threshold value 1.8 dS m–1. Above this threshold, different thresholds according to the effect on olive yield are described (2.6, 3.7, and 5.6 dS m–1). Areas in black are those in which the values are greater than the specified limits for each map.

In 17.7 and 13.0% of the land potentially irrigated with surface water, ECw was higher than 1.8 and 2.6 dS m^{-1}, respectively (Table 5.2; Figure 5.3). ECw values greater than 3.7 were observed in 2.9% of the area potentially irrigated with surface water. For groundwater, ECw above 1.8, and 2.6 dS m^{-1} was observed in 14.6 and 11.9% of the surface potentially irrigated with this water source, respectively (Table 5.2; Figure 5.3). For this source, the area potentially irrigated with water with EC higher than 3.7 was negligible (Table 5.2, Figure 5.3).

5.3.2. Application of water blending strategy

Sub-basins with surface water supply coincident with aquifers accounted for 8030 km^2. It was possible the use of surface water with ECw lower than 1.8 dS m^{-1} in 11111 km^2. This accounted for 82.4% of the total area irrigable with surface water. Thus, in this area it was not necessary any measure to improve irrigation water quality. Only in 1130 km^2 of the remaining 2378 km^2 irrigable with surface water it was feasible water blending with underground water. With this blending, it was possible to maintain an EC in irrigation water lower than 1.8 dS m^{-1} in 1056 km^2 by using different surface to underground water ratios (Table 5.3; Figure 5.4). On the other hand, when underground water had ECw higher than 1.8 dS m^{-1}, it was possible the obtaining of irrigation water below this threshold by blending with surface water in 1102 km^2 (Table 5.3; Figure 5.4). The defined ECw threshold was unfeasible with water blending in 74 km^2 of the area with overlap of both sources of water (Table 5.3).

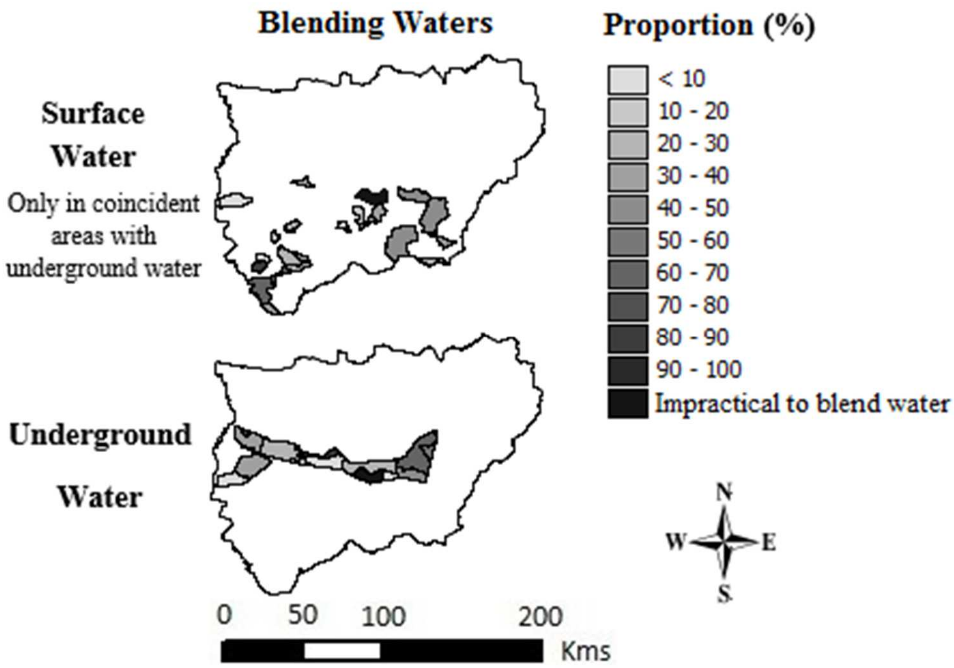

Figure 31. Proportion of surface water and area where this proportion is feasible to achieve an electrical conductivity in irrigation water of 1.8 dS m^{-1} after water blending

Table 19. Proportion of surface water in water blending and area where this proportion is feasible to achieve an electrical conductivity in irrigation water of 1.8 dS m^{-1} after water blending

Proportion of surface water in irrigation water	Surface water area with ECw > 1.8 dS m^{-1} water where blending with underground water is possible[a]		Underground water area with ECw >1.8 dS m^{-1} water where blending with underground water is possible[1]	
%	km^2	% Area	km^2	% Area
< 10	129	11.4	203	17.3
10 - 20	48	4.3	-	-
20 - 30	210	18.6	319	27.1
30 - 40	98	8.7	236	20.1
40 - 50	407	36.0	72	6.1
50 - 60	-	-	37	3.1
60 - 70	128	11.4	199	16.9
70 - 80	3	0.2	3	0.3
80 - 90	33	2.9	33	2.8
90 - 100	-	-	-	-
Total area where blending can be applied obtaining an ECw < 1.8 dS m^{-1}	1056	93.5	1102	93.7
Total area where water blending is impractical[b]	74	6.5	74	6.3
Total area	1130	100	1176	100

% Area is referred to the area studied potentially irrigated with this water source.
[a]Water blending is possible, but not required to achieve the threshold value.
[b]Area where water blending is impractical is that with overlap of both water sources where it is not possible to achieve an electrical conductivity of 1.8 dS m^{-1} after blending.

5.3.3. Application of leaching fraction (LF)

In sub-basins with ECw higher than the defined threshold value where it is not possible to mix water, i.e. not coincident aquifers (1248 km^2; Table 5.4) as well as where water blending is impractical for achieving defined thresholds for ECw (74 km^2; Table 5.4) the leaching fraction criteria was applied. The model provided different leaching fractions for the defined yield loss threshold (10%), which was achievable in all the targeted area defined above (1322 km^2; Table 5.4, Figure 5.5).

Table 20. Areas with water salinity above 1.8 dS m^{-1} where different leaching fraction (LF) are required to avoid salt accumulation in root zone

Risk in the use of water	Leaching Fraction	A		B		C	Area
		km^2					%
Low	< 5	-	+	1143	=	1143	86.5
	5 - 10	74	+	-	=	74	5.6
Medium	10 - 15	-	+	-	=	-	-
	15 - 20	-	+	-	=	-	-
	20 - 25	-	+	82	=	82	6.2
	25- 30	-	+	-	=	-	-
High	> 30		+	23	=	23	1.7
Total area affected		74	+	1248	=	1322	100

A = Areas with overlap of both water sources where it is impractical to blend water because it is not possible to achieve a final electrical conductivity of 1.8 dS m^{-1}.
B = Areas where there is not overlap of both sources of water, surface and underground.
C = Sum of A and B.
% Area is referred to the area accounting for cases A and B.

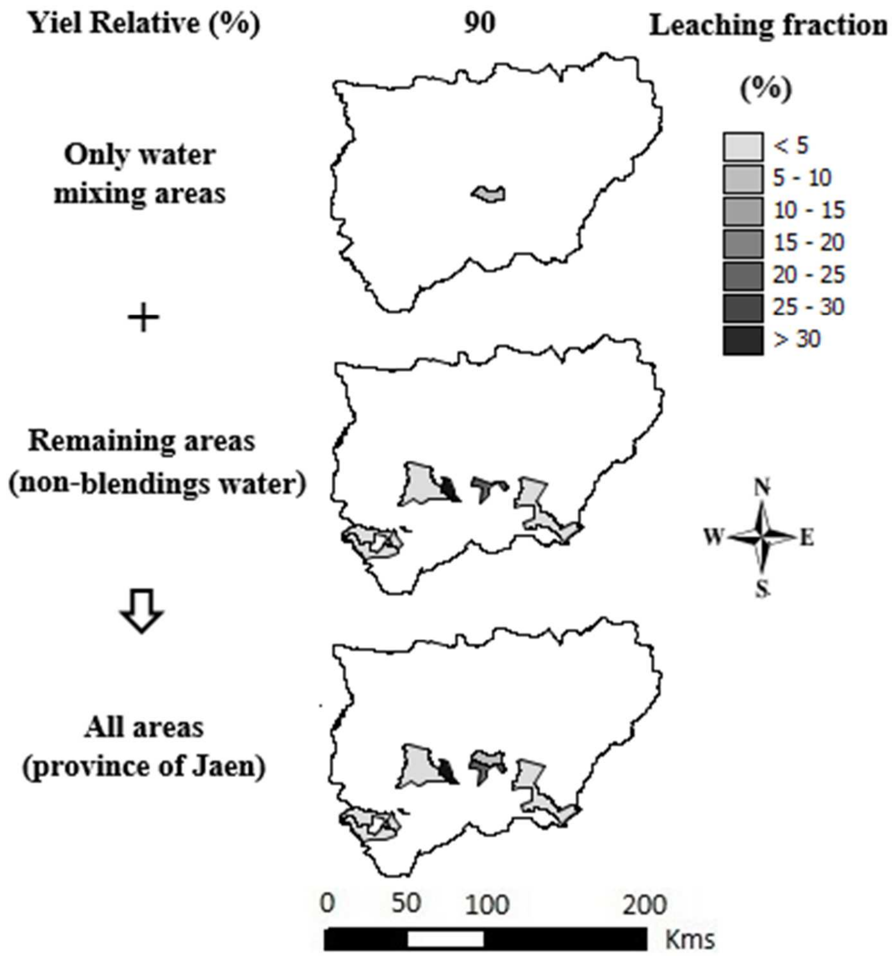

Figure 32. Areas with water salinity above 1.8 dS m^{-1} where different leaching fraction (LF) should be applied to avoid yield reduction in olive

5.3.4. Irrigable areas with different approaches

There was not any expectable negative effect ascribed to water salinity, i.e. ECw < 1.8 dS m^{-1}, in 6.900 km^2 of the area irrigable indifferently with superficial or underground water (overlap of both sources), and in 4211 km^2 of the area irrigable with surface water where it do not overlap with underground (Table 5.5). When the EC of both sources of water was lower than 1.8 dS m^{-1}, it was not necessary water blending or LF. Only in 2158 km^2 (16% of the total irrigable land), and 1322 km^2 (9.8%), it was required water blending and LF, respectively, according to the defined premises in the model (Table 5.5).

Table 21. Benchmarking of irrigation water based on salinity control criteria (yield preservation)

	Area	% Area	Irrigation Cost	Production Cost	IWE
	km^2	%	Mill €	Mill €	
Surface (A) or Underground Water (ECw < 1.8 dS m^{-1})	6900	51.2	478	1516	8.66
Surface Water (B) (ECw < 1.8 dS m^{-1})	4211	31.2	292	925	8.66
Blending water for surface water with EC > 1.8 dS m^{-1}	1056	7.8	73	232	8.66
Blending water for underground water with EC > 1.8 dS m^{-1}	1102	8.2	76	242	8.66
Leaching Fraction (A)	74	0.5	5	16	7.09
Leaching Fraction (B)	1248	9.3	95	247	7.09
Total potentially irrigable area	13489	100	943	2936	-

A, Area where surface water overlap with underground water; B, Area where surface water do not overlap with underground.
ECw, electrical conductivity in water; IWE, irrigation water efficiency = kg of olive produced per cost m^3 of water used for olive groves irrigation.
Sum of all water use strategy is greater than the total potentially irrigable area since 1102 km^2 of underground water with EC >1.8 dS m^{-1} overlaps with surface water with EC <1.8 dS m^{-1}.
Economic data for the olive grove in the province of Jaén (Alarcón, 2016):

- Irrigation cost: 692.74 € ha^{-1}. Fixed cost of irrigation for 1500 m^3 ha^{-1}.
- Production value: 2197.2 € ha^{-1}, for a production of 6000 kg ha^{-1} of olives (equivalent to 1280 kg ha^{-1} olive oil).

Leaching fraction for relative yield of 90%, which means an increase in irrigation cost (+10%) and a decrease in production (–10%).
% Area is referred to the area potentially irrigated with both surfaces of water, surface and underground water (13489 km^2).

If we define a different approach, which is the preservation of water without any action to preserve soils or yields (no water blending and no LF as defined in the model), land or irrigation rates for areas with LF can be increased. In fact, this is the current irrigation strategy in the province of Jaen. With this premise of water preservation, 11111 km^2 (82.42%) was irrigable with water with EC till 1.8 dS m^{-1}, as estimated for the yield preservation approach defined above in the GIS-based model. However, in 762 km^2 (5.7%) were potentially irrigated with water ranging from 1.8 to 2.6 dS m^{-1}, and consequently with an expectable yield decrease up to 10%, and 1616 km^2 (10.9%) with water ranging from 2.6 to 3.7 dS m^{-1}, thus potentially promoting a yield decrease of up to 25% (Table 5.6).

Table 22. Benchmarking of irrigation without blending based on water preservation strategies (no leaching fraction applied)

	Area	% Area	Irrigation cost	Production value	IWE
	km^2	%	Mill €	Mill €	
Surface (A) or Underground Water (Ecw < 1,8 dS m^{-1})	6900	51.2	478	1516	8.66
Surface Water (B) (ECw < 1.8 dS m^{-1})	4211	31.2	292	925	8.66
Surface Water (ECw = 1,8 - 2,6 dS m^{-1})	617	4.6	43	122	7.80
Surface Water (ECw = 2,6 - 3,7 dS m^{-1})	659	4.9	46	109	6.50
Underground Water (ECw = 1,8 - 2,6 dS m^{-1})	145	1.1	10	29	7.80
Underground Water (ECw = 2,6 - 3,7 dS m^{-1})	957	7.0	66	158	6.50
Total	13489	100	935	2859	-

A, Area where surface water overlap with underground water; B, Area where surface water do not overlap with underground.
ECw, electrical conductivity in water; IWE: is the average irrigation water efficiency: kg of olive produced per cost m^3 of water used for olive groves irrigation.
Economic data for the olive grove in the province of Jaén (Alarcón, 2016):
- Irrigation cost: 692.74 € ha^{-1}. Fixed cost of irrigation for 1500 m^3 ha^{-1}.
- Production value: 2197.2 € ha^{-1}, for a production of 6000 kg ha^{-1} of olives (equivalent to 1280 kg ha^{-1} olive oil).

Surface and/or Underground Water (to 1.8 ds m^{-1}): no yield decrease is assumed.
Surface and/or Underground Water (1.8 – 2.6 dS m^{-1}): 10% yield decrease is assumed.
Surface and/or Underground Water (2.6 – 3.7 dS m^{-1}): 25% yield decrease is assumed.
Area and % Area is referred to the area potentially irrigated with both sources of water, surface and underground (13489 km^2).

5.3.5. Benchmarking

Overall, with the yield preservation strategy defined in the model, the cost of irrigation in the irrigable land of the province of Jaen was € 943 million, meanwhile the value of the production was € 2936 million (Table 5.5). In this case, the ratio of olive yield to volume of water used (IWE) was 8.66. Above the ECw threshold of 1.8 dS m^{-1} defined in the model, LF was applied. This means that production decreased with increased volume of water used for salt leaching. As a result, IWE decreased to 7.09 (Table 5.5). With this LF requirement, it is assumed that irrigation costs increased by 10% with a decrease in production of the same percentage (10%).

With the premise of water preservation without any action, the value of crop production and the irrigation cost in the irrigable land decreased to 2859 and 935 million €, respectively (Table 5.6). Regarding IWE, it varied according to the source of water used. For the threshold value 1.8 dS m^{-1}, IWE was 8.66, meanwhile for ECw thresholds of 2.6 and 3.7, it decreased to 7.80 and 6.50, respectively, due to yield losses (Table 5.6).

On a regional basis, yield preservation approach defined in our GIS-based decision tool implied an increased irrigation cost of 8 million €; however, it was expectable an increased value of the harvest of near 80 million € (Tables 5.5 and 5.6). It should be remarked that this increased gross income was mostly obtained in the 2158 km^2 where water blending is possible when compared with the water preservation strategy without any action.

5.4. Discussion.

The proposed GIS-based decision tool was useful in managing hydrochemical information of irrigation water intended to create maps of qualities and irrigable surfaces which each source of water (surface and underground). Similar results were obtained in other geographical areas with analogous water quality criteria (e.g. Romanelli et al., 2012 for Argentine Pampas). However, in contrast with previous literature on the use of GIS in predicting soil salinization risks, our model applied decision criteria for defining the best management option with the premise of yield preservation and soil protection. The information released is not only a risk map. Our GIS-based tool was useful to estimate where the blending of both water sources is possible to calculate LF requirements to achieve the minimum yield loss defined in the model. Our approach is similar to that used by Chowdary et al. (2003) for providing best solutions for each zone of an irrigated land for groundwater preservation. The proposed GIS-based tool was useful for using irrigation water efficiently in order to avoid constraints ascribed to water salinity. Alternatively, the model can handle the information by applying different decision criteria, e.g. with a water preservation approach (i.e. without blending or LF) instead the yield preservation approach. Although the water preservation approach lead to less sustainability in the agricultural land (salinization will occur), its implementation in the model allow us to compare IWE with different approaches and the potential economic implications of different irrigation strategies. The approach based in yield preservation by avoiding salt accumulation in soil by water blending or LF led to an increased IWE in the areas affected by irrigation with saline water. This was achieved by decreasing LF requirements with blending or by increasing potential crop yield in the cases that LF had to be applied. Although area affected by water blending amounted to 16% of the total irrigable area of the province of Jaen, the economic impact in this affected area was significant. Water blending was an effective strategy to maintain IWE in the highest value (8.66) in 2158 km^2. Without any control measure, IWE would diminish in this area due to the reduction in crop yield. Thus, in these affected areas, economic implications of water quality and best management options for irrigation are truly relevant. Water blending implies an expected cost in the infrastructure required for this strategy. However, the economic study revealed that this investment can be affordable at least partially with expected benefits in affected areas.

The proposed tool can facilitate the analysis and processing of data, allowing the visualization of the geographic information and offering all the functionalities of manipulation of the geographic data. This can be used in the planning and decision making processes (Peragón et al., 2015, 2016). With these capabilities, GIS can be considered as a decision support system involving the integration of spatially referenced data in a problem solving environment (Cowen, 1988). However, the proposed GIS-based tool was effective in defining the best management options for irrigation and represented the next step to previous models. These previous models were only able to make a geospatial analysis of water quality and constraints derived from its use, such as models proposed by Peragón et al. (2015, 2016); for the same area and crop. Thus, the proposed tool is able to transform and combine geographical data and value judgments to obtain information for decision making. It provides procedures for structuring decision problems, and designing, evaluating and prioritizing alternative decisions. Thus, it can be considered an example of GIS-based multicriteria decision analysis (Feick and Hall, 2004; Malczewski, 2006).

The GIS-based decision tool proposed here is able to define best management options for salinity control in each area after defining the target to be achieved, which in a first step is an irrigation water below a given ECw value. This is very relevant in the arid regions such as the area of study where water availability is scarce. In the province of Jaen, with an assigned limit of 1500m^3 ha^{-1}, deficit irrigation is only posible (Pastor et al., 2002). Mixing both sources of water up to the threshold of water salinity in the irrigation that is established as tolerance limit for olive orchard (1.8 dSm^{-1}) will allow a reasonable control of water salinity effects while increasing water availability to crop by decreasing LF. It should be highlighted that high LF requirements cannot be considered suitable which such a low water irrigation rates (Peragón et al., 2016) and alternative strategies such as water blending can contribute to the sustainability of olive production in these areas. Usually, the GIS techniques have been used as a tool for storing, analyzing, and displaying spatial information in an efficient manner for water resources management (Singh, 2016). We demonstrated here that spatial information can be successfully processed for providing best solutions in each zone of an irrigated land with an economic analysis at regional scale. This spatial and economic analysis of control measures for avoiding salinization risks related to irrigation water quality was never described in literature. However, this is a relevant issue not only with a view of analyzing potential economic benefits. Frequently, in the implementation of changes in irrigating schemes, social benefits prevail and large public investments are required. In this regard, GIS-based tools can help governmental policymakers in taking decisions (Neji and Turki, 2015).

This type of GIS-based tools is also able to adapt decisions to fast changes in water composition as previously proved by Peragón et al. (2016). The GIS-based decision tool proposed was developed for olive crop in the province of Jaen in Spain. This is a representative example of crop and environment with increasing risk of soil salinization by irrigation. However, this tool can be easily extrapolated to other regions and crops and it can be an useful tool for helping stakeholders to take decisions on irrigation management at regional scales.

5.5. Conclusions

The proposed GIS-based is able to transform and combine geographical data and value judgments for decision making. This was useful in defining best irrigation practices to avoid salinization risks in the different areas of the irrigated land studied. In those areas where water blending was possible, this strategy allowed the best irrigation water efficiency. Without blending and leaching fraction, this efficiency decreased with increased salt concentration in water due to yield reductions. With water blending and leaching fraction when necessary, the annual gross income in the province can be increased by 80 mill €. Further research is however required to check the long-term efficiency of this tool in avoiding soil salinization and for implementations of more complete GIS-based decision tools providing accurate irrigation rates for different crops.

5.6. Acknowledgments

Mr. Juan Manuel Peragón received a grant from the Doctoral School of the University of Jaen. This work has been complementary funded by the National Research, Development and Innovation Plan (Plan Estatal de I+D+i) from the Ministry of Economy and Innovation and by European Regional Development Fund of the European Union through the National Research, Development and Innovation Program (Plan Nacional I+d+i, AGL2014-57835-C2-1-R).

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Capítulo 6. Discusión general

El objetivo propuesto en esta Tesis Doctoral fue contribuir al uso eficiente de los recursos hídricos en el riego del olivar de la provincia de Jaén, en función a la calidad el agua disponiblede teniendo presente la influencia diversos factores: calidad de aguas, agroclimatológicos, edafológicos, etc. Para ello, se implementó un Sistema de Información Geográfico (GIS) integrado con herramientas de evaluación multicriterio-multiobjevo (EMC-EMO). Se estableció así un marco conceptual que ha proporcionado alternativas sostenibles a nivel agrónómico, económico y medioambiental que permitirán ayudar en los procesos de toma de decisión y planificación en el sector del olivar.

Inicialmente, en el Capítulo I se realizó una aproximación al conocimiento del cultivo del olivar en la provincia de Jaén, las necesidades y recursos hídricos, tipología de riego, interpretación de la calidad del agua de riego en función a su procedencia (superficial y subterránea), los efectos negativos sobre la planta derivados de su uso, influencia de la climatología y tipología de suelos. Además se analizó la normativa ha tener en cuenta y los medios que a nivel general (marco conceptual) se iban a emplear en el desarrollo de los objetivos específicos definidos.

El Capítulo II se ha dedicado a identificar los factores de riesgos relacionados con el uso del agua de riego. Para ello, se definió geográficamente el área de estudio, donde se integraron los datos agroclimáticos y de calidad de agua superficial y subterránea, facilitados por diferentes administraciones públicas, así como estadísticos propios, en la base de datos implementada en el GIS diseñada para capturar, almacenar, manipular, analizar y desplegar en todas sus formas la información geográficamente referenciada. El conjunto de parámetros introducidos en la base de datos fue lluvia diaria, temperaturas máximas, mínimas y medias, evapotranspiración, precipitación efectiva, índice de arídez de la FAO, pH, conductividad eléctrica, concentración de Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, NO_3^-, PO_4^{3-}, NH_4^+, B, Ca_2^+, K^+, y Na^+, SARadj, RSC, relación Ca/Mg, la dureza del agua (en ºfH), y el índice de Langelier. Cada parámetro incluido en la base de datos dispone de información geográfica (información alfanumérica), que se encuentra asociada por un identificador común (estaciones de toma de muestras), y a los objetos gráficos mostrados en un mapa (subcuencas hidrográficas, masas de agua subterránea, índices climáticos, etc.). De esta forma, señalando un objeto se conocen sus atributos e, inversamente, preguntando por un registro de la base de datos se puede saber su localización geográfica en la provincia de Jaén. Se estableción una gradación riesgo para cada variable y se realizó un análisis espacial multicriterio (EMC) en función a los objetivos de diferentes tipos de riesgo derivados de la utilización de aguas superficiales y subterráneas para el riego: la degradación del suelo, los trastornos nutricionales de las plantas, la obstrucción de los sistemas de riego y los problemas en los embalses (proliferación de micro y macro organismos). Como resultado se obtuvo un mapa para cada uno de los riesgos enumerados. Cabe destacar que, en función a la fuente de agua empleada, superficial o subterránea, los riesgos potenciales del uso de agua de riego difieren, obteniéndose mayores restricciones con el empleo de aguas superficiales para riego respecto a las aguas subterráneas. La degradación de suelo y los trastornos nutricionales implican mayor riesgo con el empleo del agua superificial, debido típicamente a la mayor salinidad y sodicidad de esta fuente de agua, como revelaban la EC, las concentraciones de Na y Cl, y el SARadj. En aguas superficiales, los contenidos de Cl y Na, y en aguas subterráneas los de Cl y bicarbonato, pueden ser las principales causas de problemas nutricionales en el olivar. En los dos casos se dío un paso más y se aplicó una nueva EMC mediante correcciones climáticas derivadas de aplicar el índice de arídez de la FAO. Ambos tipos de agua presentaron un alto riesgo de obstrucción de sistemas de riego a través de la precipitación de compuestos de Ca y Mg. Además, el alto contenido en nutrientes del agua superficial, debido a que están enriquecidas con nutrientes por efecto de la escorrentía y la lixiviación de tierras agrícolas, plantea restricciones más severas sobre las reservas de agua que las aguas subterráneas. El desarrollo de la elaboración del GIS para la determinación de estos factores de riesgo potencial derivados del uso de ambas fuentes de agua, superficial y subterránea, fue la base previa para el desarrollo de los otros objetivos definidos, que fueron desarrollados en los siguientes capítulos.

En el Capítulo III, se elaboraron estrategias con el objetivo de evitar la acumulación excesiva de sales en los suelos de olivar de la provincia de Jaén. El GIS se retroalimentó con las características de la tipología de riego de olivar a nivel de comarcas agrarias. Se establecieron las funciones más adecuadas para la obtención de fracciones de lavado (LF) a aplicar en función de diferentes rendimientos relativos (YR) del cultivo del olivo. Este rendimiento sería la relación entre el rendimiento esperado para una conducitividad eléctrica dada en el agua y el rendiminento no limitado por la salinidad del agua. También, se establecieron funciones para el empleo conjunto de aguas superficiales y subterráneas (mezcla de aguas). Para la mezcla de aguas, se superpuso el mapa de ECw de aguas superficiales con el área ocupada por las masas de agua subterránea. Se proporcionaron dos soluciones. La primera fue estimar la relación de mezcla de agua de origen diferente para conseguir una ECw dada para que fuese necesaria una mínima LF. La segunda fue proporcionar la ECw final y la LF para relaciones de mezcla previamente establecidas. Se obtuvo que la conductividad eléctrica y, en consecuencia, los requerimientos de lixiviación, fueron mayores para las aguas superficiales que para las aguas subterráneas. Esto fue consecuencia de la composición de agua. En las aguas superficiales existió además mayor variabilidad de la concentración de sales disueltas con el tiempo. Esto se explica por las oscilaciones meteorológicas entre meses y años, y se propueso como ejemplo para ello la cuenca del Guadiana Menor. En este ejemplo, la mezcla de agua superficial y subterránea contribuye a lograr una LF mucho más baja. Esta cuenta sirvió también como ejemplo para ver la capacidad de adaptación del GIS a cambios en la composición del agua. Esta aplicación, se puede extender al resto de areas donde ambas fuentes de agua se superponen. En donde no hay coincidencia geográfica entre ambas fuentes de agua, para elevadas ECw la solución consitió en aplicar LF. Las LF eran tanto mayores, cuanto mayor era el rendimiento relativo establecido como objetivo.

En el Capítulo IV se identificaron, mediante técnicas GIS, las áreas con riesgos potenciales de obstrucción de sistemas emisores en riego localizado, procediendo al análisis de posibles causas. En la provincia de Jaén, estas causas se deben a la precipitación de sales insolubles, que en riego por goteo puede ser el resultado de la precipitación del carbonato cuando las aguas duras se utilizan para el riego. También pueden deberse al manejo incorrecto de fertilizantes en fertirrigación. El riesgo de obturación se evaluaó con diferentes índices quimiométricos del agua: (i) grados hidrotimétricos franceses (ºfH) para el riesgo de precipitación de los compuestos de Ca y Mg, y (ii) la precipitación de carbonatos de Ca con el índice de Langelier (Ayers y Wescot, 1985). El RSC también puede ser útil para estimar el riesgo de precipitación de carbonatos. La relación Ca/Mg también fue considerada en la evaluación de este problema. Con el empleo de ambas fuentes de agua, superficial y subterránea, el riesgo de obstrucción en el riego por goteo fue elevado, siendo más acusado en el agua superficial. Para minimizar el riesgo de obstrucción, se plantearon estrategias integradas de riegos y fertilización en el GIS. En estas estrategias se consideraron diferentes frecuencias de riego, de diaria a semanal, y se determinaron las cantidades de ácido a añadir y los tiempos de inyección, que osciló entre 15 y 30 minutos. La concentración de ácido a añadir se basó en el índice de Lagelier, de tal manera que su valor se reducía con la aplicación del ácido y la consiguiente elminación de carbonatos y bicarbonatos a valores para los cuales los riesgos eran mínimos. El ácido nítrico se seleccionó para este fin, porque las inyecciones con este ácido se pueden adaptar mejor a la fertirrigación del cultivo ya que puede ser parte del fertilizante nitrogenado aplicado. Se desestimó el ácido fosfórico o sulfúrico porque las necesidades de P y S del olivo no son relevantes en comparación con las de N. El volumen de ácido nítrico a inyectar varió ampliamente en función a las fuentes de agua, requieriendo mayores volúmenes de ácido en la zona que se podía regar con agua superficial que en la que se podía regar con agua subterránea. Por el contrario, el suministro de N atribuido a la concentración inherente de N de agua de riego fue mayor en aguas subterráneas, atribuible a la acumulación de N soluble (nitrato) en los acuíferos. El suministro de N con el manejo del agua de riego para reducir el riesgo de obstrucción y el que contiene el agua de riego puede cubrir una porción relevante de los requerimientos de N del cultivo. La evaluación de la inyección de ácido y N suministrada con un manejo óptimo del riego por goteo pudo ser fácilmente evaluada usando la herramienta GIS.

Finalmente, en el Capítulo V, se procedió a un análisis en profundidad de los resultados obtenidos en los capítulos anteriores. Identificadas las zonas, el manejo del agua de las mismas y las características del cultivo, se procedió a definir estrategias y realizar propuestas de uso eficiente del agua de riego en el olivar de la provincia de Jaén. Se definieron valores de "salinidad umbral en agua" y dos soluciones posibles para alcanzar este umbral: la mezcla de las dos fuentes de aguas disponibles (superficial o subterránea), y cuando sea necesario, la aplicación de fracciones de lixiviación (LF) para evitar la acumulación de sales en los bulbos de humectación. Fue posible el uso de ambas fuentes de agua por debajo del umbral definidido sin aplicar mezcla ni LF en aproximadamente el 80% del area de estudio. Cuando el umbral de salinidad se excedía por una de las fuentes, se obtuvo la calidad de agua definida mezclando agua de riego a diferentes proporciones en las áreas donde coincidían ambas fuentes de agua. En esta area coincidente fue necesario aplicar LF en 74 km^2 para evitar riesgos de acumulación de sal en el suelo. Donde no se podía aplicar mezcla (areas no coincidentes), se requirío fracción de lavado en 1322 km^2. La herramienta basada en GIS perimitió el análisis de las soluciones proporcionadas para evaluar la eficiencia en el uso del agua de riego (IWE). Esto permite una evaluación de las implicaciones económicas de las soluciones propuestas. Resulto que la mejor eficiencia de agua de riego (IWE) estimada para la provincia se alcanzó cuando se aplicó la mezcla de aguas dónde esta era posible. Sin embargo, IWE disminuyó con el aumento de LF debido a la pérdida de agua por drenaje para lixiviar las sales. Desde un punto de vista económico, sin tener en cuanta el coste de las infraestructuras precisas para ello, el uso de la mezcla de aguas donde era posible permitió el mejor balance económico del olivar a nivel provincial.

Los resultados de la secuencia de estudios planificados en la presente Tesis Doctoral, revelan que es posible un manejo más sostenible de las aguas en el riego de olivar para evitar los riesgos asociados a la calidad del agua de riego. Se comprueba, que las herramientas de decisión basadas en GIS pueden permitir obtener soluciones a nivel provincial, desde la identificación de los riesgos, a las opciones de manejo para evitar los efectos negativos asociados al agua de riego en suelos, cultivo o instalaciones de riego. La herramienta se adapta fácilmente a los cambios en la composición de las aguas, algo que en las superficiales es contínuo. Aunque el estudio se ha desarrollado en la provincia de Jaén, el marco conceptual aplicado es fácilmente extrapolable a otras regiones y cultivos para aportar soluciones en el manejo de aguas de mala calidad en el riego. Puede servir de base o de guía para diversidad de trabajos en relación con el cultivo del olivo, entre ellos:

- Estudio de la elección de variedades de olivo adaptables a los distintos medios en función al modelo establecido en la provincia de Jaén.
- Estudio de la influencia que tiene en la calidad del aceite, el riego y/o fertirriego en función a la calidad del agua, climatología y edafología. Calendario de riego.
- Implementacion de técnicas GIS mediante el uso de teledetección y/o drones, para identificar periodos de estrés hídrico y/o acumulación de agua en el olivar tanto de secano como regadío discriminando entre variades de olivo.
- Cuantificación de la producción diferenciando entre olivar de riego y secano a través de teledetección y/o drones aplicando técnicas GIS.

Todas estas líneas, empleando el marco conceptual actual, se pueden extrapolar y adaptar, en función a las peculiarides intrínsecas, a cualquier otro tipo de cultivo y a cualquier otra zona.

Capítulo 7. Conclusiones

El trabajo realizado demuestra que es posible desarrollar una herramienta basada en GIS que contribuya a la toma de decisiones en el manejo del agua de riego en olivar. La aplicación del marco conceptual ha permitido el desarrollo de esta herramienta que se ha comprobado que permite: (i) rápida actualización; (ii) integración con herramientas de análisis multicriterio-multiobjetivo, y (iii) proporcionar un análisis de alternativas que permitan ayudar en los procesos de toma de decisión y planificación. De manera específica, la herramienta desarrollada en aplicación del marco conceptual definido, permite:

- Visualizar la información geográfica y proporcionar toda la funcionalidad de manejo de datos geográficos.

- Manejar información agroclimática e hidroquímica del agua de riego destinada a crear mapas de calidades y superficies de riego que cada fuente de agua (superficial y subterránea).

- Detectar mediante la integración de técnicas EMC-EMO los principales riesgos relacionados con el uso de las dos fuentes de agua, y la definición de los lugares y la superficie afectada, con el fin de establecer medidas de prevención y corrección.

- Manejar datos espaciales, tomar decisiones, y facilitar el análisis y procesamiento de datos para proporcionar una solución adicional, como la basada en la mezcla de agua de diferentes orígenes, así como aplicaciones de fracciones de lavado.

- Adaptar las decisiones a cambios rápidos en la composición del agua, como lo revelan las estimaciones de LF en cuencas con cambios evidentes de composición del agua de riego.

- Actualizar y retroalimentar fácilmente el sistema, para una gestión integrada más precisa, como por ejemplo para el mantenimiento del riego por goteo y la fertilización.

- Capacidad de integrar mucha información y de proporcionar, tras el análisis de la información, soluciones complejas que integran distintos aspectos del manejo del cultivo.

- Resolución de soluciones complejas, que integran muchos criterios de decisión, probablemente no al alcanze de los agricultores, mejorando la ayuda en la toma de decisiones técnico-administrativas.

- Definir las mejores prácticas de riego para evitar los riesgos de salinización, sodización y fitotoxicidad en las diferentes comarcas agrarias de la región estudiada.

Todo ello, contribuirá a preservar los rendimientos de los cultivos, a la sostenibilidad del riego deficitario en la provincia de Jaén y al mantenimiento de la producción olivar a nivel provincial. El modelo puede adaptarse fácilmente a otras áreas geográficas y cultivos para ayudar en el proceso de toma de decisiones, ayudándolas a mejorar la gestión de los recursos hídricos disponibles.

Capítulo 8. Difusión del trabajo

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 relación de lo indicado:

Revistas

- Publicación 1. Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., 2015. A GIS-based quality assessment model for olive tree irrigation water in southern Spain. Agricultural Water Management 148:232-240.
- Publicación 2. Peragón, J.M., Delgado, A., Rodríguez-Díaz, J.A., Pérez-Latorre, F.J., 2016. A GIS-based decision tool for reducing salinization risks in olive orchards. Agricultural Water Management 166:33-41.
- Publicación 3. Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., 2017. A GIS-based tool for integrated management of clogging risk and nitrogen fertilization in drip irrigation. Agricultural Water Management 184:86-95.
- Publicación 4. Peragón, J.M., Pérez-Latorre, F.J., Delgado, A., Tóth, T. 2018. Best management irrigation practices assessed by a GIS-based decision tool for reducing salinization risk in olive orchards. Agricultural Water Management 202:33-41.

Congresos

- XXXV Congreso Nacional de Riegos (AERYD) 2017: Estimación de las necesidades de riego en la provincia de Jaén aplicando técnicas SIG.

- XXXIV Congreso Nacional de Riegos (AERYD) 2016: Estudio de la mejora de la calidad del agua para el olivar de riego de la provincia de Jaén mediante la aplicación de herramientas SIG.
- XXXIII Congreso Nacional de Riegos (AERYD) 2015: Aplicación de herramientas SIG en la estimación de las necesidades de ácido nítrico para evitar la obturación de emisores por depósitos calizos en los sistemas de riego localizado en el olivar de la provincia de Jaén.
- XVII Simposium Expoliva 2015. Foro del Olivar y del Medioambiente. Ref: OLI-43. Aplicación del los SIG en la mejora de la calidad del agua de riego de olivar de la provincia de Jaén (España) mediante la mezcla de aguas superficiales y subterráneas.
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- XXX Congreso Nacional de Riegos (AERYD) 2012: Aproximación al conocimiento de la calidad de agua de riego en el olivar de la provincia de Jaén mediante la elaboración de un Sistema de Información Geográfico.

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Anexos

Anexo 1. Capítulo 1 Datos Agroclimáticos e hidroquímicos

Apéndice A) Datos agroclimáticos

Estaciones agroclimáticas: ubicación.

ESTACIONES	X_UTM ETRS89 H30N	Y_UTM ETRS89 H30N
Alcaudete	404891	4159667
Andujar	404975	4210340
Arroyo del Ojanco	506412	4240315
Baeza	452952	4197513
Baños de la Encina	441547	4227670
Bedmar-Garciez	464784	4183738
Carcheles	444222	4166450
Castellar	489067	4237792
Castillo de Locubín	414668	4155039
Chiclana de Segura	504003	4239630
Higuera de Arjona	413493	4203441
Huelma	463283	4170800
Huesa	494672	4177995
Jaén	432285	4194160
Jódar	470716	4192610
La Higuera de Arjona	411565	4200824
Linares	443111	4212750
Los Villares	429796	4176318
Mancha Real	447686	4196913
Marmolejo	400901	4212858
Martos	405236	4173759
Mengibar (IFAPA)	430899	4199788
Peal de Becerro	485346	4194802
Pozo Alcón	506267	4169627
Quesada	494283	4192911
Sabiote	479441	4214871
San José de los Propios	479835	4190273
Santisteban del Puerto	483234	4224487
Santo Tomé	492827	4209275
Torreblascopedro	439562	4204997
Torreperogil	478684	4203206
Torres de Albanchez	528787	4250883
Úbeda	473694	4199725
Villacarrillo 1	482519	4213079
Villacarrillo 2	499152	4211886

Estaciones agroclimáticas: datos.

Estaciones Agroclimáticas	Medias Anuales (mm)			Clasificación FAO	
	P	ETo	Pe	Pe/Eto	Clasificación
Alcaudete	524,96	1204,01	452,26	0,38	Semiáridos
Andújar	477,22	2023,85	400,47	0,20	Áridos
Arroyo del Ojanco	816,17	2101,94	629,86	0,30	Semiáridos
Baeza	482,98	2074,51	420,28	0,20	Áridos
Baños de la Encina	545,45	2045,23	454,20	0,22	Áridos
Bedmar-Garciez	428,67	1626,70	375,93	0,23	Áridos
Carcheles	669,55	1997,53	529,05	0,26	Semiáridos
Castellar	513,55	1904,32	436,10	0,23	Áridos
Castillo de Locubín	548,43	1938,99	467,79	0,24	Áridos
Chiclana de Segura	519,98	1272,32	445,62	0,35	Semiáridos
La Higuera 1	494,30	2052,36	414,70	0,21	Áridos
Huelma	440,35	1810,84	387,07	0,17	Áridos
Huesa	332,16	1794,11	305,41	0,32	Semiáridos
Jaén	466,98	1261,76	403,34	0,37	Semiáridos
Jódar	469,03	1120,26	415,29	0,20	Áridos
La Higuera 2	503,74	1215,74	427,21	0,35	Semiáridos
Linares	498,60	1393,15	429,26	0,31	Semiáridos
Los Villares	586,13	1565,98	492,28	0,31	Semiáridos
Mancha Real	414,70	1472,28	371,23	0,25	Áridos
Marmolejo	531,98	1291,50	458,02	0,35	Semiáridos
Martos	537,43	2043,53	460,17	0,23	Áridos
Mengibar (IFAPA)	696,35	1140,51	541,15	0,47	Semiáridos
Peal de Becerro	369,88	2086,52	333,51	0,16	Áridos
Pozo Alcón	413,32	1266,03	373,80	0,30	Semiáridos
Quesada	450,18	2048,86	400,39	0,20	Áridos
Sabiote	479,68	1450,84	418,34	0,29	Semiáridos
San José de los Propios	389,46	1577,10	352,70	0,22	Áridos
Santisteban del Puerto	519,01	2032,38	448,52	0,22	Áridos
Santo Tomé	514,62	1156,31	446,52	0,39	Semiáridos
Torreblascopedro	483,71	1225,04	418,93	0,34	Semiáridos
Torreperogil	540,87	1414,52	464,06	0,33	Semiáridos
Torres de Albanchez	600,28	1975,55	484,26	0,25	Semiáridos
Úbeda	507,08	1248,13	441,74	0,35	Semiáridos
Villacarrillo 1	542,00	941,54	457,21	0,49	Semiáridos
Villacarrillo 2	577,28	1708,53	484,45	0,28	Semiáridos

Apéndice B) Clasificación hidroquímica: aguas superficiales.

Aguas superficiales: ubicación estaciones toma de muestras

ID	ESTACIONES	X_UTM ETRS 89 H30N	Y_UTM ETRS 89 H30N
1	Aguascebas Y/O Rio Guadalquivir En Mogón	500078,7266	4213911,0012
2	Cañada De La Yedra En Canena	457653,2250	4211308,3684
3	Embalse Del Centenillo	436139,9850	4247674,4724
4	Manantiales De Martos	416031,1795	4170805,1422
5	Rio Cañamares En Chilluevar	500174,7282	4205407,8925
6	Rio Ceal En Huesa	496048,2608	4175195,3226
7	Río Dañador Embalse Del Dañador	496594,3874	4251061,7416
8	Río Beas Confluencia Con Río Guadalimar	503426,4944	4237991,7751
9	Río Frío En Puente Jontoya	434000,2210	4179800,3582
10	Río Guadalbullón En La Cerradura	446562,4059	4167455,4046
11	Rio Guadalbullón En Mengibar	431522,4750	4202703,6589
12	Rio Guadalbullón En Puente Tabla	433890,3411	4184306,0160
13	Rio Guadalen Embalse Del Guadalen	458133,5135	4223854,5163
14	Rio Guadalentín En Canal Guadalentín	408498,1370	4179344,6353
15	Rio Guadalimar En Puente Genave	512136,5655	4244056,6383
16	Rio Guadalimar En Sabiote	475935,3202	4219430,5569
17	Rio Guadalimar En Torreblascopedro	444027,5123	4207757,4516
18	Rio Guadalmena En Albadalejo	518750,8845	4262905,3663
19	Rio Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	483358,5837	4201342,5478
20	Rio Guadalquivir Aguas Abajo De Pedro Marín	460259,5498	4197916,8268
21	Rio Guadalquivir Embalse De Mengibar	430332,4840	4204568,6234
22	Río Guadalquivir En Arroyo Maria	514716,5045	4225674,7484
23	Río Guadalquivir En Arroyo Martingordo	412628,3676	4208077,6486
24	Río Guadalquivir En Marmolejo	395993,2234	4213021,6981
25	Río Guadalquivir En Mengibar	429257,4843	4205187,6135
26	Río Guadalquivir En Mogón	497255,7388	4214433,1015
27	Río Guadiana Menor En Posito	481408,6926	4192097,6582
28	Río Guadiel En Bailén	431885,5288	4209649,5208
29	Río Guadiel En Ctra Linares-Baño De L A Encina	438092,6206	4220253,4154
30	Río Guarrizas Embalse De La Fernandina	450054,6076	4225916,4779
31	Río Guarrizas Embalse Panzacola	452234,6218	4232976,4789
32	Río Guarrizas En Aldea Quemada	459561,5532	4240945,3854
33	Río Hornos En Orcera	526319,6145	4240754,6595
34	Río Jándula Embalse Del Encinarejo	413012,6274	4224562,3876
35	Río Jándula En La Ropera	403047,2732	4214417,6031
36	Río Jandulilla En Bélmez De La Moraleda	468349,6125	4177754,0415
37	Río Quiebrajano Embalse Del Quiebrajano	435736,2159	4165314,3210
38	Río Rumblar Embalse Del Rumblar	429461,6974	4223980,4206
39	Río Rumblar En Zocueca	427108,5985	4216696,4566
40	Río San Juan En Castillo De Locubín	416627,8605	4154626,0511
41	Río Torres En Puente Del Obispo	451392,5052	4200749,6692
42	Río Vega De Cazorla En Santo Tomé	488988,6109	4208993,3514
43	Río Viboras En Alcaudete	410758,1811	4166259,0592
44	Arroyo Salado	440753,4498	4194525,8106

ID	ESTACIONES	X_UTM ETRS 89 H30N	Y_UTM ETRS 89 H30N
45	Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	397778,1856	4209224,7678
46	Arroyo Salado En Porcuna	398516,1855	4187218,0498
47	Cabecera Del Río Guadalquivir	511907,6178	4208582,5977
48	Río Jándula En La Alameda	416282,1257	4250486,2504
49	Río Aguasmulas En Coto Ríos	515281,5729	4212699,6138
50	Río Borosa Antes De Confluencia Con Río Guadalquivir	512401,6230	4206928,5467
51	Río Carrizas Puente Sobre El Río	539570,1936	4250132,8874
52	Río Cuadros En Area Recreativa Río Cuadros	463918,4921	4182133,9723
53	Río De Los Molinos Puente Sobre El Carril	536713,9959	4247177,9054
54	Río Grande Puente Jv-5030	438169,8617	4240108,5051
55	Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	452418,5335	4217004,4818
56	Río Guadalen Vado Del Carril	476990,4691	4248714,0793
57	Río Guadalmena Embalse Guadalmena	507599,5172	4246252,6432
58	Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	443132,4807	4199787,6576
59	Río Guadalmena En Ctra Cm-412	537069,5545	4278314,4038
60	Río Jandula Aguas Abajo Embalse Del Encinarejo	408525,4990	4223242,4432
61	Río San Juan Tras La Confluencia Con El Río Caicena	397537,0659	4159111,0447
62	Río Trujala Camino Segura De La Sierra	530205,4902	4237633,7719
63	Río Valderazo Vado Del Camino Forestal	438465,2281	4162116,3741
64	Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	415414,1027	4164385,0850
65	Río Yeguas Aguas Arriba Embalse Del Yeguas	397195,4666	4227039,4396
66	Río Yeguas Embalse Del Yeguas	390250,2965	4213985,7222

Conductividad eléctrica y sales totales

ESTACIONES	CE Media Anual (µS/cm)	CE Media OCT-MAR (µS/cm)	CE Media ABR-SEP (µS/cm)	Sales Totales Media Anual (mg/L)	ST Media OCT-MAR (mg/L)	ST Media ABR-SEP (mg/L)
Aguascebas Y/O Río Guadalquivir En Mogón	425	419	421	267	271	275
Cañada De La Yedra En Canena	1140	1182	1096	730	361	342
Embalse Del Centenillo	128	76	202	82	33	
Manantiales De Martos	961	915	1033	615	586	661
Río Cañamares En Chilluevar	602	550	942	385	352	603
Río Ceal En Huesa	598	574	664	383	367	425
Río Dañador Embalse Del Dañador	293	287	291	188	184	186
Río Beas Confluencia Con Río Guadalimar	801	810	755	513	518	483
Río Frío En Puente Jontoya	717	666	746	459	426	477
Río Guadalbullón En La Cerradura	1648	1579	1746	1055	1010	1064
Río Guadalbullón En Mengibar	2216	2071	2441	1418	1325	1562
Río Guadalbullón En Puente Tabla	1671	1471	1865	1070	941	1194
Río Guadalen Embalse Del Guadalen	405	403	397	259	258	254
Río Guadalentín En Canal Guadalentín	411	350	483	263	224	309
Río Guadalimar En Puente Genave	751	734	771	481	470	494
Río Guadalimar En Sabiote	715	718	698	458	460	447
Río Guadalimar En Torreblascopedro	796	915	706	509	586	452
Río Guadalmena En Albadalejo	803	852	747	514	545	478
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	519	556	475	332	356	304
Río Guadalquivir Aguas Abajo De Pedro Marín	1356	1554	1216	868	995	753
Río Guadalquivir Embalse De Mengibar	1308	1350	1192	837	864	763
Río Guadalquivir En Arroyo Maria	434	448	422	278	287	270
Río Guadalquivir En Arroyo Martingordo	1336	1568	1115	855	1003	714
Río Guadalquivir En Marmolejo	1194	1385	1019	764	887	652
Río Guadalquivir En Mengibar	1366	1623	1190	874	1038	761
Río Guadalquivir En Mogón	455	456	444	291	302	287

Río Guadiana Menor En Posito	2682	2649	2706	1717	1695	1732
Río Guadiel En Bailén	1031	982	1074	660	628	687
Río Guadiel En Ctra Linares-Baño De L A Encina	1047	1000	1072	670	640	686
Río Guarrizas Embalse De La Fernandina	269	284	262	172	182	168
Río Guarrizas Embalse Panzacola	252	242	250	162	152	160
Río Guarrizas En Aldea Quemada	290	294	285	186	188	182
Río Hornos En Orcera	717	718	705	459	460	451
Río Jándula Embalse Del Encinarejo	500	497	500	320	318	320
Río Jándula En La Ropera	573	571	599	367	365	383
Río Jandulilla En Bélmez De La Moraleda	1752	1576	1896	1121	1009	1213
Río Quiebrajano Embalse Del Quiebrajano	495	501	495	317	321	317
Río Rumblar Embalse Del Rumblar	353	353	359	226	226	230
Río Rumblar En Zocueca	286	292	271	183	183	173
Río San Juan En Castillo De Locubín	1186	1154	1203	759	738	770
Río Torres En Puente Del Obispo	7415	7112	6912	4746	4552	4424
Río Vega De Cazorla En Santo Tomé	716	689	773	459	441	495
Río Viboras En Alcaudete	1858	1703	2022	1189	1090	1294
Arroyo Salado	24476	25365	18346	15665	16234	11741
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	1385	1729	686	886	1106	439
Arroyo Salado En Porcuna	3220	4078	2909	2061	2610	1861
Cabecera Del Río Guadalquivir	394	395	376	252	253	240
Río Jándula En La Alameda	1743	1804	1686	1115	1154	1079
Río Aguasmulas En Coto Ríos	368	460	288	235	295	184
Río Borosa Antes De Confluencia Con Río Guadalquivir	295	276	301	189	176	193
Río Carrizas Puente Sobre El Río	756	649	863	484	416	552
Río Cuadros En Area Recreativa Río Cuadros	857	805	909	548	515	582
Río De Los Molinos Puente Sobre El Carril	558	573	498	357	366	319
Río Grande Puente Jv-5030	1147	957	1337	734	612	856
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	718	927	508	459	593	325
Río Guadalen Vado Del Carril	439	439	440	281	281	282

Río Guadalmena Embalse Guadalmena	664	694	625	425	444	400
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	1701	1815	1211	1089	1162	775
Río Guadalmena En Ctra Cm-412	903	862	947	578	467	606
Río Jandula Aguas Abajo Embalse Del Encinarejo	533	479	536	341	306	343
Río San Juan Tras La Confluencia Con El Río Caicena	3131	2904	3495	2004	1858	2236
Río Trujala Camino Segura De La Sierra	692	633	716	443	405	458
Río Valderazo Vado Del Camino Forestal	600	701	500	384	448	320
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	2357	2327	1410	1509	1489	902
Río Yeguas Aguas Arriba Embalse Del Yeguas	97	99	86	62	63	55
Río Yeguas Embalse Del Yeguas	149	154	144	95	99	92

SAR y SARadj

ESTACIONES	RAS Anual (mEq/L)	RAS Ajustada Anual (mEq/L)
Río Ceal En Huesa	0,378	2,478
Río Dañador Embalse Del Dañador	0,514	1,814
Río Beas Confluencia Con Río Guadalimar	0,225	2,825
Río Guadalbullón En La Cerradura	1,647	4,147
Río Guadalbullón En Mengibar	3,711	6,311
Río Guadalbullón En Puente Tabla	2,13	4,53
Río Guadalen Embalse Del Guadalen	0,608	2,408
Río Guadalentín En Canal Guadalentín	0,161	2,261
Río Guadalimar En Puente Genave	0,515	2,915
Río Guadalimar En Sabiote	0,415	2,815
Río Guadalimar En Torreblascopedro	1,091	3,491
Río Guadalmena En Albadalejo	0,397	2,797
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	0,356	2,456
Río Guadalquivir Aguas Abajo De Pedro Marín	3,288	5,588
Río Guadalquivir Embalse De Mengibar	2,994	5,394
Río Guadalquivir En Arroyo Maria	0,243	2,443
Río Guadalquivir En Arroyo Martingordo	1,98	4,38
Río Guadalquivir En Marmolejo	2,069	4,469
Río Guadalquivir En Mengibar	2,641	5,041
Río Guadalquivir En Mogón	0,133	2,433
Río Guadiana Menor En Posito	4,725	7,225
Río Guadiel En Bailén	2,192	4,592
Río Guadiel En Ctra Linares-Baño De L A Encina	1,908	4,508
Río Guarrizas Embalse Panzacola	0,639	2,139
Río Guarrizas En Aldea Quemada	0,563	2,163
Río Hornos En Orcera	0,34	2,84
Río Jándula Embalse Del Encinarejo	2,104	3,604
Río Jándula En La Ropera	1,97	3,67
Río Jandulilla En Bélmez De La Moraleda	0,588	3,188
Río Quiebrajano Embalse Del Quiebrajano	0,24	2,24
Río Rumblar Embalse Del Rumblar	0,363	1,963
Río Rumblar En Zocueca	0,377	1,877
Río San Juan En Castillo De Locubín	0,574	2,974
Río Torres En Puente Del Obispo	10,126	12,826
Río Vega De Cazorla En Santo Tomé	0,672	3,172
Río Viboras En Alcaudete	2,208	4,408
Arroyo Salado	57,203	59,803
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	1,758	4,158
Arroyo Salado En Porcuna	11,416	13,816

Cabecera Del Río Guadalquivir	0,144	2,344
Río Jándula En La Alameda	7,463	9,563
Río Aguasmulas En Coto Ríos	0,15	2,25
Río Borosa Antes De Confluencia Con Río Guadalquivir	0,205	2,305
Río Carrizas Puente Sobre El Río	0,453	2,953
Río Cuadros En Area Recreativa Río Cuadros	2,452	4,552
Río De Los Molinos Puente Sobre El Carril	0,362	2,762
Río Grande Puente Jv-5030	0,279	2,479
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	1,215	3,215
Río Guadalen Vado Del Carril	0,507	2,607
Río Guadalmena Embalse Guadalmena	0,351	2,451
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	2,073	4,673
Río Guadalmena En Ctra Cm-412	0,472	2,972
Río Jandula Aguas Abajo Embalse Del Encinarejo	2,128	3,828
Río San Juan Tras La Confluencia Con El Río Caicena	5,57	8,07
Río Trujala Camino Segura De La Sierra	0,663	3,163
Río Valderazo Vado Del Camino Forestal	0,35	2,55
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	4,294	6,794
Río Yeguas Aguas Arriba Embalse Del Yeguas	0,602	1,602
Río Yeguas Embalse Del Yeguas	0,56	1,46

Calcio, magnesio y sodio

ESTACIONES	Ca^{2+} Anual mg/L	Ca^{2+} OCT-MAR mg/L	Ca^{2+} ABR-SEP mg/L	Mg^{2+} Anual mg /L	Mg^{2+} OCT-MAR mg/L	Mg^{2+} ABR-SEP mg/)	Na^{+} Anual mg/L	Na^{+} OCT-MAR mg/)	Na^{+} ABR-SEP mg/L
Río Ceal En Huesa	78	88	68	19	21	16	15	21	8
Río Dañador Embalse Del Dañador	22	22	22	9	9	9	11	12	11
Río Beas Confluencia Con Río Guadalimar	97	99	95	57	57	57	11	13	10
Río Guadalbullón En La Cerradura	237	243	226	65	65	65	107	109	108
Río Guadalbullón En Mengibar	217	208	230	59	53	67	243	232	243
Río Guadalbullón En Puente Tabla	177	175	176	43	36	48	120	109	138
Río Guadalen Embalse Del Guadalen	39	39	38	15	14	16	22	22	17
Río Guadalentín En Canal Guadalentín	42	41	46	17	17	17	5	5	5
Río Guadalimar En Puente Genave	84	84	87	41	37	42	24	25	22
Río Guadalimar En Sabiote	88	86	86	47	45	50	21	25	14
Río Guadalimar En Torreblascopedro	80	90	71	40	43	37	49	68	51
Río Guadalmena En Albadalejo	99	99	84	42	42	40	20	21	16
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	61	65	57	29	31	27	14	16	11
Río Guadalquivir Aguas Abajo De Pedro Marín	130	115	138	45	31	53	197	208	307
Río Guadalquivir Embalse De Mengibar	130	119	126	47	31	55	136	138	128
Río Guadalquivir En Arroyo Maria	55	58	52	25	26	24	9	9	9
Río Guadalquivir En Arroyo Martingordo	138	158	106	48	45	51	107	140	65
Río Guadalquivir En Marmolejo	109	125	95	55	60	50	104	130	93
Río Guadalquivir En Mengibar	134	146	116	37	40	33	133	156	117
Río Guadalquivir En Mogón	62	60	63	29	32	23	5	5	5
Río Guadiana Menor En Posito	234	235	237	84	82	87	341	368	314
Río Guadiel En Bailén	83	82	85	22	22	22	86	86	91
Río Guadiel En Ctra Linares-Baño De L A Encina	104	103	108	34	33	34	111	106	93
Río Guarrizas Embalse De La Fernandina	32	32					18	18	

Río Guarrizas Embalse Panzacola	28	29	27	11	12	10	15	17	14
Río Guarrizas En Aldea Quemada	37	45	35	19	21	19	17	15	22
Río Hornos En Orcera	85	84	93	45	47	45	17	18	13
Río Jándula Embalse Del Encinarejo	27	27	28	14	14	14	58	62	66
Río Jándula En La Ropera	45	56	38	13	13	13	62	66	65
Río Jandulilla En Bélmez De La Moraleda	197	195	178	58	58	57	40	43	31
Río Quiebrajano Embalse Del Quiebrajano	75	79	75	17	22	14	10	11	8
Río Rumblar Embalse Del Rumblar	33	36	26	14	16	12	12	12	9
Río Rumblar En Zocueca	32	31	31	11	7	13	9	10	9
Río San Juan En Castillo De Locubín	183	186	176	41	35	44	41	41	31
Río Torres En Puente Del Obispo	357	316	429	89	74	113	1193	1116	1042
Río Vega De Cazorla En Santo Tomé	74	98	65	37	36	37	29	36	26
Río Viboras En Alcaudete	134	134	128	33	32	32	135	132	108
Arroyo Salado	838	895	482	134	141	105	6823	7078	4416
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	143	166	96	46	56	29	96	122	54
Arroyo Salado En Porcuna	242	292	225	44	46	46	737	629	825
Cabecera Del Río Guadalquivir	57	58	59	20	17	27	5	5	5
Río Jándula En La Alameda	68	79	60	35	38	34	304	238	360
Río Aguasmulas En Coto Ríos	56	67	48	19	37	10	5	5	5
Río Borosa Antes De Confluencia Con Río Guadalquivir	50	48	52	16	17	16	7	5	8
Río Carrizas Puente Sobre El Río	77	69	84	48	42	53	21	19	23
Río Cuadros En Area Recreativa Río Cuadros	72	72	72	14	15	13	87	88	86
Río De Los Molinos Puente Sobre El Carril	61	63	59	40	42	38	15	17	9
Río Grande Puente Jv-5030	122	102	141	98	78	116	17	17	17
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	72	84	60	21	22	20	47	69	26
Río Guadalen Vado Del Carril	46	52	41	26	24	27	17	14	21

Río Guadalmena Embalse Guadalmena	67	64	69	34	34	34	14	13	15
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	219	246	136	59	62	52	134	138	122
Río Guadalmena En Ctra Cm-412	67	61	71	50	48	52	21	23	16
Río Jandula Aguas Abajo Embalse Del Encinarejo	52	47	53	12	12	12	64	53	69
Río San Juan Tras La Confluencia Con El Río Caicena	283	270	296	53	51	60	390	377	446
Río Trujala Camino Segura De La Sierra	74	73	74	48	43	50	30	22	35
Río Valderazo Vado Del Camino Forestal	92	91	93	22	33	12	14	17	12
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	193	191	180	40	37	40	258	238	141
Río Yeguas Aguas Arriba Embalse Del Yeguas	11	11	11	5	5	6	10	11	8
Río Yeguas Embalse Del Yeguas	14	13	17	5	5	5	10	10	9

Bicarbonatos y carbonatos

ESTACIONES	HCO_3^- Media Anual (mg/L)	HCO_3^- Media OCT-MAR (mg/L)	HCO_3^- Media ABR-SEP (mg/L)	CO_3^{2-} Media Anual (mg/L)	CO_3^{2-} Media OCT-MAR (mg/L)	CO_3^{2-} Media ABR-SEP (mg/L)
Río Ceal En Huesa	230	224	236	2	2	2
Río Dañador Embalse Del Dañador	79	72	85	2	2	2
Río Beas Confluencia Con Río Guadalimar	359	372	346	2	2	3
Río Guadalbullón En La Cerradura	247	253	238	2	2	2
Río Guadalbullón En Mengibar	309	318	298	2	2	2
Río Guadalbullón En Puente Tabla	257	275	213	2	2	2
Río Guadalen Embalse Del Guadalen	130	137	123	4	2	6
Río Guadalentín En Canal Guadalentín	213	213	216	2	2	2
Río Guadalimar En Puente Genave	322	315	325	3	3	2
Río Guadalimar En Sabiote	303	312	257	3	3	2
Río Guadalimar En Torreblascopedro	265	295	234	7	2	9
Río Guadalmena En Albadalejo	290	306	244	2	2	2
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	251	262	237	4	4	5
Río Guadalquivir Aguas Abajo De Pedro Marín	269	268	278	2	2	2
Río Guadalquivir Embalse De Mengibar	300	315	265	3	2	4
Río Guadalquivir En Arroyo Maria	255	264	247	3	5	2
Río Guadalquivir En Arroyo Martingordo	283	280	278	2	2	2
Río Guadalquivir En Marmolejo	250	272	226	5	5	6
Río Guadalquivir En Mengibar	305	320	266	2	1	4
Río Guadalquivir En Mogón	267	274	260	2	2	2
Río Guadiana Menor En Posito	233	245	225	2	2	2
Río Guadiel En Bailén	363	353	372	2	2	2
Río Guadiel En Ctra Linares-Baño De L A Encina	425	436	359	2	2	2
Río Guarrizas Embalse De La Fernandina	102	102		2	2	
Río Guarrizas Embalse Panzacola	97	100	90	2	2	3

Río Guarrizas En Aldea Quemada	101	102	114	3	2	4
Río Hornos En Orcera	345	351	340	2	3	2
Río Jándula Embalse Del Encinarejo	95	95	95	5	3	7
Río Jándula En La Ropera	148	155	130	2	2	2
Río Jandulilla En Bélmez De La Moraleda	259	259	246	2	2	2
Río Quiebrajano Embalse Del Quiebrajano	189	216	172	2	2	2
Río Rumblar Embalse Del Rumblar	82	89	65	2	2	2
Río Rumblar En Zocueca	86	84	89	2	2	2
Río San Juan En Castillo De Locubín	248	255	236	2	2	2
Río Torres En Puente Del Obispo	261	271	260	2	2	2
Río Vega De Cazorla En Santo Tomé	336	369	316	2	1	2
Río Viboras En Alcaudete	166	184	144	2	2	2
Arroyo Salado	126	131	137	3	3	2
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	274	337	212	2	2	2
Arroyo Salado En Porcuna	232	209	251	2	2	2
Cabecera Del Río Guadalquivir	266	265	268	2	2	4
Río Jándula En La Alameda	231	228	240	2	2	2
Río Aguasmulas En Coto Ríos	218	254	189	2	2	2
Río Borosa Antes De Confluencia Con Río Guadalquivir	226	233	223	2	2	2
Río Carrizas Puente Sobre El Río	375	373	377	2	2	3
Río Cuadros En Area Recreativa Río Cuadros	221	219	224	2	3	2
Río De Los Molinos Puente Sobre El Carril	335	348	310	2	2	2
Río Grande Puente Jv-5030	98	89	107	2	2	2
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	209	220	199	2	2	2
Río Guadalen Vado Del Carril	223	239	208	3	4	2
Río Guadalmena Embalse Guadalmena	185	182	188	2	2	2
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	310	323	246	2	2	2
Río Guadalmena En Ctra Cm-412	346	345	344	2	2	2
Río Jandula Aguas Abajo Embalse Del Encinarejo	109	92	127	2	2	2

Río San Juan Tras La Confluencia Con El Río Caicena	246	243	270	2	2	2
Río Trujala Camino Segura De La Sierra	385	363	395	2	2	2
Río Valderazo Vado Del Camino Forestal	266	299	233	2	2	2
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	276	281	225	2	2	2
Río Yeguas Aguas Arriba Embalse Del Yeguas	53	50	56	2	2	2
Río Yeguas Embalse Del Yeguas	58	55	67	2	2	2

Carbonato sódico residual

ESTACIONES	Carbonato Sódico Residual Anual (mEq/L)	RSC OCT-MAR (mEq/L)	RSC. ABR-SEP (mEq/L)
Río Ceal En Huesa	1,628	2,418	0,838
Río Dañador Embalse Del Dañador	0,534	0,624	0,445
Río Beas Confluencia Con Río Guadalimar	3,641	3,498	3,743
Río Guadalbullón En La Cerradura	13,166	13,41	12,775
Río Guadalbullón En Mengibar	10,653	9,523	12,148
Río Guadalbullón En Puente Tabla	8,196	7,233	9,252
Río Guadalen Embalse Del Guadalen	0,987	0,868	1,002
Río Guadalentín En Canal Guadalentín	0,018	0,098	0,11
Río Guadalimar En Puente Genave	2,239	2,037	2,467
Río Guadalimar En Sabiote	3,277	2,822	4,179
Río Guadalimar En Torreblascopedro	2,78	3,152	2,498
Río Guadalmena En Albadalejo	3,63	3,384	3,426
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	1,204	1,428	0,998
Río Guadalquivir Aguas Abajo De Pedro Marín	5,777	3,879	6,684
Río Guadalquivir Embalse De Mengibar	5,438	3,285	6,414
Río Guadalquivir En Arroyo Maria	0,542	0,54	0,501
Río Guadalquivir En Arroyo Martingordo	6,171	7,017	4,943
Río Guadalquivir En Marmolejo	5,724	6,643	5,023
Río Guadalquivir En Mengibar	4,732	5,378	4,047
Río Guadalquivir En Mogón	1,089	1,147	0,73
Río Guadiana Menor En Posito	14,841	14,487	15,362
Río Guadiel En Bailén	0,021	0,063	0,099
Río Guadiel En Ctra Linaresbaño De L A Encina	0,979	0,656	2,327
Río Guarrizas Embalse De La Fernandina	0,136	0,136	0
Río Guarrizas Embalse Panzacola	0,685	0,776	0,635
Río Guarrizas En Aldea Quemada	1,679	2,261	1,317

Río Hornos En Orcera	2,252	2,254	2,727
Río Jándula Embalse Del Encinarejo	0,811	0,827	0,779
Río Jándula En La Ropera	0,835	1,261	0,834
Río Jandulilla En Bélmez De La Moraleda	10,358	10,318	9,57
Río Quiebrajano Embalse Del Quiebrajano	1,982	2,168	2,029
Río Rumblar Embalse Del Rumblar	1,441	1,631	1,219
Río Rumblar En Zocueca	1,048	0,725	1,116
Río San Juan En Castillo De Locubín	8,487	7,949	8,545
Río Torres En Puente Del Obispo	20,94	17,455	26,485
Río Vega De Cazorla En Santo Tomé	1,237	1,792	1,121
Río Viboras En Alcaudete	6,661	6,272	6,671
Arroyo Salado	50,896	54,251	30,587
Arroyo Salado De Arjona En La Ctra Marmolejoarjonilla	6,451	7,364	3,679
Arroyo Salado En Porcuna	11,954	14,952	10,897
Cabecera Del Río Guadalquivir	0,099	0,074	0,665
Río Jándula En La Alameda	2,5	3,309	1,851
Río Aguasmulas En Coto Ríos	0,773	2,199	0,077
Río Borosa Antes De Confluencia Con Río Guadalquivir	0,092	0,096	0,185
Río Carrizas Puente Sobre El Río	1,635	0,769	2,371
Río Cuadros En Area Recreativa Río Cuadros	1,063	1,167	0,958
Río De Los Molinos Puente Sobre El Carril	0,862	0,827	0,955
Río Grande Puente Jv5030	12,588	10,081	14,858
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	1,892	2,383	1,359
Río Guadalen Vado Del Carril	0,7	0,559	0,842
Río Guadalmena Embalse Guadalmena	3,039	3,001	3,077
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	10,737	12,163	7,076
Río Guadalmena En Ctra Cm412	1,712	1,264	2,155
Río Jandula Aguas Abajo Embalse Del Encinarejo	1,737	1,775	1,489
Río San Juan Tras La Confluencia Con El Río Caicena	14,471	13,688	15,344

Río Trujala Camino Segura De La Sierra	1,322	1,216	1,312
Río Valderazo Vado Del Camino Forestal	2,053	2,318	1,787
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	8,334	7,959	8,547
Río Yeguas Aguas Arriba Embalse Del Yeguas	0,087	0,103	0,053
Río Yeguas Embalse Del Yeguas	0,098	0,091	0,116

Dureza del agua

ESTACIONES	Dureza Media Anual (mg/l de CaCO3)	D Media Anual ((ºfH) Franceses)	D Media Anual ((ºdH) Alemanes)
Río Ceal En Huesa	272,397	27,24	15,303
Río Dañador Embalse Del Dañador	94,021	9,402	5,282
Río Beas Confluencia Con Río Guadalimar	479,775	47,977	26,954
Río Guadalbullón En La Cerradura	862,932	86,293	48,479
Río Guadalbullón En Mengibar	788,335	78,833	44,288
Río Guadalbullón En Puente Tabla	622,828	62,283	34,99
Río Guadalen Embalse Del Guadalen	161,726	16,173	9,086
Río Guadalentín En Canal Guadalentín	177,044	17,704	9,946
Río Guadalimar En Puente Genave	380,006	38,001	21,349
Río Guadalimar En Sabiote	416,151	41,615	23,379
Río Guadalimar En Torreblascopedro	366,591	36,659	20,595
Río Guadalmena En Albadalejo	422,111	42,211	23,714
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	272,918	27,292	15,332
Río Guadalquivir Aguas Abajo De Pedro Marín	511,578	51,158	28,74
Río Guadalquivir Embalse De Mengibar	522,006	52,201	29,326
Río Guadalquivir En Arroyo Maria	240,656	24,066	13,52
Río Guadalquivir En Arroyo Martingordo	542,709	54,271	30,489
Río Guadalquivir En Marmolejo	499,562	49,956	28,065
Río Guadalquivir En Mengibar	489,612	48,961	27,506
Río Guadalquivir En Mogón	276,585	27,658	15,538
Río Guadiana Menor En Posito	934,958	93,496	52,526
Río Guadiel En Bailén	299,327	29,933	16,816
Río Guadiel En Ctra Linares-Baño De L A Encina	400,205	40,021	22,483
Río Guarrizas Embalse De La Fernandina	79,5	7,95	4,466
Río Guarrizas Embalse Panzacola	117,28	11,728	6,589

Río Guarrizas En Aldea Quemada	170,678	17,068	9,589
Río Hornos En Orcera	399,4	39,94	22,438
Río Jándula Embalse Del Encinarejo	126,02	12,602	7,08
Río Jándula En La Ropera	165,78	16,578	9,313
Río Jandulilla En Bélmez De La Moraleda	732,586	73,259	41,157
Río Quiebrajano Embalse Del Quiebrajano	256,475	25,647	14,409
Río Rumblar Embalse Del Rumblar	142,258	14,226	7,992
Río Rumblar En Zocueca	125,623	12,562	7,057
Río San Juan En Castillo De Locubín	630,708	63,071	35,433
Río Torres En Puente Del Obispo	1263,496	126,35	70,983
Río Vega De Cazorla En Santo Tomé	339,357	33,936	19,065
Río Viboras En Alcaudete	472,051	47,205	26,52
Arroyo Salado	2651,999	265,2	148,989
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	549,921	54,992	30,894
Arroyo Salado En Porcuna	790,094	79,009	44,387
Cabecera Del Río Guadalquivir	227,223	22,722	12,765
Río Jándula En La Alameda	317,521	31,752	17,838
Río Aguasmulas En Coto Ríos	220,562	22,056	12,391
Río Borosa Antes De Confluencia Con Río Guadalquivir	193,213	19,321	10,855
Río Carrizas Puente Sobre El Río	392,236	39,224	22,036
Río Cuadros En Area Recreativa Río Cuadros	238,305	23,831	13,388
Río De Los Molinos Puente Sobre El Carril	320,626	32,063	18,013
Río Grande Puente Jv-5030	712,062	71,206	40,003
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	268,78	26,878	15,1
Río Guadalen Vado Del Carril	222,665	22,267	12,509
Río Guadalmena Embalse Guadalmena	306,829	30,683	17,238
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	793,554	79,355	44,582
Río Guadalmena En Ctra Cm-412	372,694	37,269	20,938

Río Jandula Aguas Abajo Embalse Del Encinarejo	179,466	17,947	10,082
Río San Juan Tras La Confluencia Con El Río Caicena	927,242	92,724	52,092
Río Trujala Camino Segura De La Sierra	384,111	38,411	21,579
Río Valderazo Vado Del Camino Forestal	323,217	32,322	18,158
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	646,041	64,604	36,294
Río Yeguas Aguas Arriba Embalse Del Yeguas	50,425	5,043	2,833
Río Yeguas Embalse Del Yeguas	55,479	5,548	3,117

Cloruro

ESTACIONES	Cl^- Media Anual (mg/L)	Cl^- Media OCT-MAR (mg/L)	Cl^- Media ABR-SEP (mg/L)
Aguascebas Y/O Río Guadalquivir En Mogón	7,845	8,776	7,5
Embalse Del Centenillo	6,784	7,183	7,183
Manantiales De Martos	65,286	60,269	69,76
Río Cañamares En Chilluevar	21,221	16,953	48,175
Río Ceal En Huesa	24,449	25,253	21,015
Río Dañador Embalse Del Dañador	19,283	18,433	19,772
Río Beas Confluencia Con Río Guadalimar	18,967	17,624	20,217
Río Frío En Puente Jontoya	30,558	28,869	29,964
Río Guadalbullón En La Cerradura	174,756	171,325	200,525
Río Guadalbullón En Mengibar	375,931	363,483	399,116
Río Guadalbullón En Puente Tabla	201,216	163,058	245,267
Río Guadalen Embalse Del Guadalen	29,887	31,011	26,265
Río Guadalentín En Canal Guadalentín	11,307	7,744	15,586
Río Guadalimar En Puente Genave	39,864	43,558	34,748
Río Guadalimar En Sabiote	32,955	33,032	32,631
Río Guadalimar En Torreblascopedro	70,119	86,897	54,569
Río Guadalmena En Albadalejo	26,635	28,759	23,275
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	36,185	39,928	32,956
Río Guadalquivir Aguas Abajo De Pedro Marín	234,335	268,76	235,157
Río Guadalquivir Embalse De Mengibar	195,868	221,219	154,857
Río Guadalquivir En Arroyo Maria	14,315	13,886	15,079
Río Guadalquivir En Arroyo Martingordo	166,534	200,655	117,094
Río Guadalquivir En Marmolejo	149,797	179,545	123,024
Río Guadalquivir En Mengibar	203,476	249,843	153,135
Río Guadalquivir En Mogón	9,885	8,731	10,82
Río Guadiana Menor En Posito	550,056	569,729	526,997
Río Guadiel En Bailén	91,659	87,07	95,57
Río Guadiel En Ctra Linares-Baño De L A Encina	133,108	140,167	85,125

Río Guarrizas Embalse De La Fernandina	20,992	22,65	20,163
Río Guarrizas Embalse Panzacola	26,975	38,47	16,468
Río Guarrizas En Aldea Quemada	25,102	23,654	26,124
Río Hornos En Orcera	36,778	33,983	43,2
Río Jándula Embalse Del Encinarejo	51,862	51,72	51,804
Río Jándula En La Ropera	62,279	57,89	70,905
Río Jandulilla En Bélmez De La Moraleda	206,151	133,592	290,789
Río Quiebrajano Embalse Del Quiebrajano	16,135	14,776	17,937
Río Rumblar Embalse Del Rumblar	19,572	19,177	21,895
Río Rumblar En Zocueca	12,411	12,949	10,896
Río San Juan En Castillo De Locubín	56,573	59,156	55,721
Río Torres En Puente Del Obispo	2629,276	2663,564	1400,233
Río Vega De Cazorla En Santo Tomé	37,351	34,572	42,086
Río Viboras En Alcaudete	349,56	342,321	393,626
Arroyo Salado	10850,35	11258,475	7062,5
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	157,575	200,167	73,9
Arroyo Salado En Porcuna	1175,4	1227,75	1159,975
Cabecera Del Río Guadalquivir	10,513	9,025	16
Río Jándula En La Alameda	240,175	186,725	283,875
Río Aguasmulas En Coto Ríos	17,104	24,4	9,5
Río Borosa Antes De Confluencia Con Río Guadalquivir	8,992	5,75	11,075
Río Carrizas Puente Sobre El Río	36,225	34,425	38,025
Río Cuadros En Area Recreativa Río Cuadros	142,413	137,575	147,25
Río De Los Molinos Puente Sobre El Carril	31,5	31,875	30,325
Río Grande Puente Jv-5030	31,492	31,625	28,475
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	106,763	144,425	69,1
Río Guadalen Vado Del Carril	19,713	12,55	26,875
Río Guadalmena Embalse Guadalmena	26,464	25,538	27,767
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	331,913	402,925	204
Río Guadalmena En Ctra Cm-412	36,363	39,717	33,3
Río Jandula Aguas Abajo Embalse Del Encinarejo	57,754	55,375	56,725

Río San Juan Tras La Confluencia Con El Río Caicena	682,888	648,7	839,25
Río Trujala Camino Segura De La Sierra	41,033	34,034	44,75
Río Valderazo Vado Del Camino Forestal	30,725	36,725	24,725
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	386,325	374,1	208,7
Río Yeguas Aguas Arriba Embalse Del Yeguas	20,975	22,375	19,45
Río Yeguas Embalse Del Yeguas	13,238	13,742	12,525

Sulfatos y fosfatos

ESTACIONES	SO_4^- Media Anual (mg/L)	SO_4^- Media OCT-MAR (mg/L)	SO_4^- Media ABR-SEP (mg/L)	PO_4^{2-} Media Anual (mg/L)	PO_4^{2-} Media OCT-MAR (mg/L)	PO_4^{2-} Media ABR-SEP (mg/L)
Aguascebas Y/O Río Guadalquivir En Mogón	23,977	19,448	32,769	0,106	0,115	0,094
Cañada De La Yedra En Canena						
Embalse Del Centenillo	9,344	6,525	14,25	0,023		0,023
Manantiales De Martos	231,411	239,557	268,733	0,447	0,445	0,395
Río Cañamares En Chilluevar	52,208	37,72	142,4	0,195	0,176	0,257
Río Ceal En Huesa	76,073	85,895	61,031	0,29	0,36	0,106
Río Dañador Embalse Del Dañador	35,303	34,929	31,681	0,096	0,09	0,099
Río Beas Confluencia Con Río Guadalimar	131,089	130,135	134,911	0,98	0,897	1,11
Río Frío En Puente Jontoya	123,897	102,444	152,293	0,214	0,221	0,231
Río Guadalbullón En La Cerradura	501,543	458,958	563,133	0,219	0,249	0,142
Río Guadalbullón En Mengibar	489,625	437,586	555,32	1,999	2,566	1,248
Río Guadalbullón En Puente Tabla	433,701	389,159	487,539	0,36	0,344	0,353
Río Guadalen Embalse Del Guadalen	45,47	43,345	47,013	0,592	0,742	0,418
Río Guadalentín En Canal Guadalentín	24,071	11,6	32,488	0,121	0,142	0,115
Río Guadalimar En Puente Genave	120,562	102,283	161,524	0,226	0,201	0,258
Río Guadalimar En Sabiote	118,133	115,815	123,741	0,257	0,302	0,173
Río Guadalimar En Torreblascopedro	144,727	164,269	125,84	1,437	1,779	1,186
Río Guadalmena En Albadalejo	219,284	256,038	187,304	0,175	0,186	0,116
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	45,611	53,091	37,344	0,172	0,194	0,127
Río Guadalquivir Aguas Abajo De Pedro Marín	252,88	298,948	186,479	0,222	0,332	0,093
Río Guadalquivir Embalse De Mengibar	224,725	252,64	195,458	0,631	0,895	0,232
Río Guadalquivir En Arroyo Maria	27,457	28,104	26,948	0,1	0,101	0,088
Río Guadalquivir En Arroyo Martingordo	269,324	301,223	212,407	1,365	1,635	1,096
Río Guadalquivir En Marmolejo	227,532	260,681	201,76	0,895	1,269	0,469
Río Guadalquivir En Mengibar	249,941	276,296	228,56	1,163	1,75	0,475
Río Guadalquivir En Mogón	39,041	41,555	37,487	0,127	0,169	0,111

Río Guadiana Menor En Posito	662,441	644,775	694,257	0,205	0,224	0,186
Río Guadiel En Bailén	114,143	115,988	112,717	6,786	6,08	7,54
Río Guadiel En Ctra Linares-Baño De L A Encina	148,569	135,2	169,825	2,154	1,954	0,854
Río Guarrizas Embalse De La Fernandina	35,034	33,7	35,7	0,226	0,18	0,271
Río Guarrizas Embalse Panzacola	33,318	30,779	33,667	0,088	0,087	0,102
Río Guarrizas En Aldea Quemada	40,533	39,985	40,606	0,203	0,142	0,255
Río Hornos En Orcera	80,208	88,978	72,5	0,188	0,197	0,18
Río Jándula Embalse Del Encinarejo	105,665	94,84	120,04	0,221	0,182	0,232
Río Jándula En La Ropera	105,795	107,481	92,713	0,169	0,17	0,159
Río Jandulilla En Bélmez De La Moraleda	611,508	531,268	731,122	0,186	0,178	0,155
Río Quiebrajano Embalse Del Quiebrajano	86,317	90,799	82,674	0,17	0,122	0,243
Río Rumblar Embalse Del Rumblar	73,39	71,856	75,061	0,1	0,13	0,091
Río Rumblar En Zocueca	57,655	59,444	62,127	0,14	0,12	0,148
Río San Juan En Castillo De Locubín	349,876	346,283	368,025	0,18	0,18	0,18
Río Torres En Puente Del Obispo	1051,078	985,19	856,357	0,398	0,522	0,13
Río Vega De Cazorla En Santo Tomé	92,607	81,162	105,782	1,861	1,795	0,95
Río Viboras En Alcaudete	382,157	377,05	414,718	0,264	0,36	0,099
Arroyo Salado	2637,117	2821,475	1547,3	0,176	0,174	0,18
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	277,038	355,734	146,6	0,415	0,485	0,348
Arroyo Salado En Porcuna	456,879	445,6	485,4	3,989	4,212	4,54
Cabecera Del Río Guadalquivir	15,413	14,825	14,9	0,177	0,174	0,18
Río Jándula En La Alameda	446,5	395,475	483,25	1,329	0,731	1,762
Río Aguasmulas En Coto Ríos	26,292	39,55	12,9	0,218	0,256	0,18
Río Borosa Antes De Confluencia Con Río Guadalquivir	12,925	12,5	13,35	0,177	0,174	0,18
Río Carrizas Puente Sobre El Río	78,3	40,375	116,225	0,304	0,174	0,434
Río Cuadros En Area Recreativa Río Cuadros	51,663	49,95	53,375	0,174	0,174	0,174
Río De Los Molinos Puente Sobre El Carril	31,625	32,25	30,05	0,177	0,176	0,18
Río Grande Puente Jv-5030	541,925	406,575	677,275	0,197	0,174	0,22
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	79,3	107,5	51,1	0,518	0,601	0,436
Río Guadalen Vado Del Carril	47,275	33,375	61,175	0,18	0,18	0,18

Río Guadalmena Embalse Guadalmena	139,785	136,198	146,267	0,177	0,175	0,18
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	303,275	308,3	290,4	0,228	0,174	0,384
Río Guadalmena En Ctra Cm-412	199,65	163,542	253,175	0,177	0,176	0,18
Río Jandula Aguas Abajo Embalse Del Encinarejo	90,017	79,225	92,425	0,182	0,18	0,183
Río San Juan Tras La Confluencia Con El Río Caicena	538,338	555,725	442,4	0,205	0,235	0,172
Río Trujala Camino Segura De La Sierra	54,2	42,592	62,9	0,177	0,174	0,18
Río Valderazo Vado Del Camino Forestal	88,875	97,2	80,55	0,177	0,174	0,18
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	354,163	340,9	348,05	0,219	0,237	0,18
Río Yeguas Aguas Arriba Embalse Del Yeguas	13,575	13,125	15	0,18	0,18	0,18
Río Yeguas Embalse Del Yeguas	12,563	11,717	12,5	0,177	0,176	0,18

Nitratos y amonio

ESTACIONES	NO_3^- Media Anual (mg/L)	NO_3^- Media OCT-MAR (mg/L)	NO_3^- Media ABR-SEP (mg/L)	NH_4^+ Media Anual (mg/L)	NH_4^+ Media OCT-MAR (mg/L)	NH_4^+ Media ABR-MAR (mg/L)
Aguascebas Y/O Río Guadalquivir En Mogón	5,037	6,051	4,692	0,193	0,185	0,231
Cañada De La Yedra En Canena	13,717	26,7	11,825	13,03	15,72	9,439
Embalse Del Centenillo	1,592	2,778	1,3	0,084	0,109	0,079
Manantiales De Martos	9,698	10,064	10,227	0,296	0,293	0,276
Río Cañamares En Chilluevar	6,255	4,93	20,3	0,088	0,083	0,12
Río Ceal En Huesa	4,791	5,656	2,334	0,253	0,371	0,135
Río Dañador Embalse Del Dañador	2,98	3,193	2,708	0,213	0,212	0,226
Río Beas Confluencia Con Río Guadalimar	20,064	20,105	21,394	0,724	0,874	0,567
Río Frío En Puente Jontoya	13,037	14,269	12,567	0,693	0,343	0,945
Río Guadalbullón En La Cerradura	9,59	9,923	9,456	0,278	0,218	0,365
Río Guadalbullón En Mengibar	20,604	20,237	20,514	3,475	4,952	1,305
Río Guadalbullón En Puente Tabla	12,221	13,492	9,031	0,904	0,674	1,123
Río Guadalen Embalse Del Guadalen	4,699	6,938	2,743	0,527	0,856	0,267
Río Guadalentín En Canal Guadalentín	2,075	1,995	1,736	0,181	0,232	0,162
Río Guadalimar En Puente Genave	6,837	7,108	6,819	0,238	0,245	0,216
Río Guadalimar En Sabiote	11,245	11,703	11,381	0,221	0,203	0,232
Río Guadalimar En Torreblascopedro	8,6	10,712	7,919	0,904	1,035	0,83
Río Guadalmena En Albadalejo	5,827	7,127	3,964	0,209	0,255	0,151
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	7,107	8,71	5,044	0,307	0,343	0,251
Río Guadalquivir Aguas Abajo De Pedro Marín	13,453	14,779	10,39	0,564	0,974	0,229
Río Guadalquivir Embalse De Mengibar	15,812	17,706	11,936	1,009	1,304	0,583
Río Guadalquivir En Arroyo Maria	3,22	4,581	2,333	0,219	0,195	0,231
Río Guadalquivir En Arroyo Martingordo	11,734	13,553	10,648	1,429	2,248	0,599
Río Guadalquivir En Marmolejo	11,093	12,64	10,017	1,007	1,372	0,553
Río Guadalquivir En Mengibar	12,064	14,165	10,479	2,388	2,72	2,123
Río Guadalquivir En Mogón	6,777	8,26	5,787	0,153	0,176	0,154
Río Guadiana Menor En Posito	6,362	7,518	5,975	0,32	0,337	0,334
Río Guadiel En Bailén	7,715	9,315	5,155	26,049	24,201	27,85

Río Guadiel En Ctra Linares-Baño De L A Encina	12,408	10,09	24,467	13,425	16,709	7,002
Río Guarrizas Embalse De La Fernandina	0,892	0,525	1,075	0,3	0,579	0,02
Río Guarrizas Embalse Panzacola	3,037	3,921	2,454	0,198	0,19	0,193
Río Guarrizas En Aldea Quemada	2,564	2,943	2,179	0,153	0,13	0,172
Río Hornos En Orcera	13,79	12,96	15,217	0,257	0,235	0,261
Río Jándula Embalse Del Encinarejo	2,914	2,998	2,792	0,337	0,414	0,234
Río Jándula En La Ropera	4,067	3,831	3,763	0,331	0,414	0,213
Río Jandulilla En Bélmez De La Moraleda	12,305	12,602	10,913	0,499	0,593	0,364
Río Quiebrajano Embalse Del Quiebrajano	6,597	6,161	7,406	0,214	0,184	0,223
Río Rumblar Embalse Del Rumblar	2,16	2,768	1,416	0,21	0,21	0,177
Río Rumblar En Zocueca	2,498	2,834	2,53	0,179	0,185	0,179
Río San Juan En Castillo De Locubín	10,588	10,445	11,083	0,24	0,262	0,261
Río Torres En Puente Del Obispo	26,163	29,486	26,283	0,903	1,425	0,314
Río Vega De Cazorla En Santo Tomé	10,721	12,599	10,608	1,389	0,571	1,848
Río Viboras En Alcaudete	7,174	7,157	7,442	0,359	0,389	0,373
Arroyo Salado	33,8	29,2	59,9	0,089	0,088	0,09
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	18,45	19,8	11,9	6,792	7,617	5,5
Arroyo Salado En Porcuna	18,129	17,5	18,5	11,726	9,345	14,425
Cabecera Del Río Guadalquivir	1,425	1,25	2	0,101	0,096	0,09
Río Jándula En La Alameda	24,659	14,3	29,575	0,25	0,42	0,186
Río Aguasmulas En Coto Ríos	2,017	2,225	1,875	0,207	0,258	0,157
Río Borosa Antes De Confluencia Con Río Guadalquivir	3,692	2,425	5,075	0,09	0,092	0,09
Río Carrizas Puente Sobre El Río	15,513	12,25	18,775	0,129	0,102	0,156
Río Cuadros En Area Recreativa Río Cuadros	3,563	4,05	3,075	0,186	0,089	0,284
Río De Los Molinos Puente Sobre El Carril	5,104	7,775	1,3	0,088	0,084	0,102
Río Grande Puente Jv-5030	1,175	1,85	0,5	0,146	0,096	0,194
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	5,525	6,375	4,675	0,511	0,521	0,503
Río Guadalen Vado Del Carril	2,809	4,975	0,2	0,108	0,101	0,114
Río Guadalmena Embalse Guadalmena	4,2	4,61	3,1	0,139	0,163	0,099
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	21,938	20,875	27,1	0,735	0,839	0,071

Río Guadalmena En Ctra Cm-412	8,775	8,617	7,75	0,1	0,085	0,144
Río Jandula Aguas Abajo Embalse Del Encinarejo	1,946	1,925	1,875	0,137	0,09	0,16
Río San Juan Tras La Confluencia Con El Río Caicena	13,013	14,225	16	0,239	0,102	0,62
Río Trujala Camino Segura De La Sierra	14,935	3,259	26,525	0,087	0,082	0,09
Río Valderazo Vado Del Camino Forestal	3,613	4,525	2,7	0,089	0,088	0,091
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	13,363	14,175	13,3	0,449	0,572	0,09
Río Yeguas Aguas Arriba Embalse Del Yeguas	1,867	1,95	1,8	0,137	0,12	0,171
Río Yeguas Embalse Del Yeguas	3,813	2,75	6,975	0,091	0,091	0,092

Potasio y boro

ESTACIONES	K^+ Media Anual (mg/L)	K^+ Media OCT-MAR (mg/L)	K^+ Media ABR-SEP (mg/L)	B Media Anual (mg/L)	B Media OCT-MAR (mg/L)	B Media ABR-SEP (mg/L)
Aguascebas Y/O Río Guadalquivir En Mogón	-	-	-	0,126	0,087	0,132
Cañada De La Yedra En Canena	-	-	-	-	-	-
Embalse Del Centenillo	-	-	-	-	-	-
Manantiales De Martos	-	-	-	0,419	0,371	0,327
Río Cañamares En Chilluevar	-	-	-	0,122	0,092	0,18
Río Ceal En Huesa	5,1	5,2	5	0,249	0,259	0,085
Río Dañador Embalse Del Dañador	5,263	5,525	5	0,24	0,237	0,11
Río Beas Confluencia Con Río Guadalimar	5,067	5	5,125	0,315	0,285	0,331
Río Frío En Puente Jontoya	-	-	-	0,24	0,239	0,228
Río Guadalbullón En La Cerradura	5,8	5,525	6,075	0,331	0,339	0,307
Río Guadalbullón En Mengibar	10,195	10,352	10,074	0,225	0,225	0,225
Río Guadalbullón En Puente Tabla	6,171	5,8	6,6	0,417	0,381	0,409
Río Guadalen Embalse Del Guadalen	7,109	6,525	7,65	0,277	0,167	0,36
Río Guadalentín En Canal Guadalentín	5	5	5	0,109	0,088	0,113
Río Guadalimar En Puente Genave	5,738	6,35	5,175	0,257	0,244	0,28
Río Guadalimar En Sabiote	8,3	8,175	8,425	0,331	0,395	0,266
Río Guadalimar En Torreblascopedro	10,605	12,163	9,231	0,118	0,135	0,1
Río Guadalmena En Albadalejo	5,05	5	5,2	0,207	0,234	0,204
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	3,09	3,229	3,117	0,167	0,167	0,15
Río Guadalquivir Aguas Abajo De Pedro Marín	6,25	6,334	6	0,325	0,356	0,261
Río Guadalquivir Embalse De Mengibar	5,678	5	6,383	0,39	0,45	0,27
Río Guadalquivir En Arroyo Maria	2,343	2,59	1,864	0,2	-	0,2
Río Guadalquivir En Arroyo Martingordo	7,274	8,9	5,308	0,473	0,492	0,384
Río Guadalquivir En Marmolejo	7,989	8,768	6,992	0,192	0,207	0,132
Río Guadalquivir En Mengibar	8,944	9,16	8,054	0,167	0,17	0,17
Río Guadalquivir En Mogón	5	5	5	0,194	0,206	0,128
Río Guadiana Menor En Posito	8,603	8,591	9,104	0,393	0,265	0,563
Río Guadiel En Bailén	18,499	17,273	19,774	0,388	0,505	0,265
Río Guadiel En Ctra Linares-Baño De L A Encina	11,346	10,55	11,925	-	-	-
Río Guarrizas Embalse Panzacola	7,1	5,1	7,2	0,116	0,088	0,119
Río Guarrizas En Aldea Quemada	5	5	5	-	-	-
Río Hornos En Orcera	5,238	5,284	5,1	-	-	-

Río Jándula Embalse Del Encinarejo	4,497	4,946	4,5	0,1	0,1	-
Río Jándula En La Ropera	6,3	6,35	6,25	0,2	0,2	-
Río Jandulilla En Bélmez De La Moraleda	5,75	5,775	5,725	0,539	0,495	0,564
Río Quiebrajano Embalse Del Quiebrajano	5	5	5	0,155	0,147	0,138
Río Rumblar Embalse Del Rumblar	5,55	5,75	5,35	0,223	0,226	0,131
Río Rumblar En Zocueca	5,2	5	5,3	0,215	0,095	0,294
Río San Juan En Castillo De Locubín	5,05	5	5,075	0,1	0,1	0,1
Río Torres En Puente Del Obispo	15,784	13,125	20	0,613	0,601	0,453
Río Vega De Cazorla En Santo Tomé	3,316	2,784	3,854	0,249	0,217	0,266
Río Viboras En Alcaudete	6,45	6,467	5,5	0,255	0,292	0,134
Arroyo Salado	39,034	39,034	32	-	-	-
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	14,1	14,1	9,8	0,14	0	0,14
Arroyo Salado En Porcuna	18,809	18,809	21,75	-	-	-
Cabecera Del Río Guadalquivir	5	5	5	-	-	-
Río Jándula En La Alameda	15,817	15,817	19,125	-	-	-
Río Aguasmulas En Coto Ríos	5	5	5	-	-	-
Río Borosa Antes De Confluencia Con Río Guadalquivir	4,398	4,398	5	-	-	-
Río Carrizas Puente Sobre El Río	5,209	5,209	5,05	-	-	-
Río Cuadros En Area Recreativa Río Cuadros	5	5	5	-	-	-
Río De Los Molinos Puente Sobre El Carril	5	5	5	-	-	-
Río Grande Puente Jv-5030	7,6	7,6	8,65	-	-	-
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	9,759	9,759	8,15	-	-	-
Río Guadalen Vado Del Carril	5	5	5	-	-	-
Río Guadalmena Embalse Guadalmena	5,3	5,3	5,45	0,097	0,095	0,1
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	9,275	9,275	5	-	-	-
Río Guadalmena En Ctra Cm-412	5,163	5,163	5,625	-	-	-
Río Jandula Aguas Abajo Embalse Del Encinarejo	5,238	5,238	5,2	-	-	-
Río San Juan Tras La Confluencia Con El Río Caicena	15,338	15,338	6,15	-	-	-
Río Trujala Camino Segura De La Sierra	5,263	5,35	5,175	-	-	-
Río Valderazo Vado Del Camino Forestal	5	5	5	-	-	-
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	7,45	7,45	5,8	-	-	-
Río Yeguas Aguas Arriba Embalse Del Yeguas	5	5	5	-	-	-
Río Yeguas Embalse Del Yeguas	5	5	5	-	-	-

pH

ESTACIONES	pH Media Anual (un. pH)	pH Media OCT-MAR (un. pH)	pH Media ABR-SEP (un. pH)
Aguascebas Y/O Río Guadalquivir En Mogón	8,034	8,003	8,036
Cañada De La Yedra En Canena	7,901	7,826	8,014
Embalse Del Centenillo	6,814	6,744	6,944
Manantiales De Martos	8,131	8,134	8,127
Río Cañamares En Chilluevar	7,863	7,922	7,725
Río Ceal En Huesa	7,84	7,853	7,798
Río Dañador Embalse Del Dañador	7,832	7,673	8,049
Río Beas Confluencia Con Río Guadalimar	7,898	7,763	8,126
Río Frío En Puente Jontoya	7,992	8,046	7,936
Río Guadalbullón En La Cerradura	7,993	7,988	8,031
Río Guadalbullón En Mengibar	7,855	7,821	7,841
Río Guadalbullón En Puente Tabla	7,989	7,963	7,988
Río Guadalen Embalse Del Guadalen	8,169	7,677	8,626
Río Guadalentín En Canal Guadalentín	7,939	8,093	7,778
Río Guadalimar En Puente Genave	8,076	8,034	8,102
Río Guadalimar En Sabiote	8,038	8,063	7,993
Río Guadalimar En Torreblascopedro	7,815	7,748	7,907
Río Guadalmena En Albadalejo	8,1	8,047	8,139
Río Guadalquivir Aguas Abajo Embalse Puente De La Cerrada	8,07	8,052	8,093
Río Guadalquivir Aguas Abajo De Pedro Marín	7,993	7,954	8,004
Río Guadalquivir Embalse De Mengibar	7,909	7,777	8,007
Río Guadalquivir En Arroyo Maria	7,976	7,959	7,989
Río Guadalquivir En Arroyo Martingordo	7,684	7,615	7,745
Río Guadalquivir En Marmolejo	7,694	7,627	7,759
Río Guadalquivir En Mengibar	7,827	7,802	7,846
Río Guadalquivir En Mogón	8,043	8	8,073
Río Guadiana Menor En Posito	7,956	7,986	7,911
Río Guadiel En Bailén	7,651	7,588	7,713
Río Guadiel En Ctra Linares-Baño De L A Encina	7,828	7,697	7,96
Río Guarrizas Embalse De La Fernandina	8,042	8,1	8,013
Río Guarrizas Embalse Panzacola	7,767	7,647	7,928
Río Guarrizas En Aldea Quemada	7,769	7,533	8,036
Río Hornos En Orcera	7,991	7,972	8,022
Río Jándula Embalse Del Encinarejo	7,873	7,795	7,95
Río Jándula En La Ropera	7,936	7,867	7,996
Río Jandulilla En Bélmez De La Moraleda	7,909	7,872	7,975
Río Quiebrajano Embalse Del Quiebrajano	7,976	7,963	7,992
Río Rumblar Embalse Del Rumblar	7,657	7,522	7,917

Río Rumblar En Zocueca	7,593	7,612	7,57
Río San Juan En Castillo De Locubín	7,942	7,932	7,948
Río Torres En Puente Del Obispo	7,894	7,794	8,042
Río Vega De Cazorla En Santo Tomé	8,06	8,057	8,15
Río Viboras En Alcaudete	8,051	8,053	8,026
Arroyo Salado	7,9	7,75	8,3
Arroyo Salado De Arjona En La Ctra Marmolejo-Arjonilla	8	8,084	7,85
Arroyo Salado En Porcuna	7,971	7,7	8,175
Cabecera Del Río Guadalquivir	8,188	8,25	7,95
Río Jándula En La Alameda	7,922	8,012	7,834
Río Aguasmulas En Coto Ríos	7,967	7,85	8,1
Río Borosa Antes De Confluencia Con Río Guadalquivir	8,017	8,2	7,925
Río Carrizas Puente Sobre El Río	7,963	7,85	8,075
Río Cuadros En Area Recreativa Río Cuadros	7,675	7,55	7,8
Río De Los Molinos Puente Sobre El Carril	8,25	8,467	7,85
Río Grande Puente Jv-5030	7,6	7,8	7,4
Río Guadalen Aguas Abajo Confluencia Con Río Guadalimar	7,775	7,975	7,575
Río Guadalen Vado Del Carril	7,425	6,975	7,875
Río Guadalmena Embalse Guadalmena	7,973	7,885	8,117
Río Guadalquivir Desde Sotogordo Hasta Embalse De Mengibar	8,125	8,1	8,3
Río Guadalmena En Ctra Cm-412	7,813	7,9	7,675
Río Jandula Aguas Abajo Embalse Del Encinarejo	8,079	8,225	8
Río San Juan Tras La Confluencia Con El Río Caicena	8,225	8,175	8,45
Río Trujala Camino Segura De La Sierra	7,71	7,675	7,75
Río Valderazo Vado Del Camino Forestal	7,95	8,075	7,825
Río Viboras Aguas Arriba Del Embalse Del Viboras Y Afluentes	8,125	8,05	8,3
Río Yeguas Aguas Arriba Embalse Del Yeguas	7,575	7,825	7,2
Río Yeguas Embalse Del Yeguas	7,731	7,584	7,879

Apéndice C) Clasificación hidroquímica: aguas subterráneas

Aguas subterráneas: ubicación centroide unidades hidrogeológicas

CODMAS	UD_HIDROGEOLÓGICA	X_UTM ETRS89 H30N	Y_UTM ETRS89 H30N
005.001	Sierra De Cazorla	511401,8100	4224594,4100
005.002	Quesada-Castril	517450,0200	4208528,7500
005.007	Úbeda	409561,4500	4162737,6100
005.013	Bailén-Guarromán-Linares	493451,0300	4163598,1000
005.014	Rumblar	468233,1400	4187010,9000
005.015	Aluvial Del Guadalquivir-Curso Medio	456274,7400	4186326,7900
005.016	Aluvial Del Guadalquivir-Curso Alto	422254,0400	4176022,4500
005.017	Porcuna	426205,1100	4180754,9900
005.018	Torres-Jimena	436166,0400	4177225,6700
005.019	Jaén	446781,2200	4178875,9400
005.020	Mancha Real-Pegalajar	451064,2000	4175728,7200
005.021	Almadén	462772,5300	4177723,6200
005.022	Guadahortuna-Larva	423152,8300	4165525,9000
005.023	Jabalcuz	477689,4100	4219303,0300
005.024	San Cristobal	439794,1800	4220626,6300
005.025	Grajales-Pandera-Carchel	422425,5100	4218479,2100
005.026	Mentidero-Montesinos	453881,9700	4203805,5800
005.027	Ahillo-Caracolera	402795,4700	4197772,0300
005.028	Montes Orientales. Sector Norte	428255,2400	4153296,8600
005.034	El Mencal	418418,1400	4140237,3500
005.037	Gracia-Ventisquero	412066,9900	4141687,5800
005.041	Albayate-Chanzas	472830,8000	4169674,2600
005.046	Madrid-Parapanda	395904,2100	4209739,7100
005.066	Bedmar-Jódar	435853,1600	4169128,4600
005.070	Sierra Mágina	426022,7900	4158806,5100
070.017	Acuíferos Inferíores De La Sierra De Segura	537167,3500	4226305,4300

Aguas subterráneas: Subunidades hidrogeológicas

Nº	Unidad Hidrogeológica	Subunidades
05.01	Cazorla	Beas de Segura Sierra de Cazorla
05.02	Quesada-Castril	Norte Sierra de Segura: Relieve invertido Jurásica Sierra de Pozo, Castril y Seca: Pliegues-Falla Central o de Pilar Negro
05.07	Ahillo-Caracolera	Ahillo Caracolera-Chircales
05.14	Bedmar-Jodar	Bedmar-Jodar La Golondrina
05.15	Torres-Jimena	Aznatín Jimena
05.16	Jabalcuz	Lías de Jabalcuz Dogger de Jabalcuz Cerro Fuente
05.17	Jaén	Castillo-La Imora Peña de Jaén
05.18	San Cristóbal	
05.19	Mancha Real-Pegalajar	
05.20	Almadén	
05.21	Sierra Mágina	Sierra Mágina Carcheles-Carluco
05.22	Mentidero-Montesinos	Mentidero Montesinos
05.23	Úbeda	
05.24	Bailén-Guarroman	Bailén-Guarroman Linares
05.25	Rumblar	
05.26	Aluvial del Guadalquivir Curso Alto	
05.27	Porcuna	
05.28	Montes Orientales	Frailes-Boleta Frailes-Montillana Sierra del Trigo-Puerto Arenas Fresnedilla-Pico Madera Alta Coloma Alcalá La Real-Santa Ana La Camuña Charilla Vadillo San Pedro-La Rábita
05.41	Guadahortuna-Larva	Guadahortuna Larva-Solera
05.46	Aluvial del Guadalquivir Curso Medio	
05.66	Grajales-Pandera-Carchel	Grajales-Pandera Carchel
05.70	Gracia-Ventisquero	Ventisquero Cornicabra-Noguerones Gracia-Morenita

Conductividad eléctrica y sales totales

Nº	Unidad Hidrogeológica	ECw (µS/cm)			Concentr. Sales Totales (mg/L)
		Medio	Máximo	Mínimo	
05.01	Cazorla	1.717	6.719	482	573
05.02	Quesada-Castril	377	685	214	278
05.07	Ahillo-Caracolera	1.057	2.420	570	676
05.14	Bedmar-Jodar	480	566	394	554
05.15	Torres-Jimena	295	500	219	249
05.16	Jabalcuz	979	5.370	300	987
05.17	Jaén	687	2.250	230	553
05.18	San Cristóbal	1.351	6.000	430	480
05.19	Mancha Real-Pegalajar	457	894	334	357
05.20	Almadén	395	600	252	234
05.21	Sierra Mágina	915	1.037	794	340
05.22	Mentidero-Montesinos	801	370	517	513
05.23	Úbeda	1.070	3.251	256	524
05.24	Bailén-Guarroman-Linares	635	1.210	410	540
05.25	Rumblar	633	911	370	575
05.26	Aluvial del Guadalquivir Curso Alto	1.232	2.485	300	1.750
05.27	Porcuna	2.423	6.880	660	1.551
05.28	Montes Orientales Sector Norte	775	2.860	200	496
05.41	Guadahortuna-Larva	1.312	11.940	110	473
05.46	Aluvial del Guadalquivir Curso Medio	51	182	9	33
05.66	Grajales-Pandera-Carchel	425	721	264	311
05.70	Gracia-Ventisquero	604	1.405	236	447

SARy SAR_{adj}

Nº	Unidad Hidrogeológica	RAS Anual (mEq/L)	RAS Ajustada Anual (mEq/L)
05.01	Cazorla	1,881	3,893
05.02	Quesada-Castril	0,119	2,39
05.07	Ahillo-Caracolera	0,742	3,111
05.14	Bedmar-Jodar	0,69	3,182
05.15	Torres-Jimena	0,373	2,485
05.16	Jabalcuz	0,202	2,502
05.17	Jaén	0,303	2,564
05.18	San Cristóbal	1,468	3,568
05.19	Mancha Real-Pegalajar	0,566	2,886
05.20	Almadén	0,151	2,141
05.21	Sierra Mágina	0,454	2,486
05.22	Mentidero-Montesinos	0,14	2,388
05.23	Úbeda	2,113	5,268
05.24	Bailén-Guarroman-Linares	1,443	2,443
05.25	Rumblar	0,567	2,867
05.26	Aluvial del Guadalquivir Curso Alto	3,714	5,34
05.28	Montes Orientales Sector Norte	0,478	3,331
05.41	Guadahortuna-Larva	0,752	3,094
05.66	Grajales-Pandera-Carchel	0,034	1,834

Calcio, magnesio, sodio y pH

Nº	Unidad Hidrogeológica	Calcio Ca^{2+} (mg/L)	Magnesio Mg^{2+} (mg/L)	Sodio Na^{+} (mg/L)	pH
05.01	Cazorla	71,956	30,154	75,633	7,95
05.02	Quesada-Castril	61,571	25,024	4,381	8,04
05.07	Ahillo-Caracolera	102,333	26,083	32,583	7,73
05.14	Bedmar-Jodar	79,000	48,750	31,750	7,60
05.15	Torres-Jimena	56,500	14,643	12,214	7,74
05.16	Jabalcuz	192,500	72,500	13,000	7,80
05.17	Jaén	136,125	27,375	14,875	7,48
05.18	San Cristóbal	62,000	30,000	56,500	8,00
05.19	Mancha Real-Pegalajar	76,643	20,857	21,714	7,73
05.20	Almadén	52,333	15,333	4,833	7,92
05.21	Sierra Mágina	61,813	19,375	16,000	7,75
05.22	Mentidero-Montesinos	83,000	20,000	5,500	7,75
05.23	Úbeda	66,900	41,600	89,700	7,94
05.24	Bailén-Guarroman-Linares	93,500	25,000	61,000	5,70
05.25	Rumblar	120,000	31,000	27,000	8,20
05.26	Aluvial del Guadalquivir Curso Alto	220,000	59,000	241,000	-
05.28	Montes Orientales Sector Norte	136,607	41,429	24,929	7,49
05.41	Guadahortuna-Larva	83,389	29,222	31,444	7,91
05.66	Grajales-Pandera-Carchel	43,000	14,000	1,000	7,10
05.70	Gracia-Ventisquero	107,929	24,286	3,000	7,04

Cloruro, bicarbonatos y carbonatos

Nº	Unidad Hidrogeológica	Cloruro Cl^- (mg/L)	Bicarbonato HCO_3^- (mg/L)	Carbonato CO_3^{2-} (mg/L)
05.01	Cazorla	116,181	288,952	2,427
05.02	Quesada-Castril	6,810	359,548	1,328
05.07	Ahillo-Caracolera	53,917	245,083	1,333
05.14	Bedmar-Jodar	72,000	703,500	0,000
05.15	Torres-Jimena	13,429	305,786	3,583
05.16	Jabalcuz	10,500	134,000	0,000
05.17	Jaén	24,375	298,875	0,000
05.18	San Cristóbal	103,500	187,500	1,000
05.19	Mancha Real-Pegalajar	37,286	383,857	0,167
05.20	Almadén	7,167	195,333	0,000
05.21	Sierra Mágina	24,750	199,438	0,438
05.22	Mentidero-Montesinos	10,250	235,000	0,000
05.23	Úbeda	105,500	583,900	1,667
05.24	Bailén-Guarroman-Linares	90,500	325,000	0,000
05.25	Rumblar	35,000	247,000	3,000
05.26	Aluvial del Guadalquivir Curso Alto	375,000	177,000	0,000
05.28	Montes Orientales Sector Norte	53,036	614,929	0,000
05.41	Guadahortuna-Larva	57,444	416,500	3,800
05.66	Grajales-Pandera-Carchel	3,000	141,000	2,500
05.70	Gracia-Ventisquero	6,714	184,000	0,000

Carbonato sódico residual y dureza del agua

Nº	Unidad Hidrogeológica	RSC	D.A. (mg/L)	D.A. (ºfH)	D.A. (ºdH)
05.01	Cazorla	1,293	305,33	30,533	17,153
05.02	Quesada-Castril	0,775	258,028	25,803	14,496
05.07	Ahillo-Caracolera	3,228	364,34	36,434	20,469
05.14	Bedmar-Jodar	3,520	400,3	40,03	22,489
05.15	Torres-Jimena	1,087	202,164	20,216	11,358
05.16	Jabalcuz	13,470	782,85	78,285	43,98
05.17	Jaén	4,188	454,193	45,419	25,516
05.18	San Cristóbal	2,493	279,8	27,98	15,719
05.19	Mancha Real-Pegalajar	0,728	278,373	27,837	15,639
05.20	Almadén	0,692	194,62	19,462	10,934
05.21	Sierra Mágina	1,421	235,131	23,513	13,21
05.22	Mentidero-Montesinos	1,964	290,7	29,07	16,331
05.23	Úbeda	2,816	340,306	34,031	19,118
05.24	Bailén-Guarroman-Linares	1,430	337,75	33,775	18,975
05.25	Rumblar	4,434	428,96	42,896	24,099
05.26	Aluvial del Guadalquivir Curso Alto	13,015	795,44	79,544	44,688
05.28	Montes Orientales Sector Norte	0,202	513,861	51,386	28,869
05.41	Guadahortuna-Larva	0,350	330,037	33,004	18,541
05.66	Grajales-Pandera-Carchel	0,922	165,74	16,574	9,311
05.70	Gracia-Ventisquero	4,404	370,85	37,085	20,834

Sulfatos, Nitratos, Amonio, Fosfatos, Potasio y Boro

Nº	Unidad Hidrogeológica	Sulfato SO_4^{-} (mg/L)	Nitrato NO_3^{-} (mg/L)	Amonio NH_4^{+} (mg/L)	Fosfatos PO_4^{2-} (mg/L)	Potasio K^{+} (mg/L)	Boro B (mg/L)
05.01	Cazorla	54,233	7,748	0,095	0,005	1,448	-
05.02	Quesada-Castril	33,075	6,816	0,000	0,000	0,575	-
05.07	Ahillo-Caracolera	131,833	7,417	0,008	0,048	2,667	-
05.14	Bedmar-Jodar	204,000	24,000	-	-	-	-
05.15	Torres-Jimena	23,071	21,500	0,000	0,050	1,000	-
05.16	Jabalcuz	600,500	2,000	0,000	0,000	0,000	-
05.17	Jaén	265,500	30,833	0,000	0,002	1,167	-
05.18	San Cristóbal	86,500	9,500	0,000	0,000	1,000	-
05.19	Mancha Real-Pegalajar	50,643	9,250	0,006	0,000	1,333	-
05.20	Almadén	15,333	16,167	0,000	0,013	0,333	-
05.21	Sierra Mágina	35,188	36,000	0,016	0,000	0,250	-
05.22	Mentidero-Montesinos	69,000	11,000	0,000	0,005	1,250	-
05.23	Úbeda	97,800	54,500	1,750	0,000	4,625	-
05.24	Bailén-Guarroman-Linares	73,000	2,500	0,000	0,080	16,000	-
05.25	Rumblar	147,000	120,000	0,000	0,000	4,000	0,000
05.26	Aluvial del Guadalquivir Curso Alto	565,500	12,000	0,000		20,500	-
05.28	Montes Orientales Sector Norte	300,500	18,136	0,004	0,120	1,333	0,100
05.41	Guadahortuna-Larva	93,667	20,500	0,057	0,012	4,750	-
05.66	Grajales-Pandera-Carchel	32,000	6,500	0,000	0,000	-	-
05.70	Gracia-Ventisquero	181,571	28,429	0,011	0,019	0,429	-

Anexo 2. Capítulo 2 Supplementary data

Appendix A) Hydrochemical indices considered in the model

Residual sodium carbonate (RSC)

RSC = (CO_3^{-} + CO_3H^{-}) – (Ca^{2+} + Mg^{2+}), CO_3^{-} , CO_3H^{-}, Ca^{2+}, and Mg^{2+} being the concentration of these cations in water expressed in $mmol_c$ L^{-1}

Sodium adsorption ratio (SAR)

SAR = $Na^{+} \cdot [(Ca^{2+} + Mg^{2+})/2]^{1/2}$

Na^{+}, Ca^{2+}, and Mg^{2+} being the concentration of these cations in water expressed in $mmol_c$ L^{-1}

Adjusted sodium adsorption ratio (SAR_{adj})

SAR_{adj} = SAR x [1+ (8.4 - pH_c)]

Where:

$pH_c = (pk_2 – pk_c) + p(Ca^{2+} + Mg^{2+}) + p(Alk)$; p = – log

$(pk_2 – pk_c) = f\,(Ca^{2+} + Mg^{2+} + Na^{+})$;

p (Alk) = $f\,(CO_3^{2-} + HCO_3^{-})$

these both functions being described by Ayer and Westcot (1985)

Langelier index

Is = pH_w - pH_c

Where:

pH_w = pH of water

pHc = $(pk_2 – pk_c) + p(Ca^{2+}) + p(Alk)$

$(pk_2 – pk_c)$ and p(Alk) as defined above

Water hardness (French degrees, ºfH)

ºfH = (2.5 Ca^{2+} + 4.12 Mg^{2+})/10

Ca^{2+}, and Mg^{2+} being the concentration in water of these cations expressed in $mmol_c$ L^{-1}

Appendix B) Aridity index

Precipitation to potential evapotranspiration ratio on an annual basis; an aridity classification of land can be done on this basis (FAO, 1993):

$Ia = P/ET_0$

Aridity classes	P/ETP_0	Precipiation (mm)
Hyperarid	< 0,05	< 200 (annual)
Arid	$0.05 < P/ET_0 < 0.20$	< 400 (winter) or < 200 (summer)
Semiarid	$0.20 < P/ET_0 < 0.50$	400–600 (winter) or 200–500 (summer)
Dry - subhumid	$0.50 < P/ET_0 < 0.65$	600–800 (winter) or 500–700 (summer)

Appendix C) Description

The description of the operation with gvSIG and required links and options is described in this appendix. Between brackets we include the name in Spanish of the different links and options since the software is developed in Spanish.

Web gvSIG: http://www.gvsig.org/web.

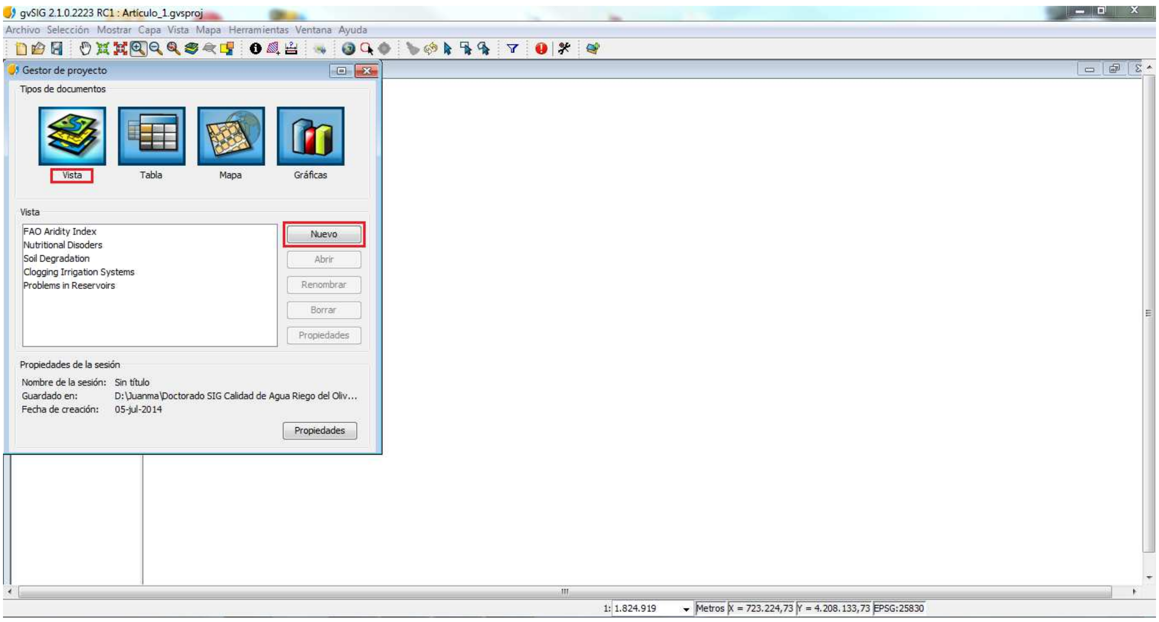
To download the program the link is: http://www.gvsig.org/plone/home/projects/gvsig-desktop/official/gvsig-2.1/descargas.

The program includes the SEXTANTE module which includes a submodule menu; each submodule implements one analytical process based on spatial analysis.

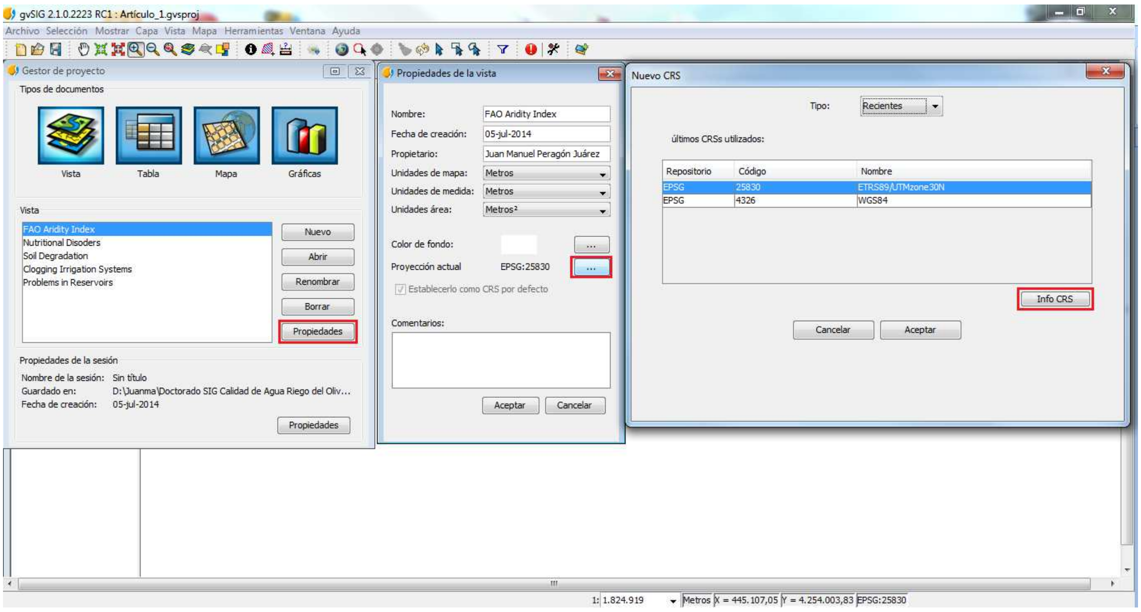
The SEXTANTE module includes a tutorial ("Ayuda") with the different commands for using each algorithm for calculation.

A) The sequence to begin to use the program is:

(i) To *create a new view* ("Vista" and then "Nuevo"),

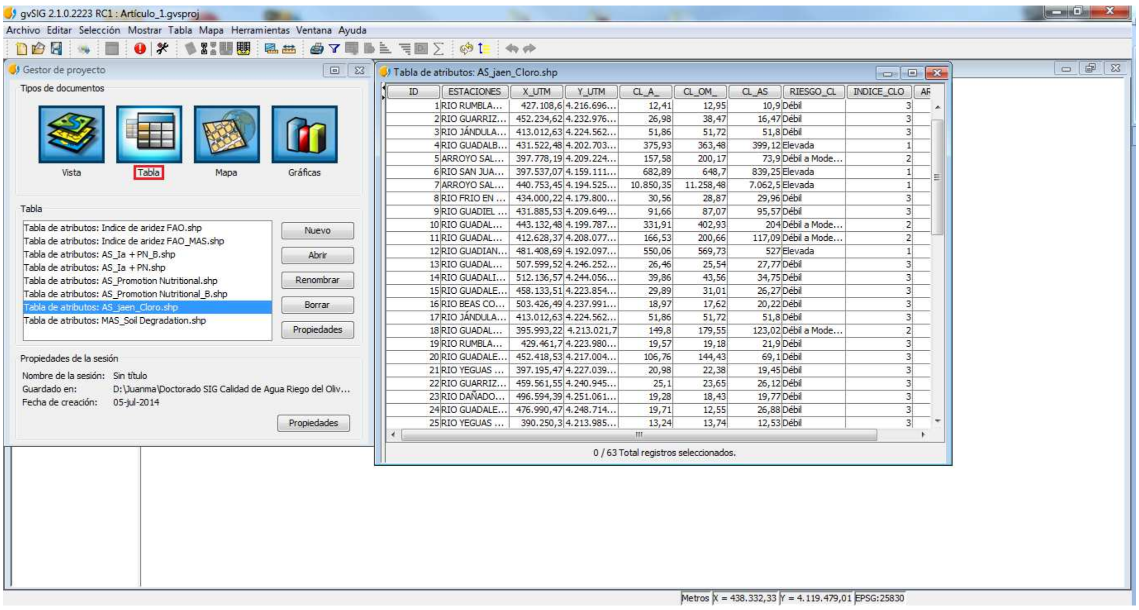


(ii) From the properties (“Propiedades”) of the new view, a *reference system* (CRS) can be created (UTM ETRS89 Huso 30N is the code 25830).

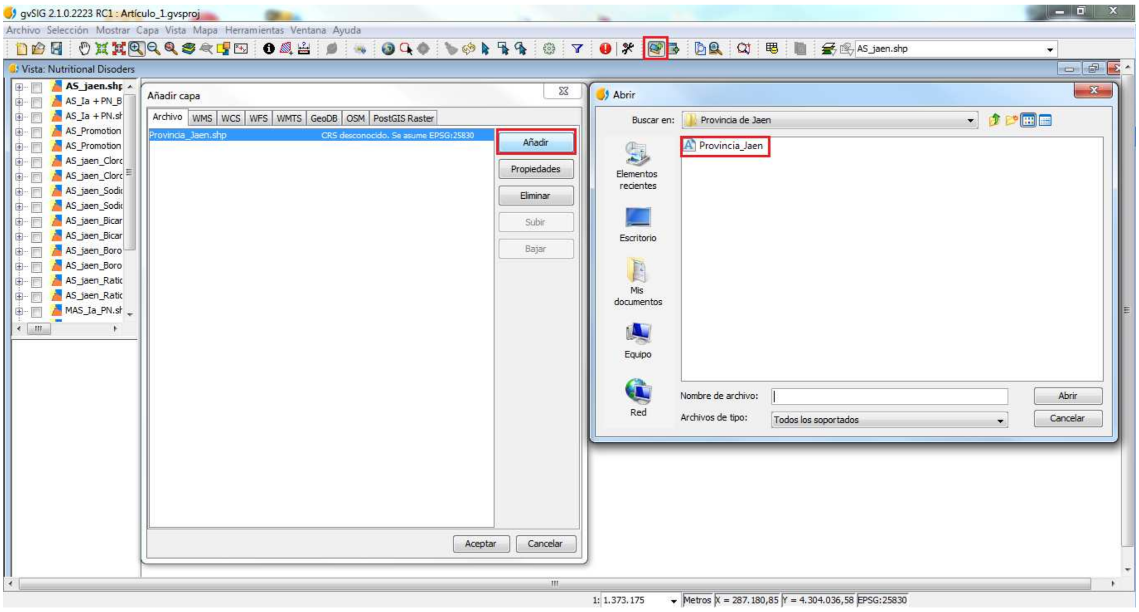


B) The sequence to perform a Kriging interpolation is:

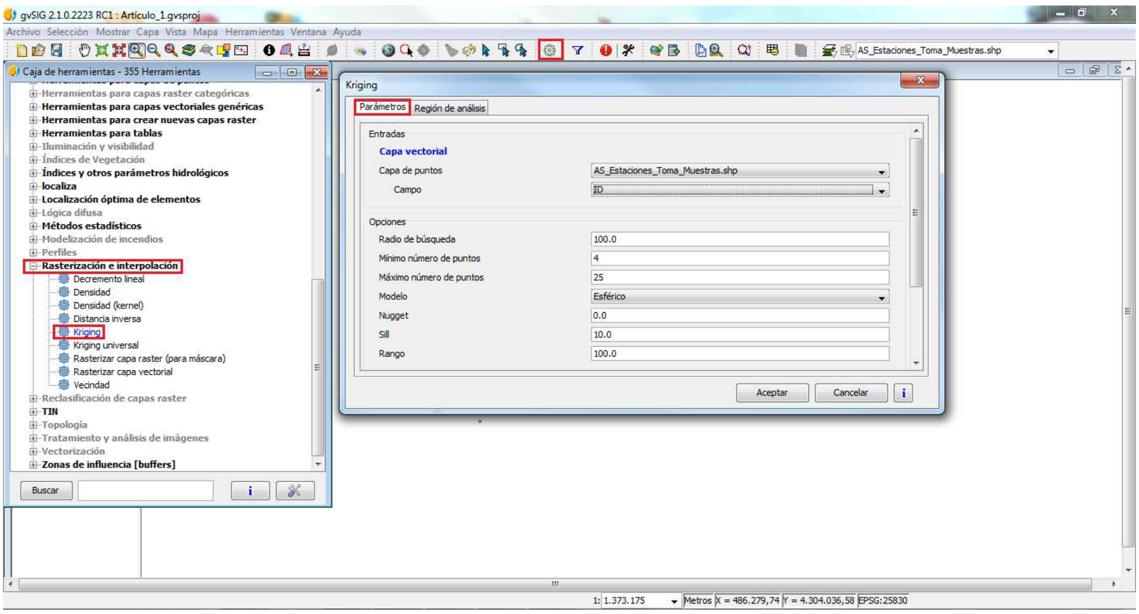
(i) Go to *tables* (“Tabla”) and add data from each sampling station (in this case defined as “estaciones”): geographical coordinates (location) and properties (in this case, water properties and hydrochemical indices) associated

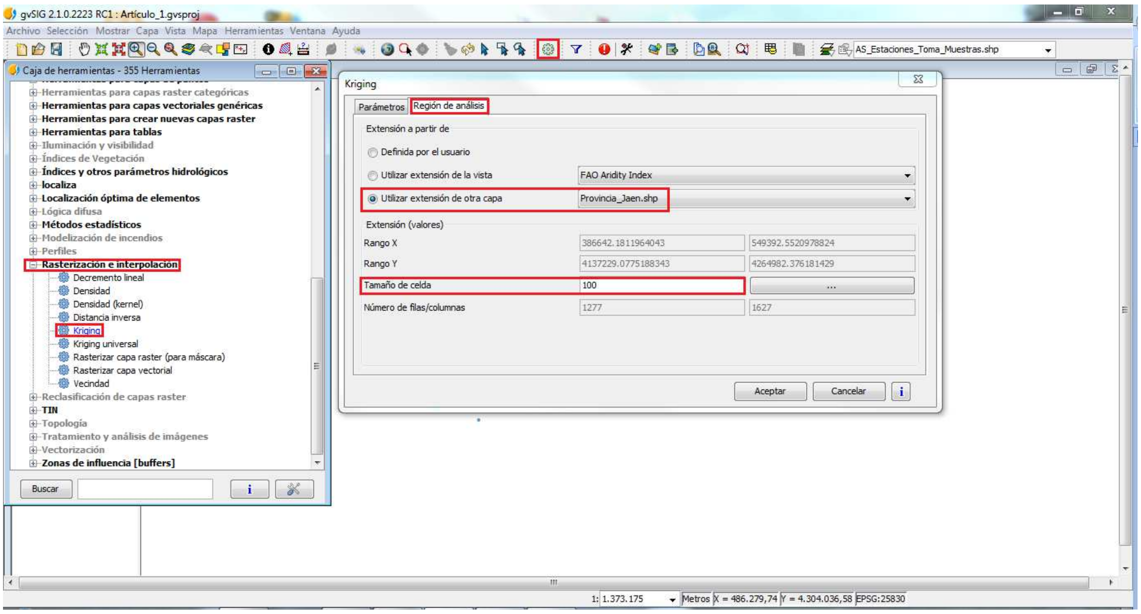


(ii) Go to *layer* (“Capas”) and add the geographic layer (Jaen province – “Provincia_Jaen” - in this case)

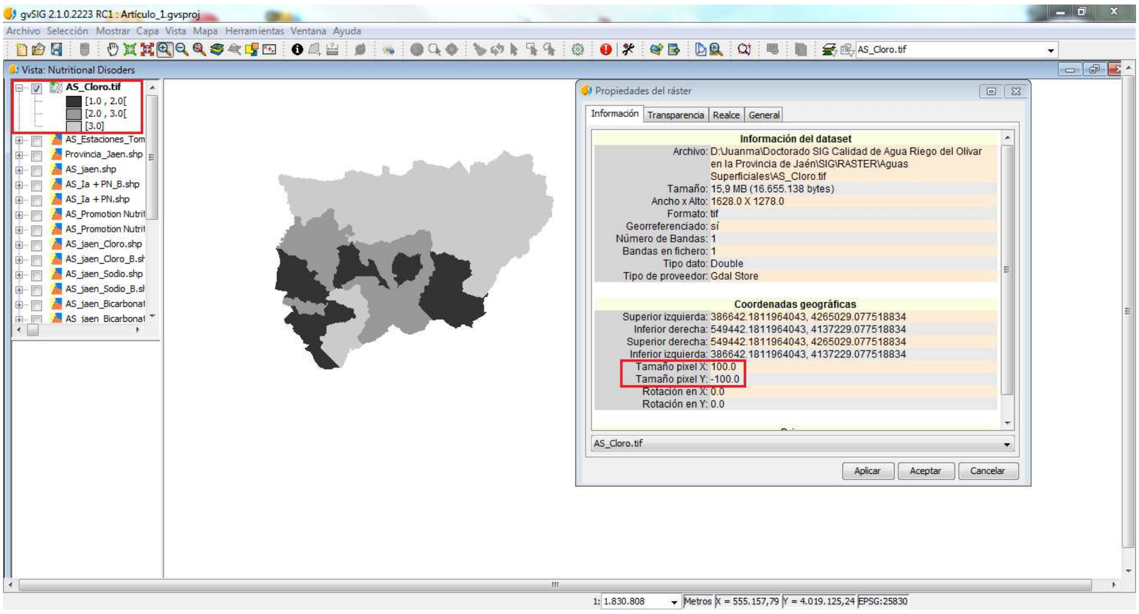


(iii) In SEXTANTE, go to *raster and interpolation* (“Rasterización e interpolación”) submodule; select the “kriging” algorithm; now you can select the layer and the table of data that is going to be interpolated and the extension for the new “layer” file which are going to be generated.



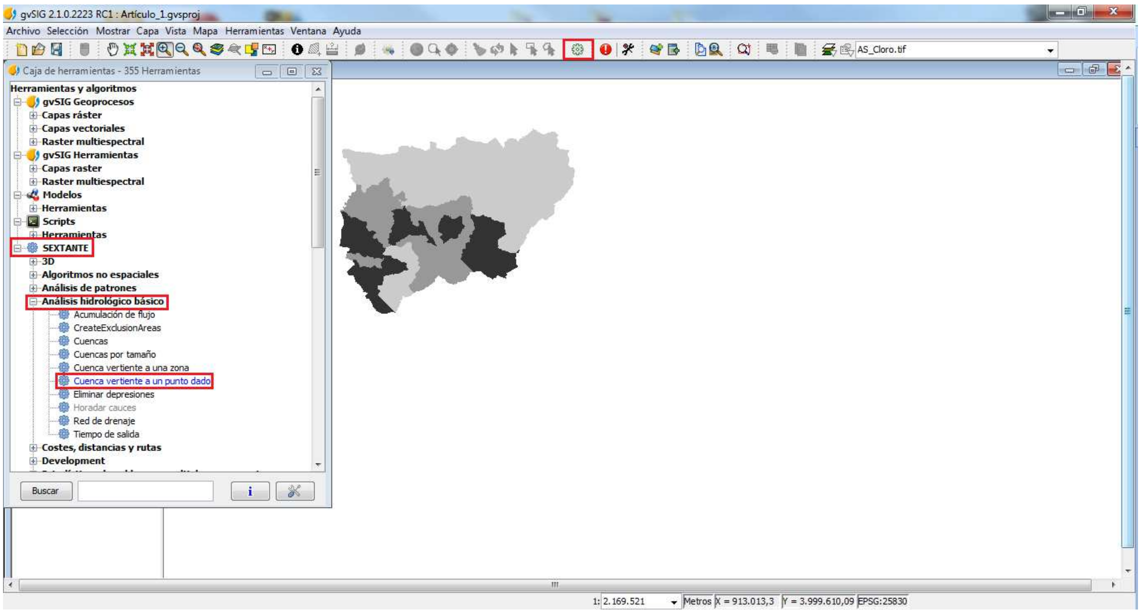


(iv) A georeferenced raster.tiff file is released.

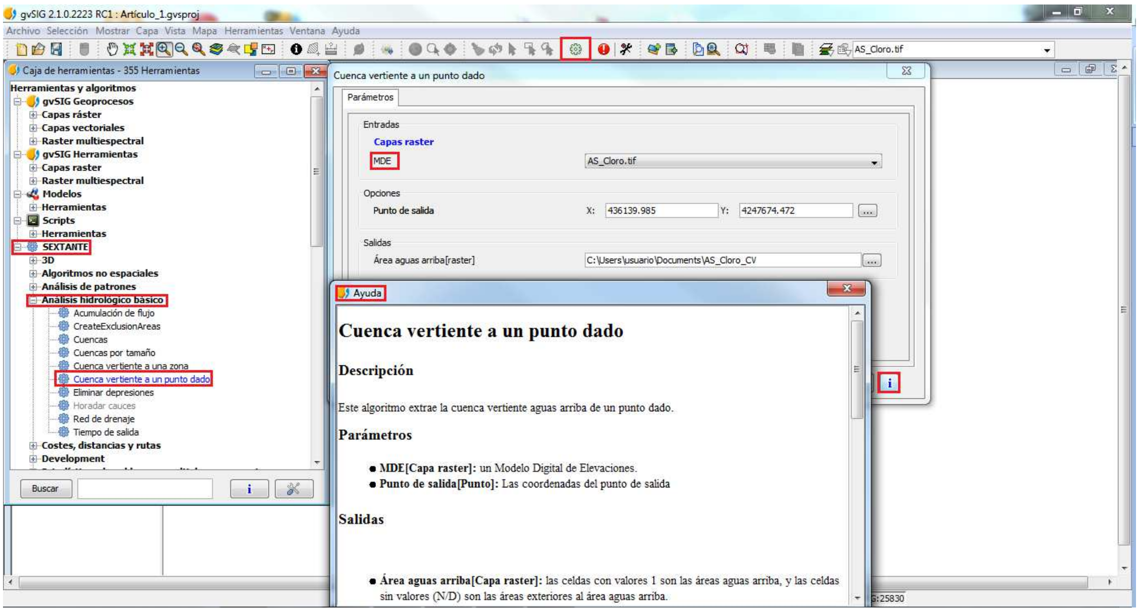


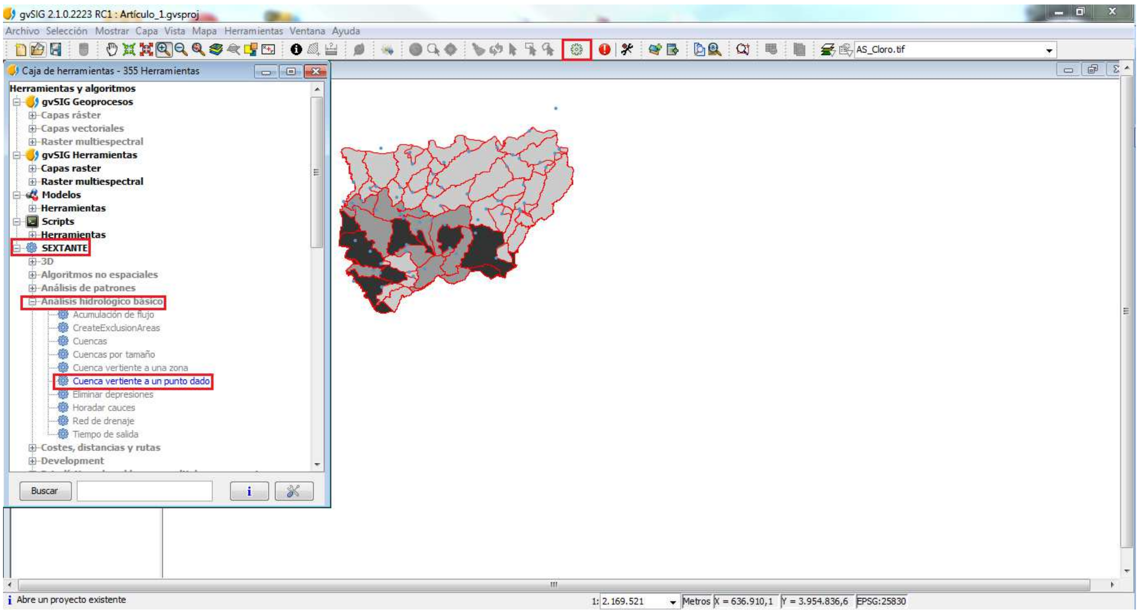
C) To perform the slope at a given point basin and geometric polygon aquifer:

(i) Go to *basic hydrologic analysis* ("análisis hidrológico básico") in the Sextante module and select the corresponding algorithms; in the case of slope at a given point basing the command is "Cuenca vertiente a un punto dado"



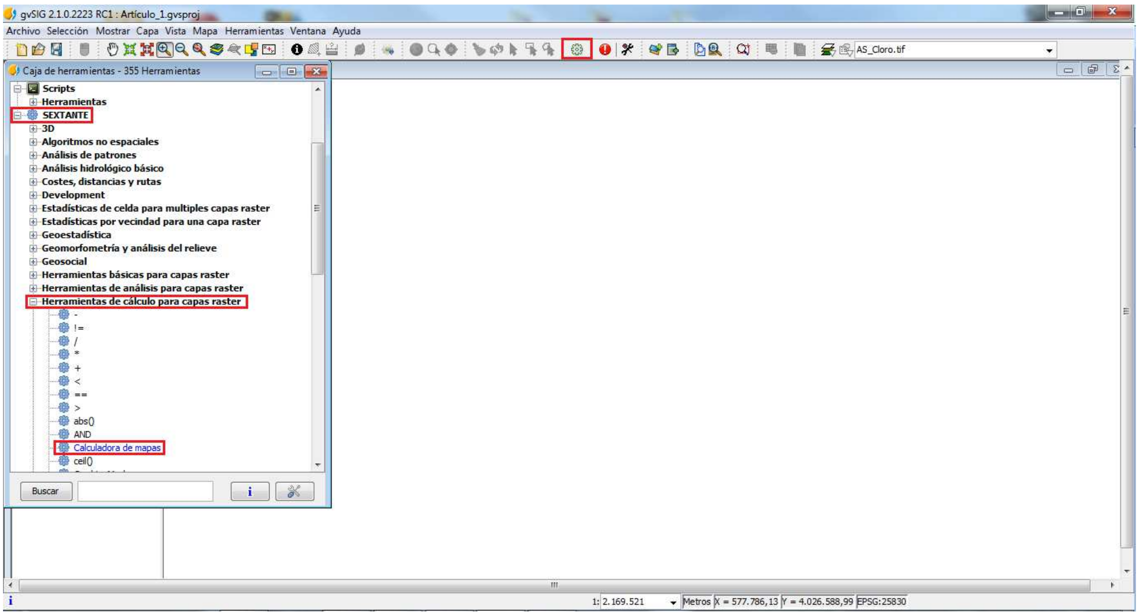
(ii) Include digital model of elevation and the sampling stations, indicating the extension of the output file.



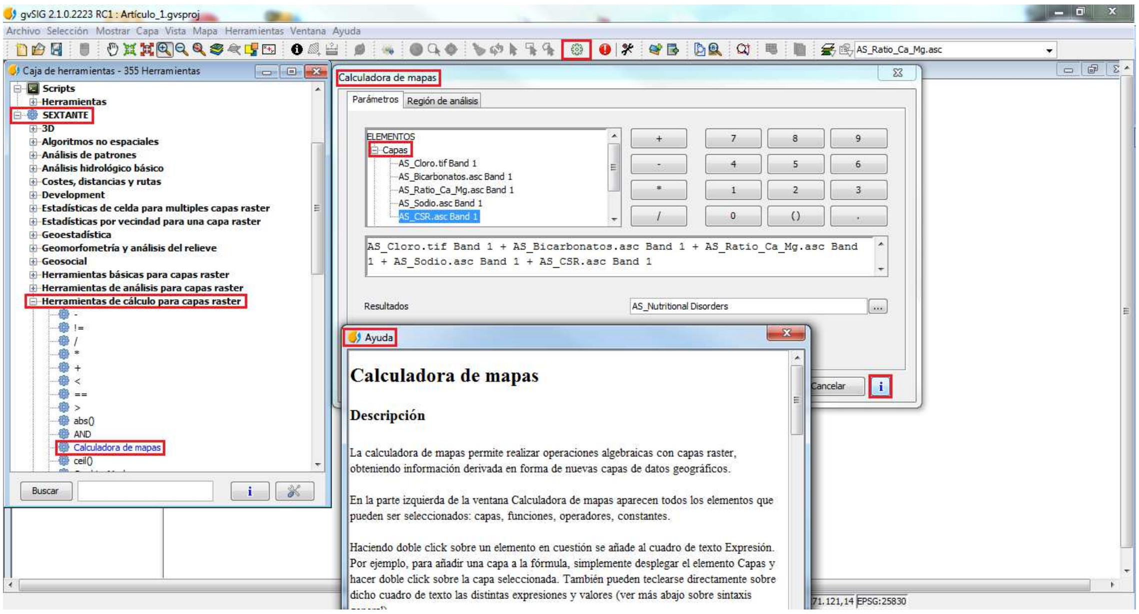


D) To combine parameters

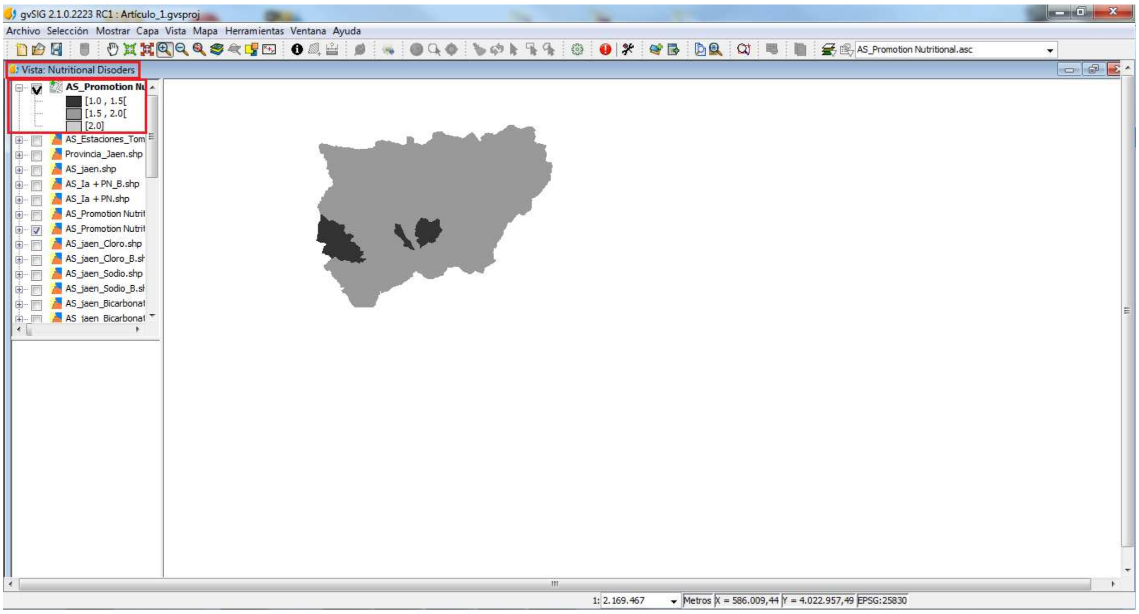
(i) Select the submodule “Calculation tools for raster layers” (“Herramientas de cálculo para capas raster”) in Sextante



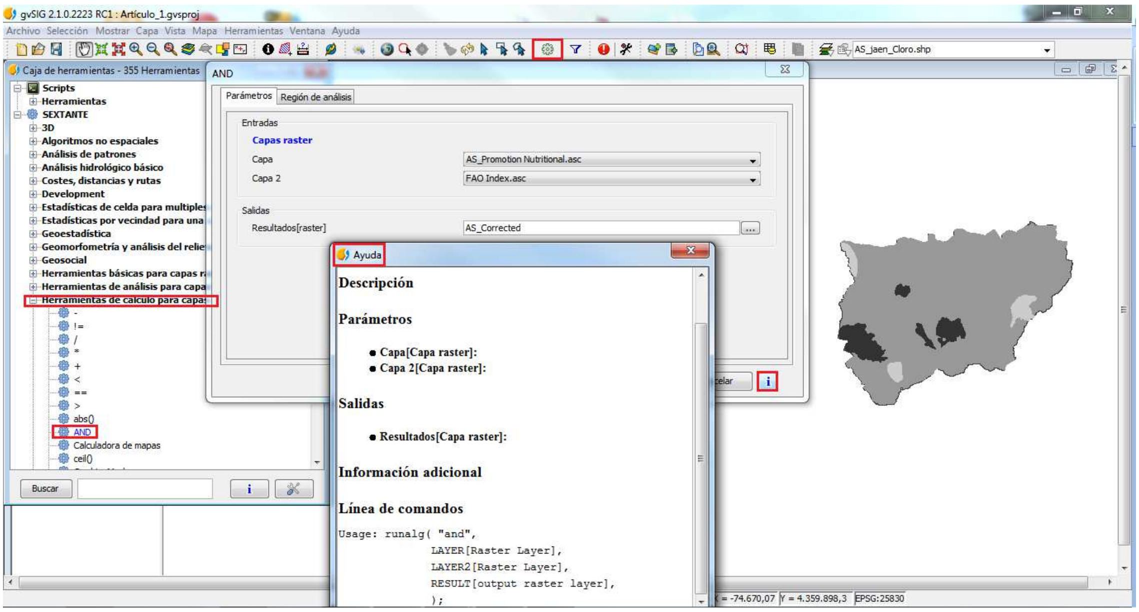
(ii) Select layers to be combined



(iii) A raster map is obtained

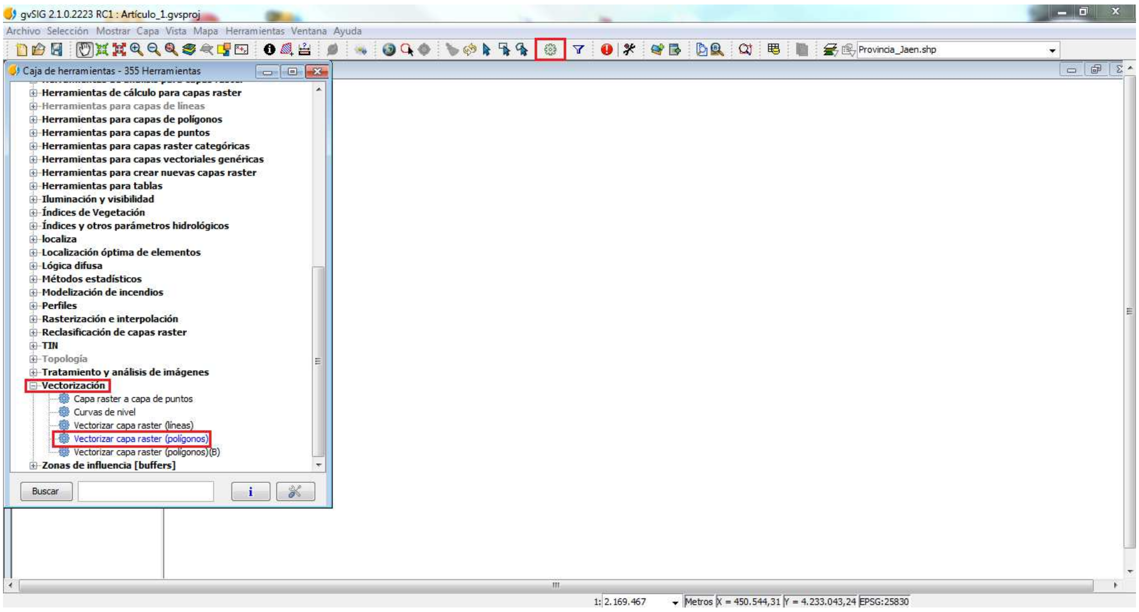


(iv) For correcting the obtained map by adding data from other map, in the same submodule select the algorithm AND to add maps. The result is a raster map corrected.

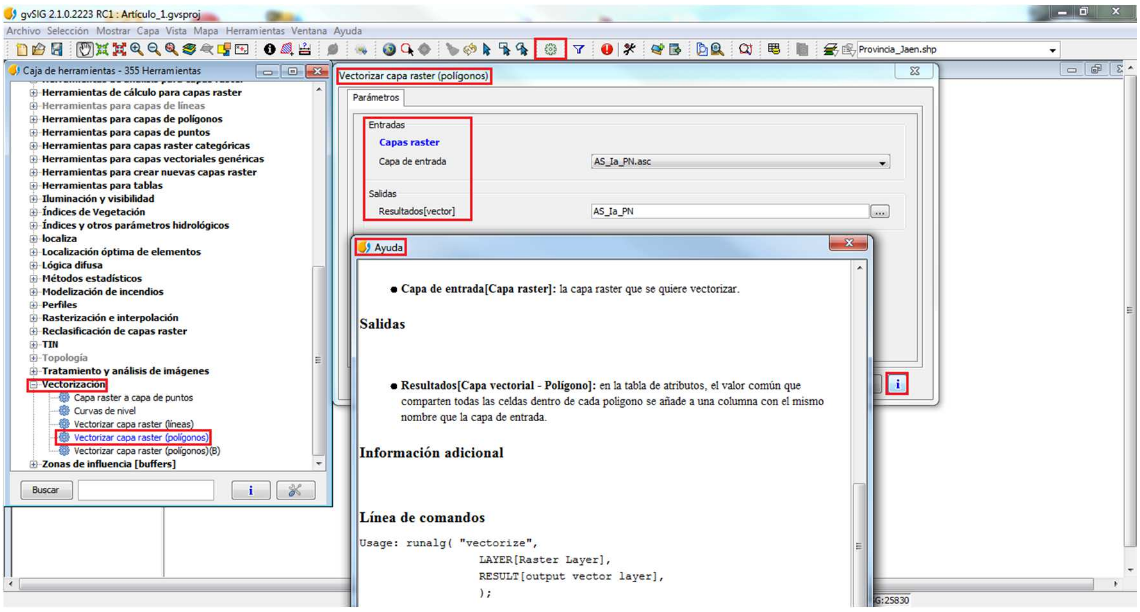


E) To obtain numerical data and polygons which define the geometry of maps and provide numerical data through a table of attributes:

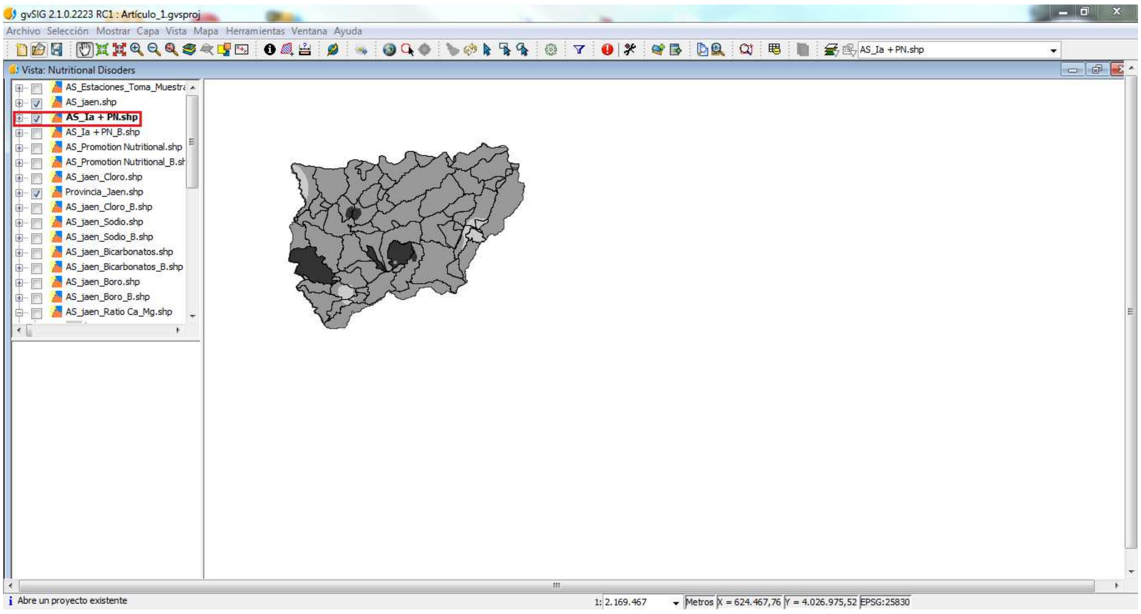
(i) Select the submodule vectorization ("Vectorización") in Sextante.



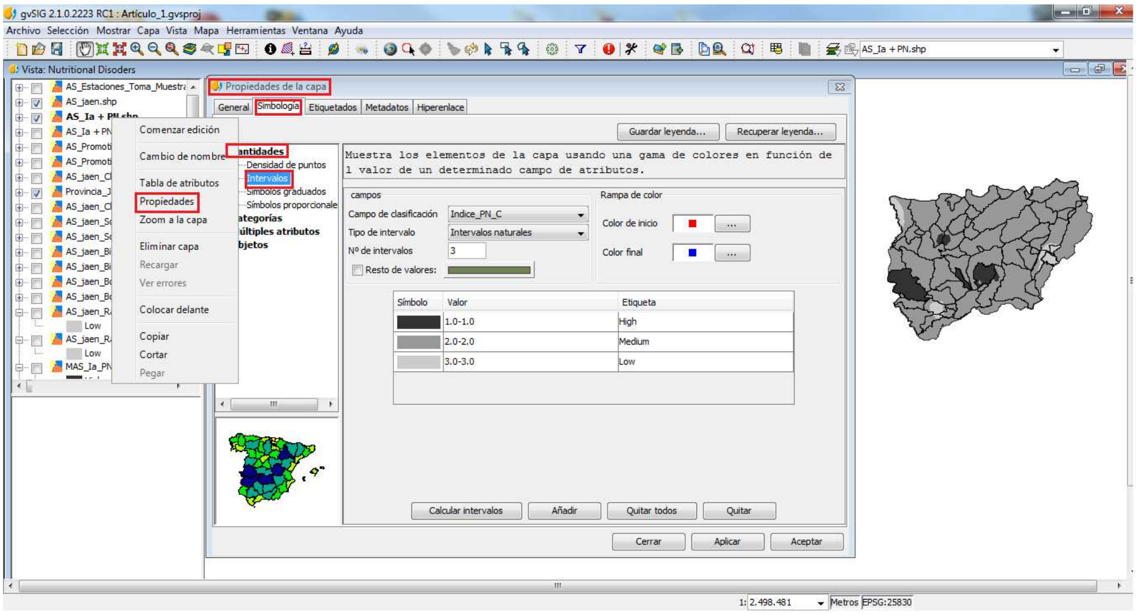
(ii) Introduce the raster map and go to the algorithm "Vectorizar capa raster (polígonos")

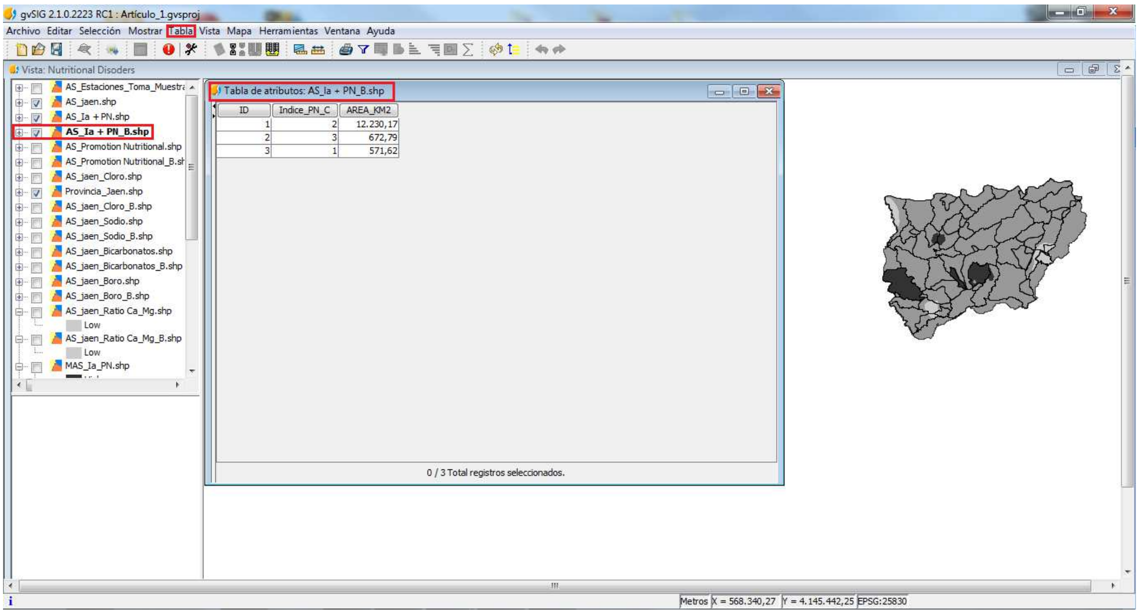


(iii) A vectorial map is obtained



(iv) In properties ("propiedades") select the options *amount* ("cantidades") and within this *intervals* ("intervalos"); depending on each particular variable studied, risk values for each one, legend and colour for graphics is selected; the output is also a vectorial map.





Anexo 3. Capítulo 3 Supplementary data

The description of the operation with gvSIG and required links and options is described in this appendix. Between brackets we include the name in Spanish of the different links and options since the software is developed in Spanish.

Web gvSIG: http://www.gvsig.org/web.

To download the program the link is:

http://www.gvsig.org/plone/home/projects/gvsigdesktop/official/gvsig-2.1/descargas.

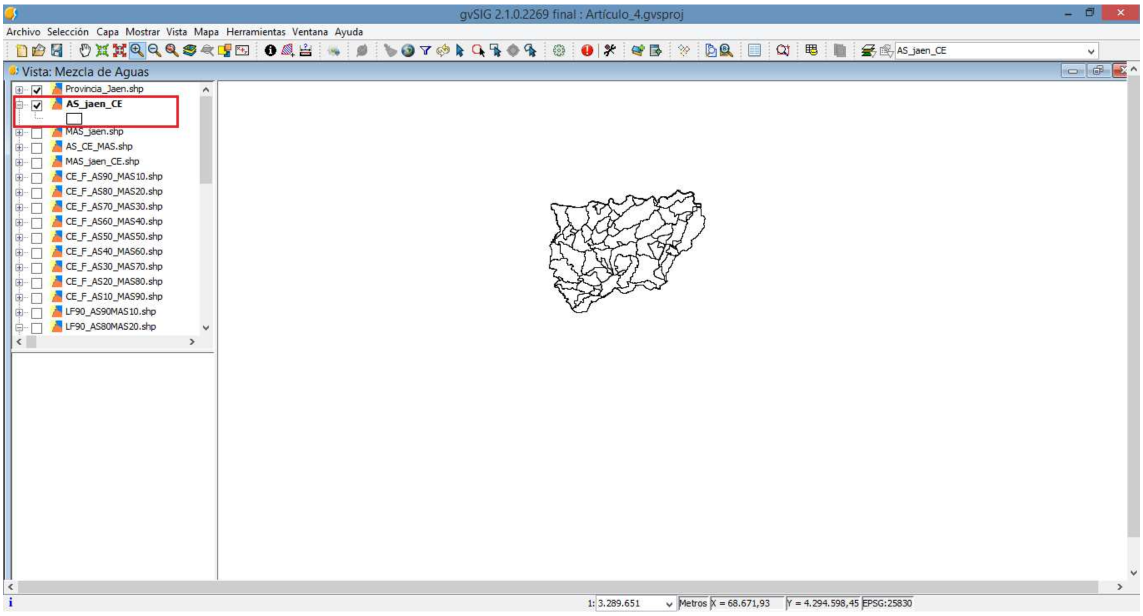
The program includes the SEXTANTE module which includes a submodule menu; each submodule implements one analytical process based on spatial analysis.

The SEXTANTE module includes a help tutorial ("Ayuda") with the different commands for using each algorithm for calculation.

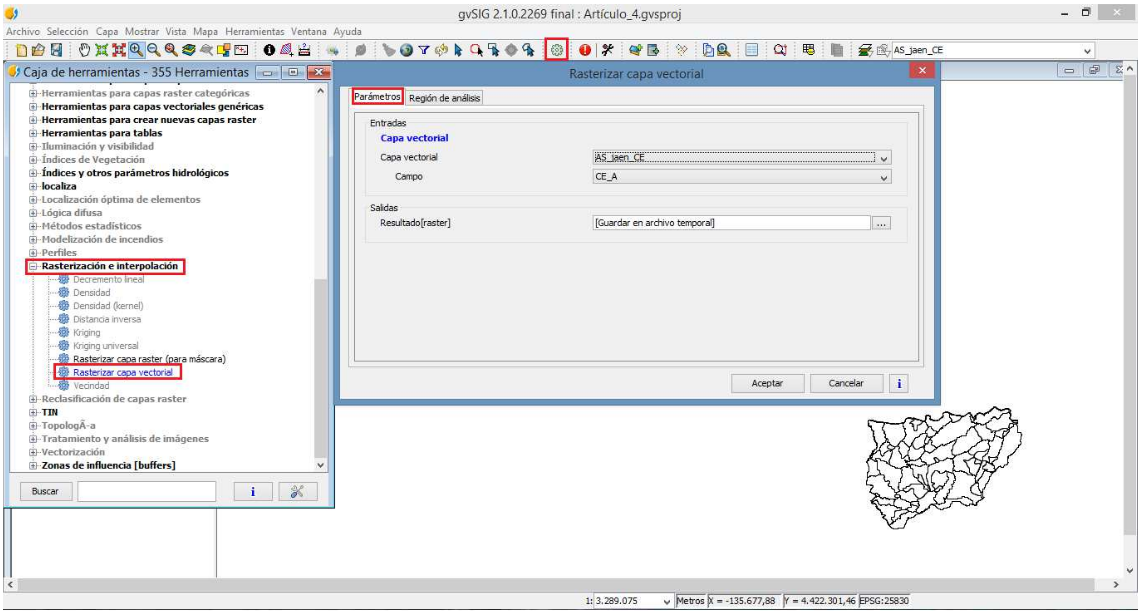
The procedure for obtaining the mixture water is:

A) Sequence to obtain the areas of surface water that coincide exclusively with the masses of groundwater (aquifers).

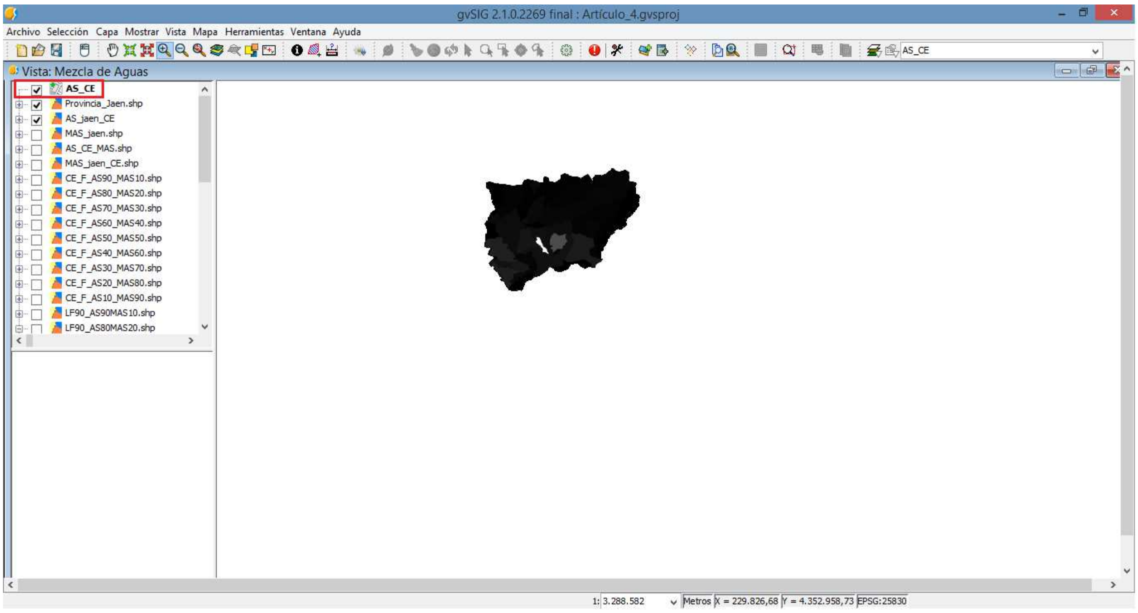
    (i) Select the vector layer sub-basin (Peragón et al., 2015), that containing the electrical conductivity values in surface waters.



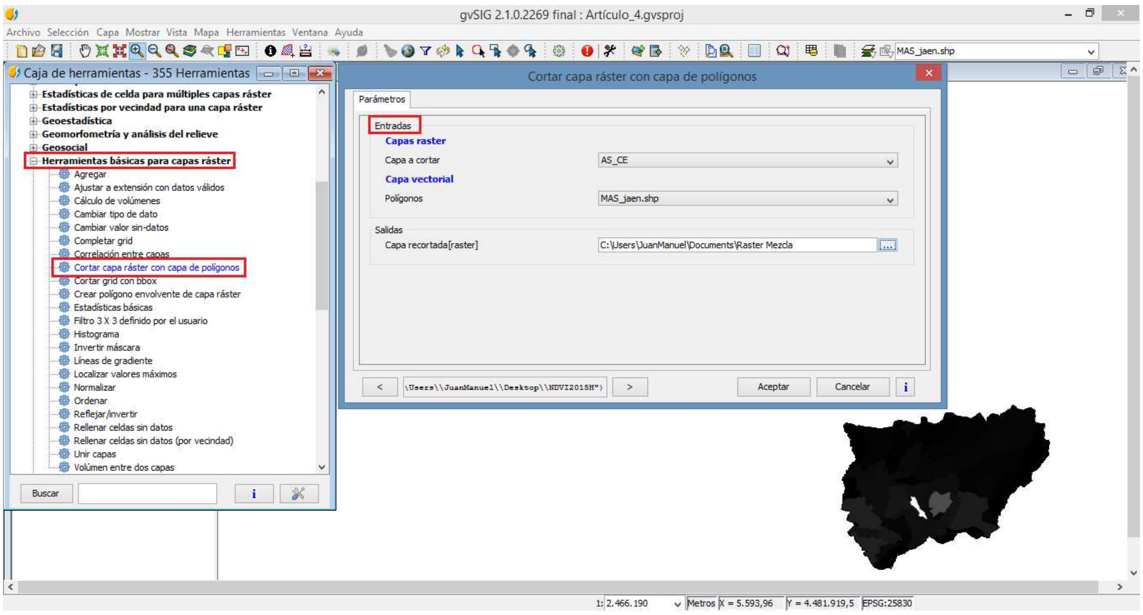
(ii) In SEXTANTE, go to *raster and interpolation* ("Rasterización e interpolación") submodule; select the "rasterized vector layer" algorithm; now you can select the layer and the table of data that is going to be rasterize and the extension for the new "layer" file which are going to be generated.



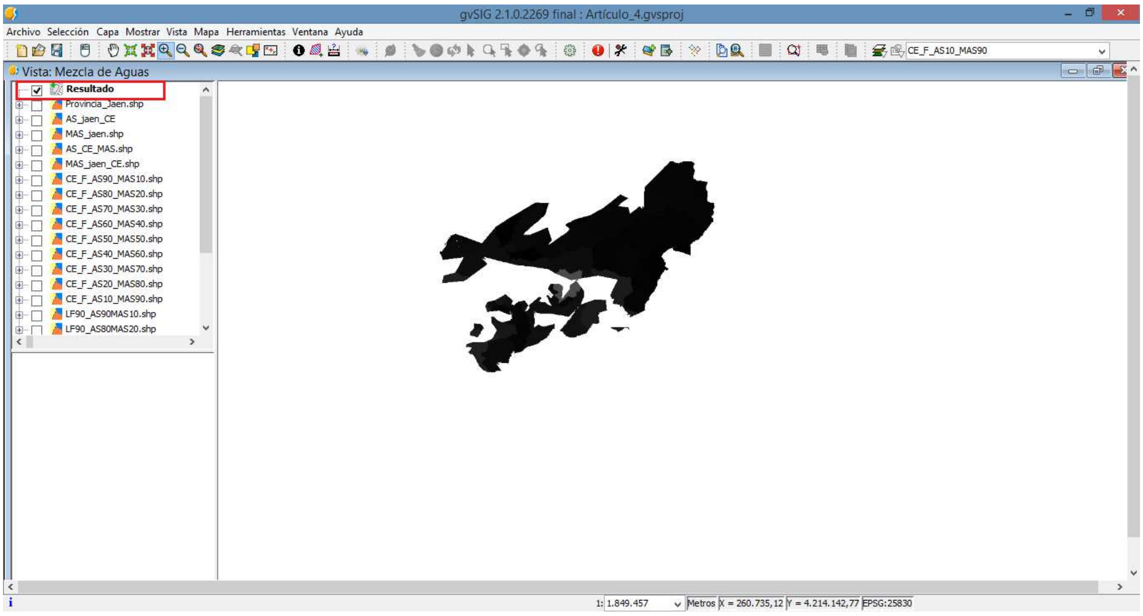
(iii) A georeferenced raster.tiff file is released.



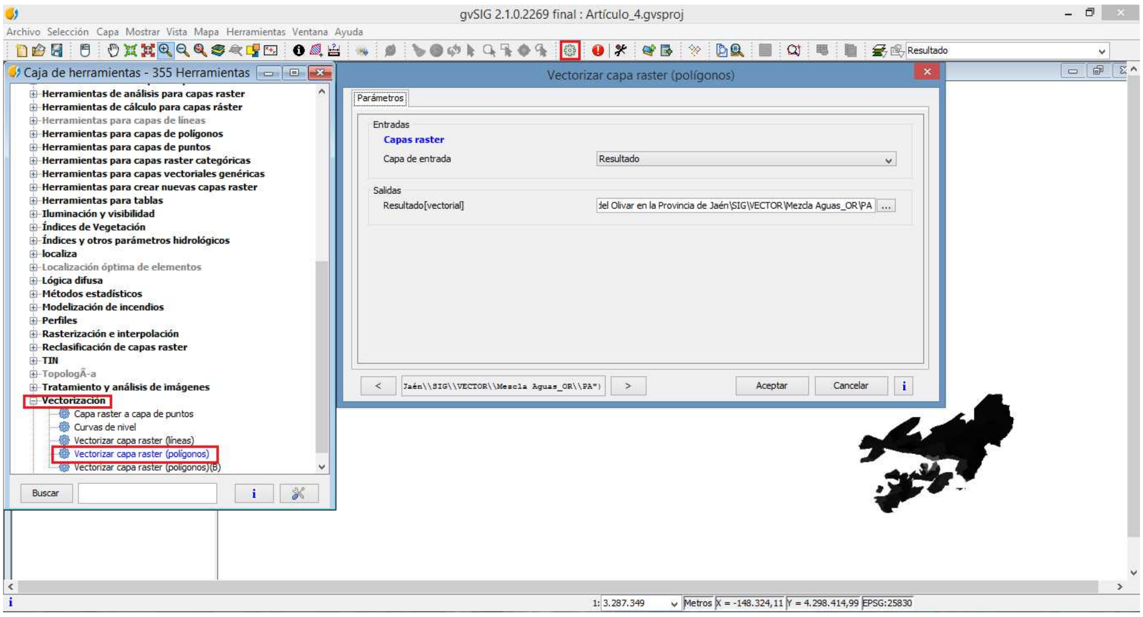
(iv) To obtain only the surface water areas overlapping with the masses of groundwater: select the submodule “Basic tools for raster layer” (“Herramientas básicas para capas raster”) in Sextante. Then "cut raster layer with vector layer". Now you can select the layers raster (obtained above) and vector (aquifers) that is going to be cut and the extension for the new “layer” file which are going to be generated.



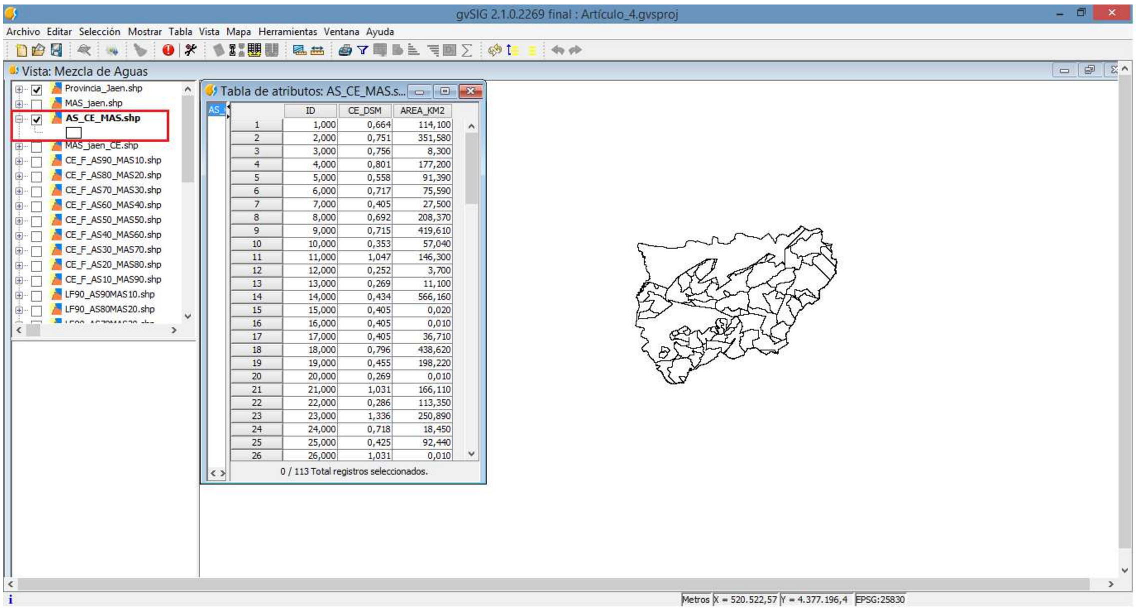
(v) A raster map is obtained.



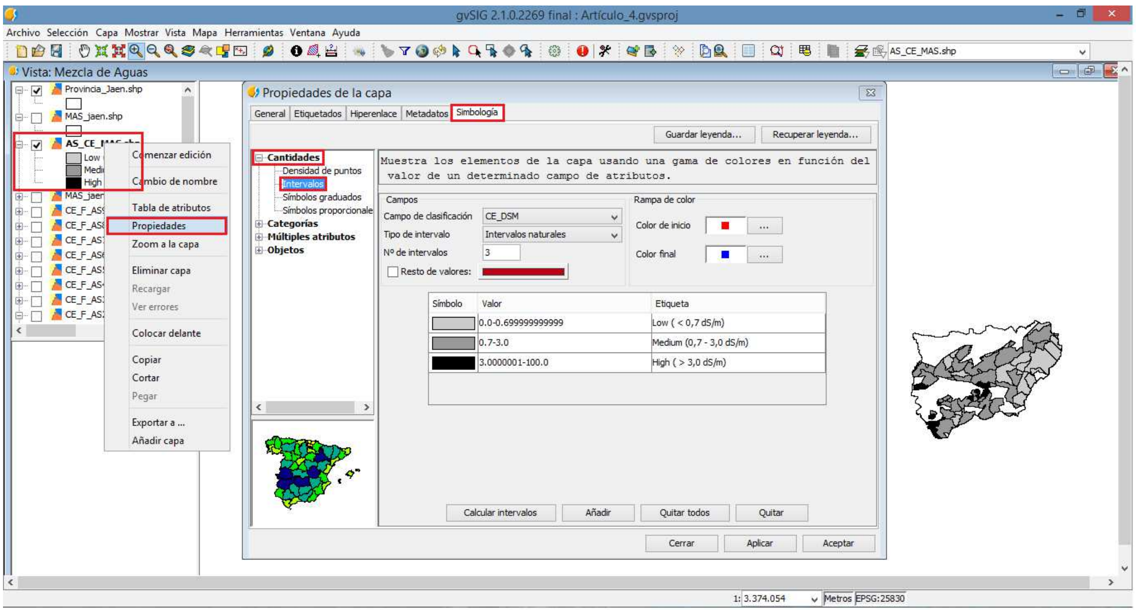
(vi) To obtain numerical data and polygons which define the geometry of maps and provide numerical data through a table of attributes: Select the submodule *vectorization* ("Vectorización") in Sextante. And introduce the raster map and go to the algorithm "vectorize raster layer (polygons)".

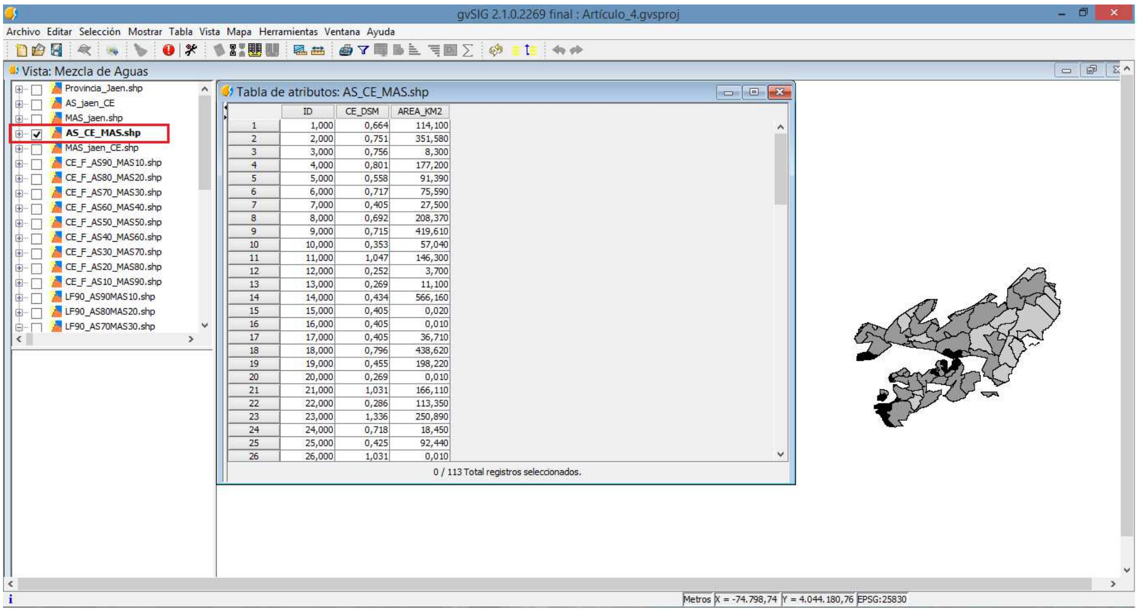


(vii) A vectorial map is obtained.



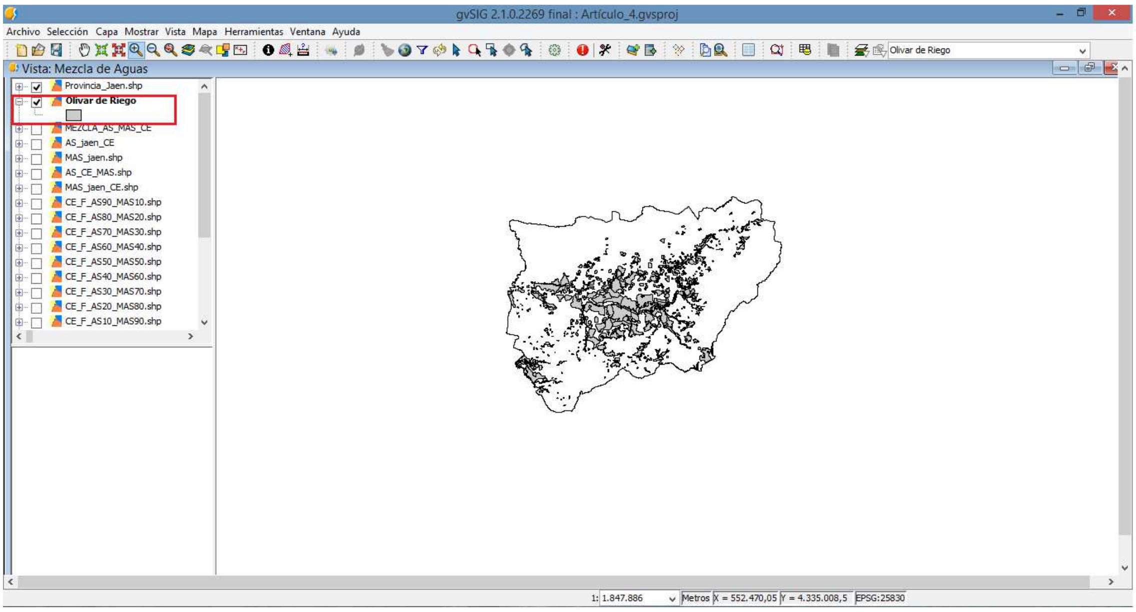
(viii) In properties ("propiedades") select the options *amount* ("cantidades") and within this *intervals* ("intervalos"); depending on each particular variable studied, risk values for each one, legend and colour for graphics is selected; the output is also a vectorial map.



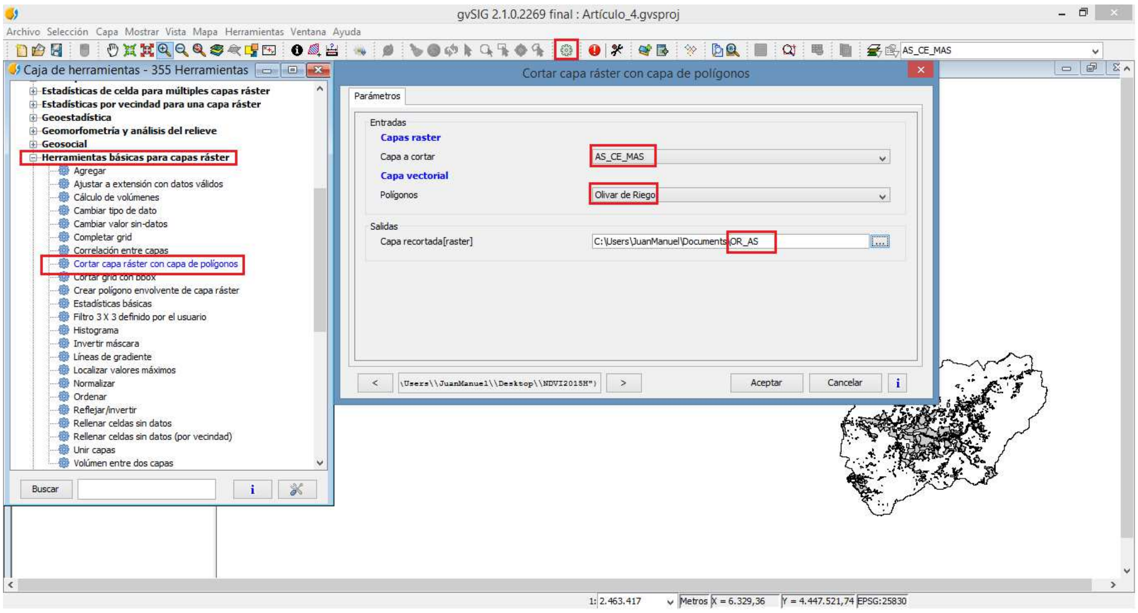


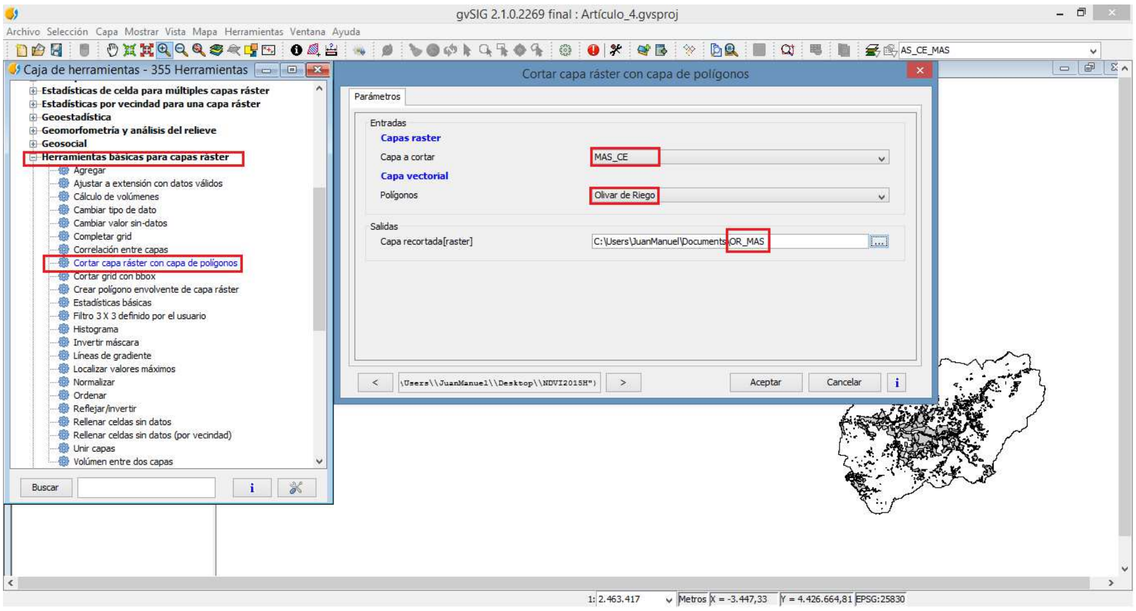
B) The sequence to obtain the areas of olive irrigation in them: surface and underground water.

(i) Select the vector layer "olive irrigation".

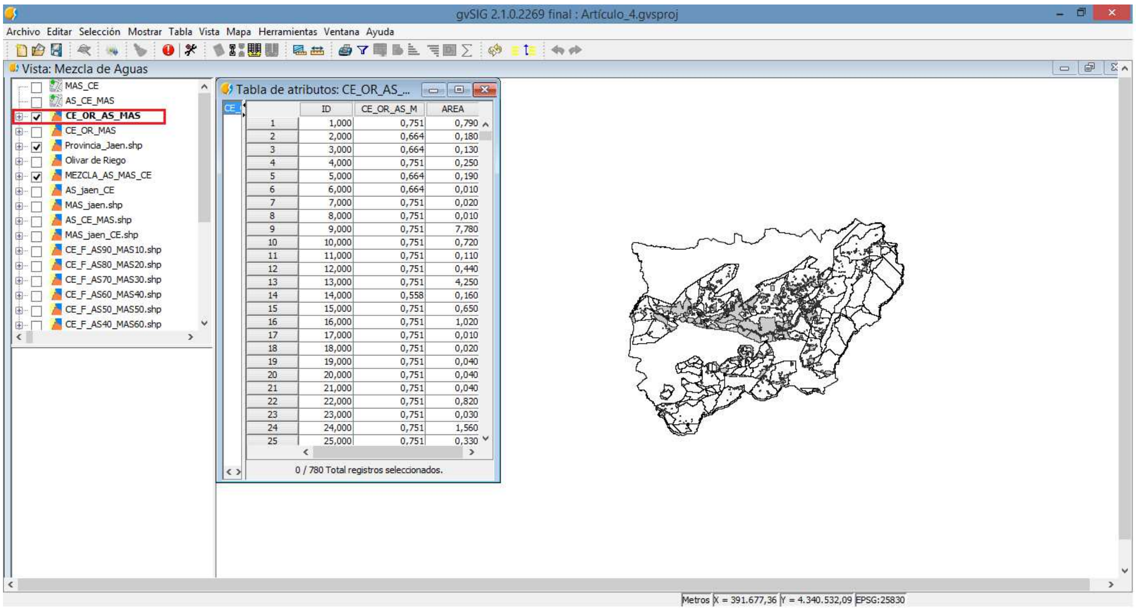


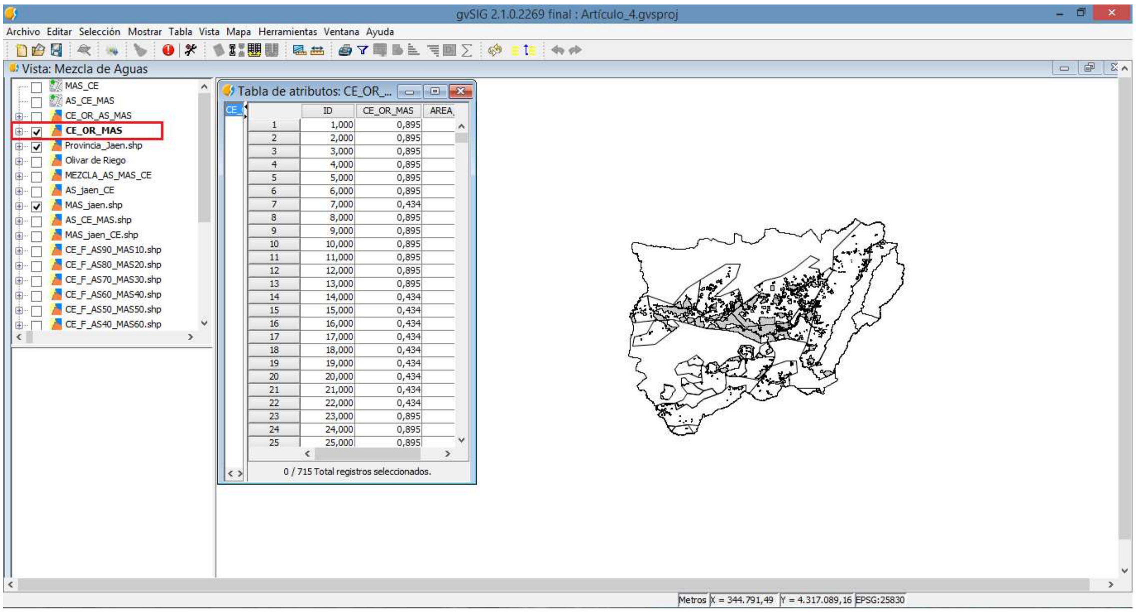
(ii) To obtain only the olive irrigation areas overlapping with the surface and underground water obtained above: select the submodule "Basic tools for raster layer" ("Herramientas básicas para capas raster") in Sextante. Then "cut raster layer with vector layer". Now you can select the layers raster (obtained above) and vector (olive irrigation) that is going to be cut and the extension for the new "layer" file which are going to be generated. First for surface water and later for underground water.





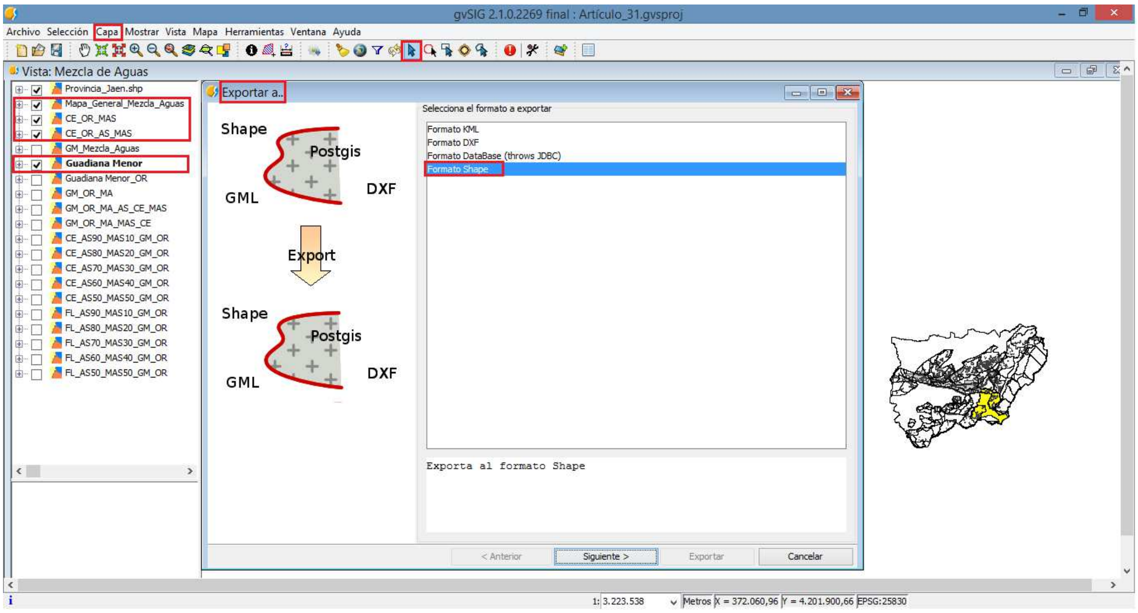
(iii) A vectorial maps is obtained.



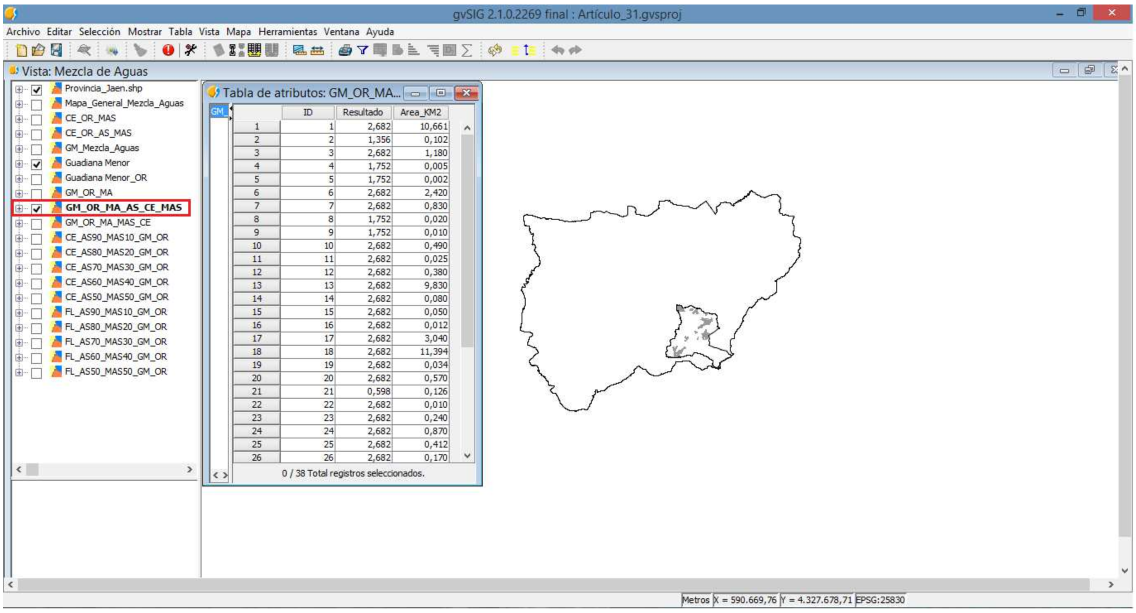


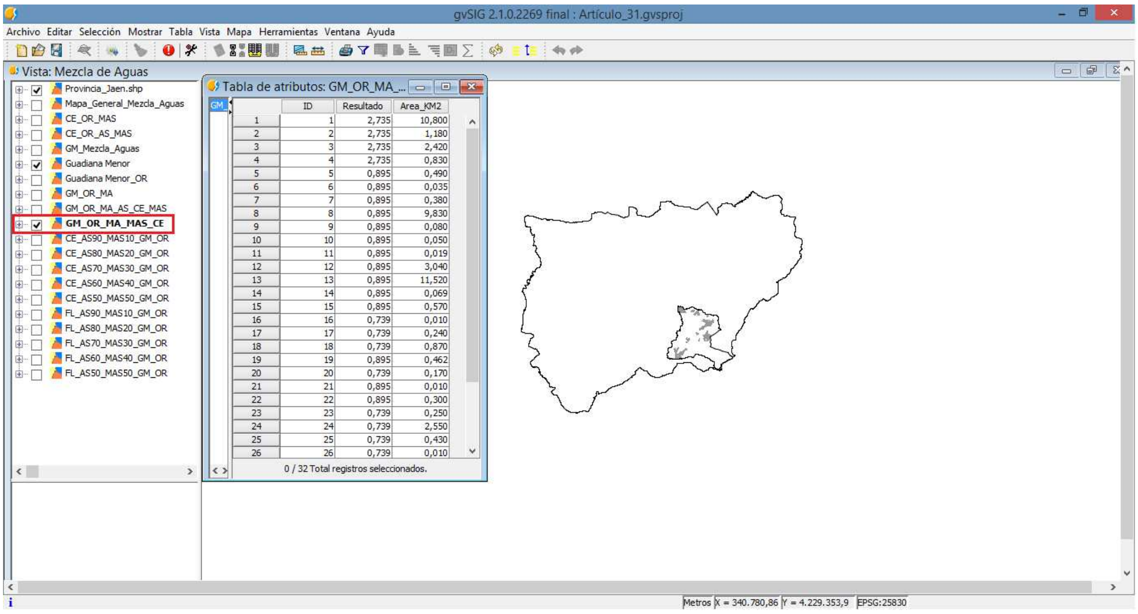
C) The sequence to obtain areas of olive irrigation in them: surface and underground water, but only in the example area: “Guadiana Menor”

(i) Activate layers olive irrigation obtained above, water mixture and sub-basin. The sub-basin Guadiana Menor is selected, with the tool simple selection “Selección Simple”. To save as a new layer for both surface and groundwater, select layer and exported as a file "shp".



(ii) Two new layers are obtained: olive irrigation in sub Guadiana Menor for surface water and groundwater.





D) Guadina Menor: Solution 1. Fix Final Concentration (example 0,7 dS/m)

D.1) Formulation applied.

CF = (CA x PA) + (CB x PB)

PB = 100 – PA

PA = (CF – CB) / (CA – CB)

CF: final concentration of the mixture (electrical conductivity is to be maintained in the irrigation water).

CA: electrical conductivity of the surface water (dS m^{-1})

CB: electrical conductivity of the underground water (dS m^{-1})

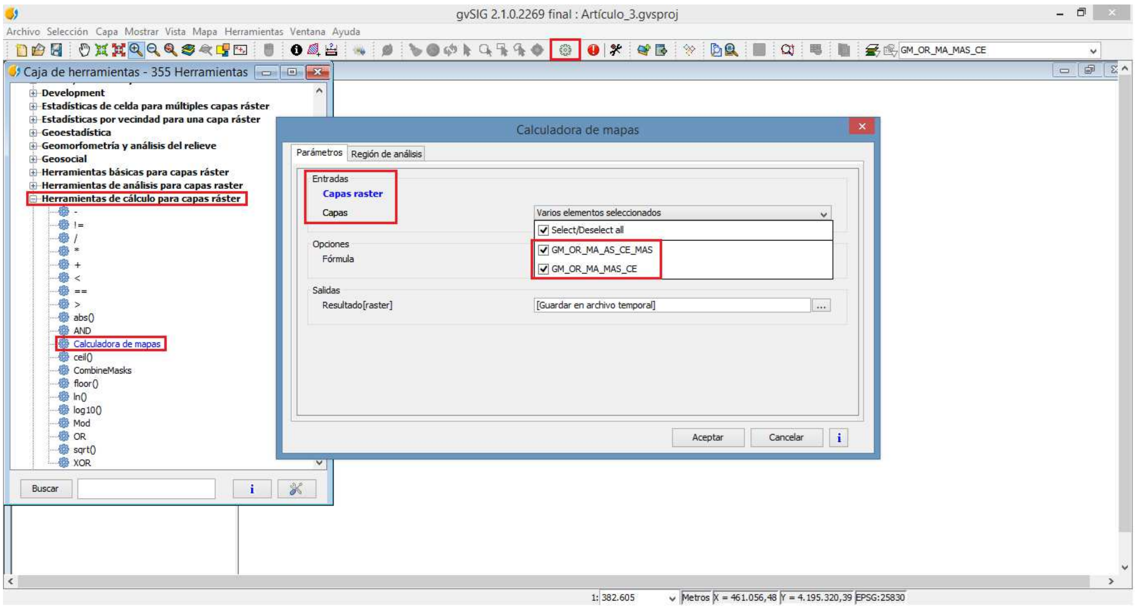
PA: proportion of surface water (%)

PB: proportion of underground water (%)

D.2) GIS processing

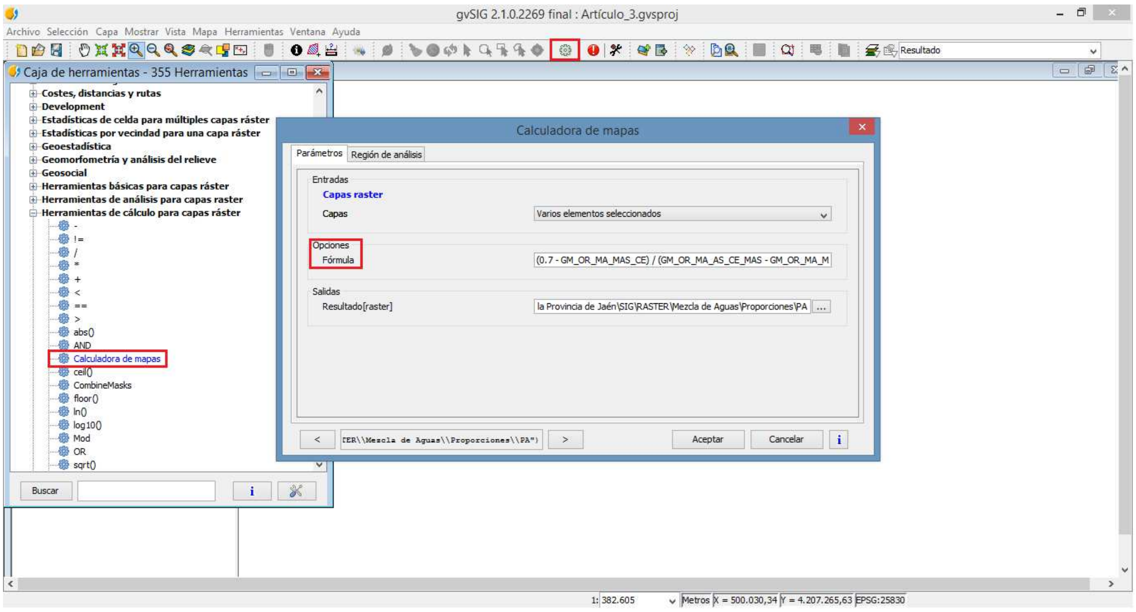
It is part of the results of paragraph C) of olive grove areas that are potential irrigated with both surface water and groundwater in the area of application Guadiana Menor

(i) Layers with the same procedure as in section A) are rasterized. Select the submodule “Calculation tools for raster layers” (“Herramientas de cálculo para capas raster”) in Sextante, and raster layers are chosen.

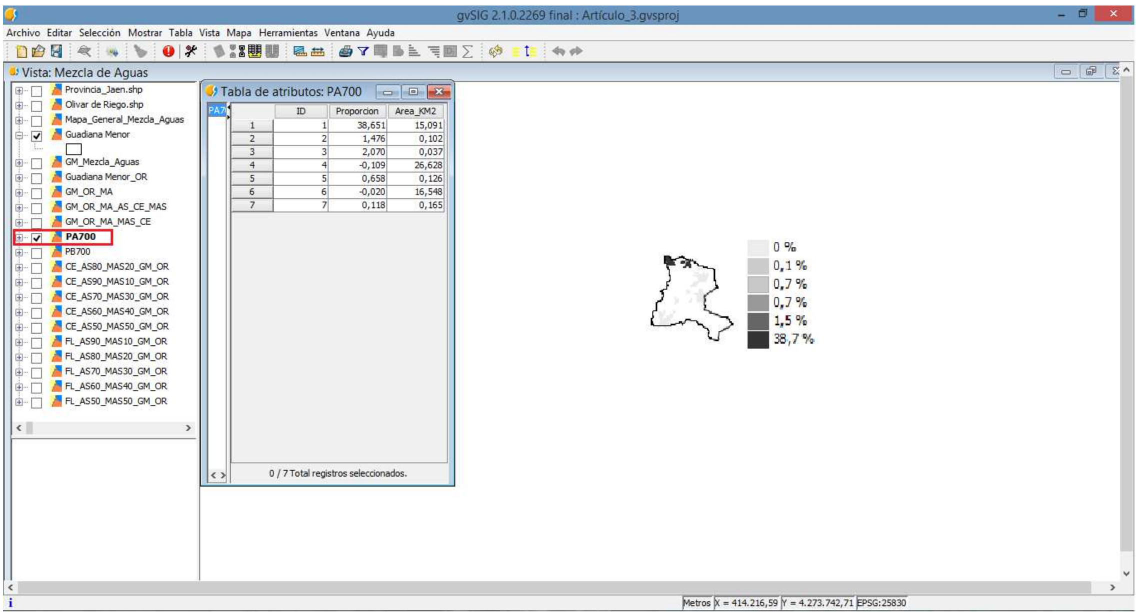


(ii) In formula, it is introduced: Proportion of Surface Water (PA) = (0.7 - CB) / (CA - CB).

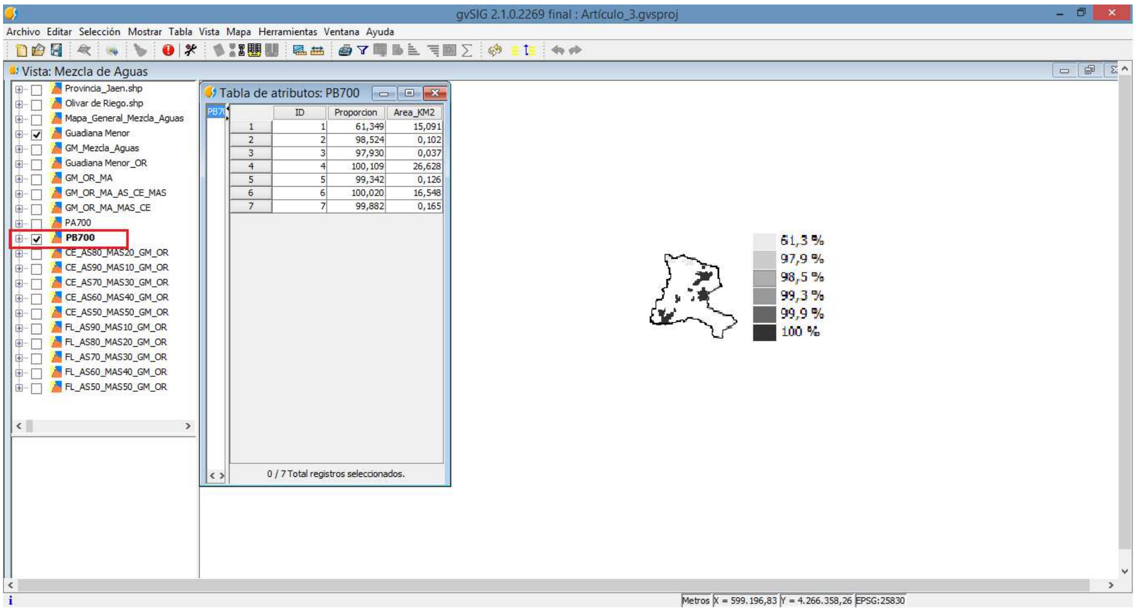
Final concentration = 0.7 dS m^{-1} (It is assumed that the electrical conductivity of irrigation water with which we water is 0.7 dS / m so that the risk is slow).



(iii) The output raster file is vectorized, and graduated in intervals according to the proportions obtained (as in paragraph A).



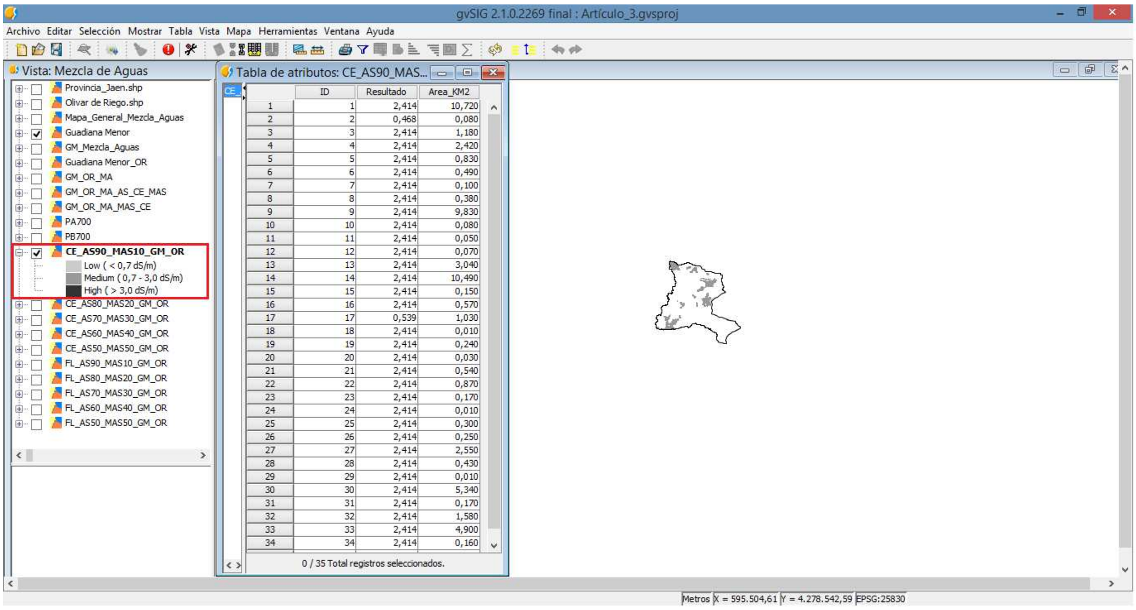
(iv) For the proportion of groundwater, the same process takes place, but the formula is introduced: PB = 1 - PA, and the resulting vector layer is obtained.



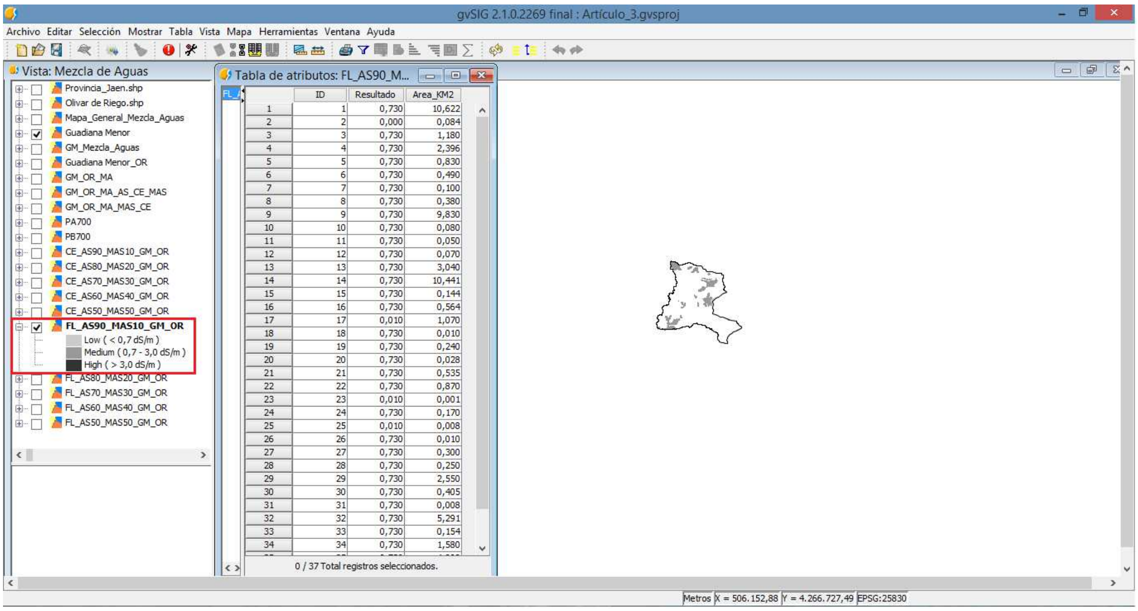
E) Guadina Menor: Solution 2. Get Final concentration from the concentrations of each type of water used, and leaching fractions.

It is the same procedure as in section D.2), but the formula proportions are to be generated are introduced. For example: 90% of surface water and 10% of underground water: (0.90 x surface water) + (0.10 x underground water). Both, EC and leaching fractions are obtained:

(i) Electrical conductivity concentrations



(ii) Leaching fraction concentrations



Anexo 4. Capítulo 4 Supplementary data

Appendix A) Calculations

Langelier index

$Is = pH_w - pH_c$

Where:

pH_w = pH of water

$pHc = (pk_2 – pk_c) + p(Ca^{2+}) + p(Alk)$

$(pk_2 – pk_c)$ and p(Alk) as defined above

Estimation of acid requirements

Based on the Langelier Index (Is), which is defined according to the following equation:

Is= pHw - pHs

where, pHw is the value of pH in irrigation water used, and pHs is the pH value at which water with a given alkalinity and Ca concentration is in equilibrium. Calculation steps are:

Calculation of the maximum concentration of carbonate and bicarbonate in water at which they both do not precipitate, usually defined referred to as Alkc, which is related to the actual Alk and Is through the equation:

p(Alkc) = p(Alk) + Is

Calculation of the concentration of carbonates to eliminate (Alke):

Alke = Alk – Alkc

The concentration of acid (expressed in $mmol_c\ L^{-1}$) to avoid precipitation is equivalent to the concentration of carbonates to eliminate.

N fertilizer requirements for trees with N concentration in leaves below 15 g kg^{-1}

Nc = N uptake by crop under non-restricted N supply conditions; under a N balance strategy, it can be considered = N in fruits + N in pruning material

$Nc = N_{fruits} + N_{pruning}$

N_{fruits} = (N concentration fruits) x (Fruit production);

Typical N concentration fruits = 2 – 3 g kg^{-1} (fresh weight basis)

$N_{prunning}$ = (N concentration pruning material) x (Pruning material production)

typical N concentration pruning = 5 – 7 g kg^{-1} (fresh weight basis)

N concentrations according to data reported by Rodrigues et al. (2012) and Fernández-Escobar et al. (2012; 2015).

For full productive trees under irrigation with a tree density of 100 tree ha^{-1}, it can be expected average yields in around 60 kg $tree^{-1}$ (100 kg year "on", and 20 kg year "off"), with average pruning material production of 60 kg $tree^{-1}$.

N concentration in fruits can be considered 2.5 g N kg^{-1}, and 6 g kg^{-1} in pruning material (on a fresh matter basis); thus

$Nc = (2.5 \times 60 + 6 \times 60)$ g N $tree^{-1}$x 100/1000 ~ 50 kg ha^{-1}

N fertilizer rate = (Nc – Nw)/E

Nw is N in irrigation water (N in nitric acid + soluble N in irrigation water); E = efficiency in N fertilization which can be considered the apparent N recovery of applied fertilizer. It is assumed: E = 0.8 for soil applied N with drip irrigation with an optimal efficiency for highly frequently drip fertigated crops and without water restrictions; with deficitary irrigations and frequency lower than daily, E = 0.7 (Singandhupe et al. 2003; Thompson et al., 2011; adapted from other crops)

This model assumes a negligible contribution of mineralization of organic matter to N supply since the concentration of organic matter in soil is usually very low (frequently < 1 %). In addition, usual no-tillage as soil management method decreases potential mineralization of organic matter.

References

Fernández-Escobar R., García-Novelo J.M., Molina-Soria C., Parra M.A.., 2012. An approach to nitrogen balance in olive orchards. Sciencia Horticulturae 135, 219-226.

Fernández-Escobar R. Sánchez-Zamora M. A. García-Novelo J. M., Molina-Soria C., 2015. Nutrient Removal from Olive Trees by Fruit Yield and Pruning. HortSciencie Vol. 50, No 3: 474-478.

Rodrigues M.A., Ferreira I.Q. Claro A.M., Arrobas M., 2012. Fertilizer recommendations for olive based upon nutrients removed in crop and pruning. Scientia Horticulturae 142, 205-211

Singandhupe R.B., Rao G. G. S. N., Patil N. G., Brahmanad P. S., 2003. Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopersicon esculentum L.*). European Journal of Agronomy 19: 327-340.

Thompson T.L., White S.A,, Walworth J., Sower GJ., 2003. Fertigation Frequency for Subsurface Drip-Irrigated Broccoli. Soil Sci. Soc. Am. J. 67, 910–918

Appendix B) Tables to complete the descriptions made in the manuscript

Table 23. Calculation of the rates of nitric acid to be injected

Times that pipes are filled with acidified water	Water volume in irrigation network (m^3 ha^{-1})	Injection time (min)	Nitric acid for 120 irrigation days (L ha^{-1})	Nitric acid for 60 irrigation days (L ha^{-1})	Nitric acid for 20 irrigation days (L ha^{-1})	Nitrogen supplied for 120 irrigation days (kg ha^{-1})	Nitrogen supplied for 60 irrigation days (kg ha^{-1})	Nitrogen supplied for 20 irrigation days (kg ha^{-1})
Two	0.80	15	14.04	6.96	2.88	2.35	1.17	0.48
Three	1.20	22.5	21.06	10.44	4.32	3.53	1.75	0.72
Four	1.60	30	28.08	13.92	5.76	4.71	2.33	0.97

Dimensions of irrigation network according to UNE 53367:2005; 50 % nitric acid.

Table 24. Surface where different volumes of acids different from nitric that should be injected in irrigation water for surface and underground water for a daily irrigation with 30 min of injection time

	L ha^{-1} of acid in the irrigation water	Hydrochloric acid		Phosphoric acid		Sulphuric Acid	
		Area affected (km^2)	% Area	Area affected (km^2)	% Area	Area affected (km^2)	% Area
Surface Water	< 0.1	3217	23.9	11624	86.2	7585	56.2
	0.1 - 0.2	829	6.1	1865	13.8	5904	43.8
	0.2 - 0.3	4938	36.6	-	-	-	-
	0.3 - 0.4	4088	30.3	-	-	-	-
	0.4 - 0.5	419	3.1	-	-	-	-
	> 0.5	-	-	-	-	-	-
Underground Water	< 0.1	2859	35.6	5021	62.5	3452	43
	0.1 - 0.2	375	4.7	3009	37.5	2834	35.3
	0.2 - 0.3	218	2.7	-	-	1744	21.7
	0.3 - 0.4	1643	20.5	-	-	-	-
	0.4 - 0.5	1192	14.8	-	-	-	-
	> 0.5	1744	21.7	-	-	-	-

Area is referred to the area potentially irrigated with this source of water; % Area is referred to the area potentially irrigated with this source of water

Concentration of acids: Hydrochloric acid, 36 %; phosphoric acid, 70 %, and sulphuric acid, 96 %

Table 25. Surface where different amounts of nitrogen are applied with surface water used for irrigation before injecting nitric acid

Kilogram of nitrogen in irrigation water (kg ha^{-1})	$N\text{-}NO_3^-$		$N\text{-}NH_4^+$		$N\text{-}NO_2^-$		Total Nitrogen	
	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
< 5	11363	84.2	12141	90.0	13489	100	9022	66.9
5 - 10	2059	15.3	491	3.6	-	-	2488	18.4
10 - 15	68	0.5	488	3.6	-	-	1610	11.9
15 - 20	-	-	179	1.3	-	-	179	1.3
20 - 25	-	-	-	-	-	-	-	-
25 - 30	-	-	-	-	-	-	-	-
30 - 35	-	-	191	1.4	-	-	191	1.4

Area is referred to the area potentially irrigated with this source of water; % Area is referred to the area potentially irrigated with this source of water.

Table 26. Surface where different amounts of nitrogen are applied with underground water used for irrigation before injecting nitric acid

Kilogram of nitrogen in irrigation water (kg ha^{-1})	$N\text{-}NO_3^-$		$N\text{-}NH_4^+$		$N\text{-}NO_2^-$		Total Nitrogen	
	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
< 5	5319	66.2	13489	100	13489	100	5319	66.2
5 - 10	112	14.6	-	-	-	-	1172	14.6
10 - 15	215	2.7	-	-	-	-	215	2.7
15 - 20	1173	14.6	-	-	-	-	-	-
20 - 25	-	-	-	-	-	-	1173	14.6
25 - 30	-	-	-	-	-	-	-	-
40 - 45	151	1.9	-	-	-	-	151	1.9

Area is referred to the area potentially irrigated with this source of water; % Area is referred to the area potentially irrigated with this source of water.

Table 27. Surface where different amounts of nitrogen per hectare are supplied taking into account soluble nitrogen in surface irrigation water and nitrogen supplied with the injection of nitric acid depending on the injection time for irrigation each two days and weekly (60 and 20 irrigation events, respectively)

Nitrogen supplied (kg ha^{-1})	Total dose in irrigation water (30 minutes and 60 days)		Total dose in irrigation water (22,5 minutes and 60 days)		Total dose in irrigation water (15 minutes and 60 days)		Total dose in irrigation water (30 minutes and 20 days)		Total dose in irrigation water (22,5 minutes and 20 days)		Total dose in irrigation water (15 minutes and 20 days)	
	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
< 5	5414	40.2	6507	48.2	7399	54.9	7413	55.0	7694	57.0	8750	64.9
5 – 10	5447	40.4	4533	33.6	3654	27.1	3870	28.7	3816	28.3	2762	20.5
10 - 15	952	7.1	785	5.8	1090	8.1	858	6.4	632	4.7	632	4.7
15 - 20	818	6.1	807	6.0	489	3.6	489	3.6	490	3.6	489	3.6
20 - 25	507	3.8	509	3.8	666	4.9	667	4.9	667	4.9	666	4.9
25 - 30	161	1.2	157	1.2	-	-	3	0.0	-	-	-	-
30 - 35	2	0.0	4	0.0	6	0.0	187	1.4	8	0.1	190	1.4
35 - 40	188	1.4	187	1.4	185	1.4	-	-	183	1.4	-	-
40 - 45	-	-	-	-	-	-	-	-	-	-	-	-
45 - 50	-	-	-	-	-	-	-	-	-	-	-	-

Area is referred to the area potentially irrigated with this source of water; % of the area is referred to the area potentially irrigated with this source of water.

Table 28. Surface where different amounts of nitrogen per hectare are supplied taking into account soluble nitrogen in underground irrigation water and nitrogen supplied with the injection of nitric acid depending on the injection time for irrigation each two days and weekly (60 and 20 irrigation events, respectively)

Nitrogen supplied (kg ha^{-1})	Total dose in irrigation water (30 minutes and 60 days)		Total dose in irrigation water (22,5 minutes and 60 days)		Total dose in irrigation water (15 minutes and 60 days)		Total dose in irrigation water (30 minutes and 20 days)		Total dose in irrigation water (22,5 minutes and 20 days)		Total dose in irrigation water (15 minutes and 20 days)	
	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area	Area (km²)	% Area
< 5	2954	36.8	2921	36.4	5245.5	65.3	5245.5	65.3	5319	66.2	5319.3	66.2
5 – 10	2551	31.8	2646	33.0	674.7	8.4	674.7	8.4	1116	13.9	1171.5	14.6
10 - 15	1146	14.3	1139	14.2	786	9.8	786	9.8	271	3.4	215.4	2.7
15 - 20	55	0.7	-	-	-	-	-	-	-	-	-	-
20 - 25	-	-	-	-	1173	14.6	1173	14.6	1173	14.6	1173	14.6
25 - 30	1173	14.6	1173	14.6	-	-	-	-	-	-	-	-
30 - 35	-	-	-	-	-	-	-	-	-	-	-	-
35 - 40	-	-	-	-	-	-	-	-	-	-	-	-
40 - 45	151	1.9	151	1.9	151	1.9	151	1.9	151	1.9	151	1.9
45 - 50	-	-	-	-	-	-	-	-	-	-	-	-

Area is referred to the area potentially irrigated with this source of water; % Area is referred to the area potentially irrigated with this source of water.

Table 29. Surface with different estimated N fertilizer rates for olive orchards with nitrogen concentration in leaves below 15 g kg^{-1} for surface and underground water

Estimated N fertilizer rate (kg ha^{-1})	Surface Water		Underground Water	
	Area (km^2)	% Area	Area (km^2)	% Area
0 - 10	-	-	-	-
10 - 20	-	-	1759	21.9
20 - 30	-	-	-	-
30 - 40	983	7.3	1262	15.7
40 - 50	4926	36.5	1564	19.5
50 - 60	4363	32.3	498	6.2
60 - 70	796	5.9	96	1
> 70	2421	17.9	2852	35.5

* > 70 is between 70 and 71.5.

Area is referred to the area potentially irrigated with this source of water; % Area is referred to the area potentially irrigated with this source of water.

Appendix C) Figures to complete the descriptions made in the manuscript

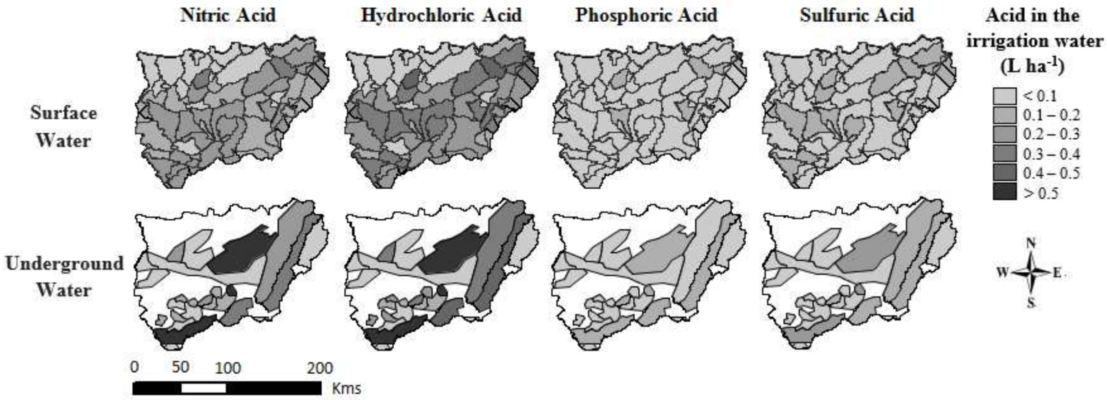


Figure 33. Volumes of acids different from nitric that should be injected in irrigation water for surface and underground water for a daily irrigation with 30 min of injection time

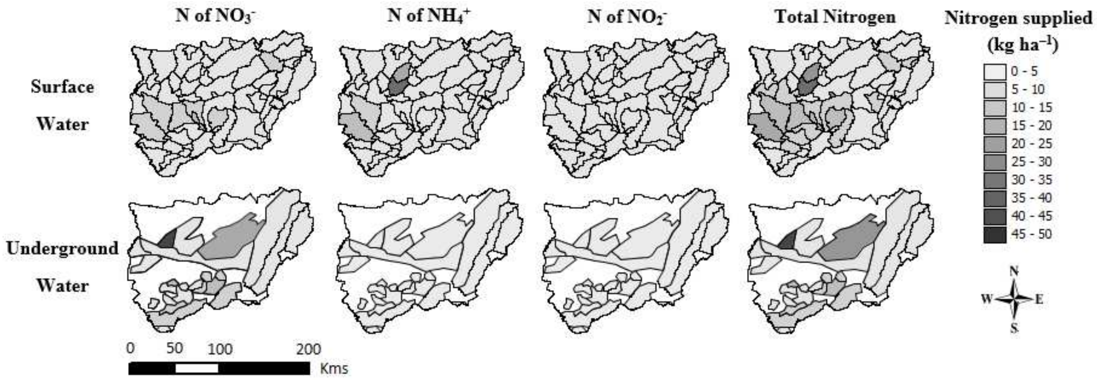


Figure 34. Amounts of nitrogen are applied with water used for irrigation before injecting nitric acid

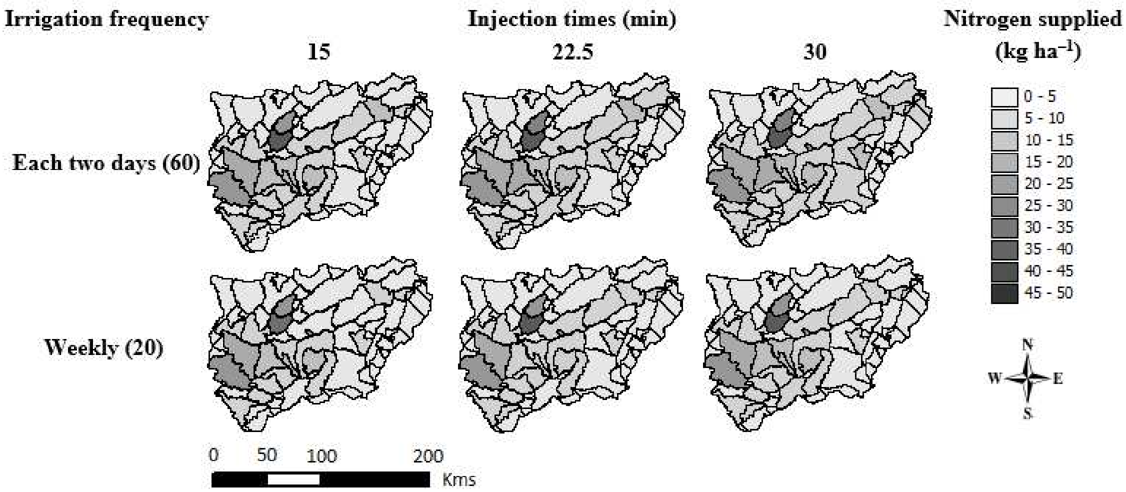


Figure 35. Amounts of nitrogen per hectare supplied taking into account soluble nitrogen in surface irrigation water and nitrogen supplied with the injection of nitric acid depending on the injection time for irrigation each two days and weekly (60 and 20 irrigation events, respectively)

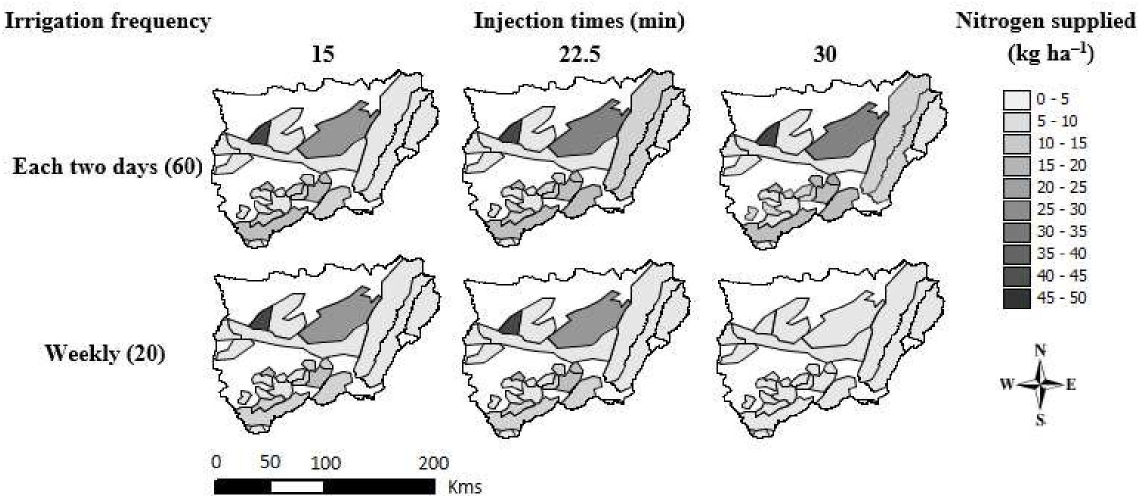


Figure 36. Amounts of nitrogen per hectare supplied taking into account soluble nitrogen in underground irrigation water and nitrogen supplied with the injection of nitric acid depending on the injection time for irrigation each two days and weekly (60 and 20 irrigation events, respectively)

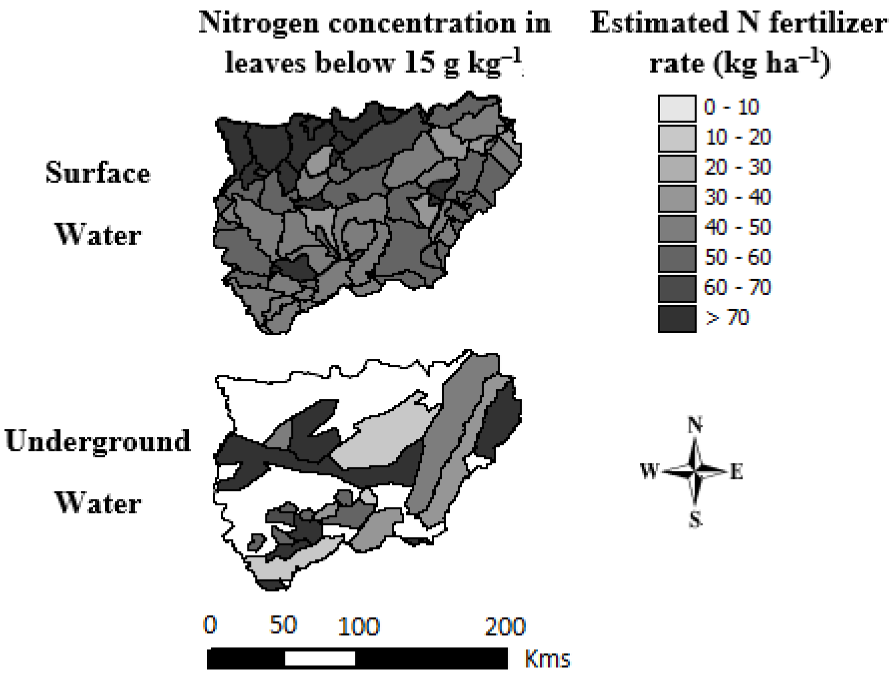


Figure 37. Estimated N fertilizer rates for olive orchards with nitrogen concentration in leaves below 15 g kg^{-1} for surface and underground water