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Programa de Doctorado
Ingeniería Agraria, Alimentaria, Forestal y del Desarrollo Rural Sostenible

TESIS DOCTORAL

EVOLUCIÓN DE LA GESTIÓN DEL REGADÍO EN ESPAÑA Y SUS IMPLICACIONES ANTE LA ESCASEZ DEL AGUA

EVOLUTION OF IRRIGATION WATER MANAGEMENT IN SPAIN AND ITS IMPLICATIONS IN THE FACE OF WATER SCARCITY

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TITULO: *Evolución de la gestión del regadío en España y sus implicaciones ante la escasez del agua*

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Tesis como compendio de publicaciones

Esta tesis se presenta como compendio de publicaciones, cumpliendo con los requisitos establecidos por la Universidad de Córdoba para este fin. Tres de los seis capítulos de esta tesis se corresponden con dos artículos científicos publicados en revistas incluidas en el primer cuartil según la última relación del Journal Citation Reports (2020), y un artículo publicado en revista incluida en Matriz de Información para el Análisis de Revistas con ICDS superior a 6 para el año de referencia (2020).

1. Espinosa-Tasón, J., Berbel, J., y Gutiérrez-Martín, C. (2020). Energized water: Evolution of water-energy nexus in the Spanish irrigated agriculture, 1950–2017. *Agricultural Water Management*, 233, 106073. Factor de impacto (2020): 4.516. Primer cuartil en el área de Agronomía con la posición 12/91, y en Recursos Hídricos con la posición 16/98.
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TÍTULO DE LA TESIS: Evolución de la gestión del regadío en España y sus implicaciones ante la escasez del agua

DOCTORANDO/A: Jaime Antonio Espinosa Tasón

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(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

El doctorando ingresó a realizar su tesis en el Programa de Doctorado de Ingeniería Agraria, Alimentaria, Forestal y del Desarrollo Rural Sostenible con el beneficio del Programa de Becas IFARHU-SENACYT del Gobierno de la República de Panamá. Inició en septiembre de 2018, llevando a cabo su investigación doctoral en el Departamento de Economía Agraria, Finanzas y Contabilidad con la colaboración del grupo de investigación *Water, Environmental and Agricultural Resources Economics* (WEARE, Grupo del Plan Andaluz de Investigación –PAIDI– SEJ-592).

En la realización del programa de doctorado su trayectoria ha sido excelente, debido a su gran interés y dedicación al mismo. Su compromiso con el desarrollo de la tesis ha sido total, siendo su progreso en el tiempo extraordinario. De los resultados de su investigación de tesis doctoral se han publicado tres artículos científicos, de los cuales dos han sido sometidos a procesos de revisión por pares en revistas científicas de impacto JCR (Q1) y un tercer artículo científico en revista incluida en MIAR con ICDS superior a 6 para el año de referencia. Los resultados de su investigación doctoral han sido igualmente publicados y presentados en diversos congresos científicos.

Esta tesis doctoral se presenta como compendio de publicaciones, a continuación, se enumeran las publicaciones derivadas de la tesis.

Artículos científicos en revistas indexadas en el Journal Citation Reports (JCR):

- Espinosa-Tasón, J., Berbel, J., y Gutiérrez-Martín, C. (2020). Energized water: Evolution of water-energy nexus in the Spanish irrigated agriculture, 1950–2017. ***Agricultural Water Management***, 233, 106073.
  Factor de impacto (2020): 4.516
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- Espinosa-Tasón, J., Berbel, J., Gutiérrez-Martín, C., y Musolino, D. A. (2022). Socioeconomic impact of 2005–2008 drought in Andalusian agriculture. ***Science of The Total Environment***, 826, 154148.
  Factor de impacto (2020): 7.963
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Artículo científico en revista incluida en Matriz de Información para el Análisis de Revistas (MIAR):

- Berbel, J., y Espinosa-Tasón, J. (2020). La gestión del regadío ante la escasez del agua. ***Presupuesto y Gasto Público***, 101, 137-152.
  Índice Compuesto de Difusión Secundaria (ICDS): 6.5

Consideramos que a lo largo de su formación doctoral ha alcanzado la suficiente madurez científica, lo que le ha permitido obtener resultados en su investigación con una alta calidad contrastable internacionalmente, tal y como lo avalan los trabajos aceptados para su publicación.

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

Córdoba, 25 de abril de 2022

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A mis hijos ***Carlos, Iker y Hanna***

A mi familia: los que están y los que se fueron antes
"NOT DEAD, BUT GONE BEFORE"

Agradecimientos

A Dios en quien he puesto mi confianza, gracias por la vida.

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Resumen

La creciente demanda de agua, energía, y alimentos por parte de la población mundial en el actual contexto de escasez de agua y variabilidad debido al cambio climático, ha reforzado una mayor atención al estado cuantitativo y cualitativo de las masas de agua continentales, subrayando la importancia y necesidad de una gestión sostenible del recurso hídrico. En España, la agricultura es el sector con mayor uso de agua, incorporando más del 70% de las extracciones de agua dulce procedente de ríos, embalses y acuíferos. La reciente modernización del regadío, estipulada en el Plan Nacional de Regadíos de 2001, impulsó la adopción de los sistemas de riego localizado y de aspersión-automotriz, disminuyéndose significativamente la superficie de riego por gravedad en la actualidad. La modernización del regadío y la adopción de sistemas más eficientes trajo consigo un considerable aumento del consumo de energía para bombeo y distribución del agua de riego, acentuando el nexo agua-energía-alimento. Además, la disponibilidad de los recursos hídricos al verse afectada por las sequías aumenta la necesidad de gestionar la demanda en un contexto de creciente complejidad en el regadío español.

La presente tesis se estructura en seis capítulos, enfocados a la evolución histórica de la gestión del regadío en España y sus repercusiones en el ámbito de la escasez del agua. El capítulo 1, es la introducción situando en contexto el tema discutido en esta tesis; los objetivos de esta se presentan en el capítulo 2, donde además se detalla la estructura del documento, así como las publicaciones y actividades derivadas de la tesis.

En el Capítulo 3 se describe la evolución del sector del regadío español y se centra en la extracción de agua, el consumo de agua y el uso de energía en el periodo 1950-2017. El análisis muestra la evidencia de que las cuencas han alcanzado el estado de cierre y el impacto en el uso de energía del suministro de riego. La respuesta en el contexto de una demanda de agua creciente con una oferta limitada ha sido la inversión en tecnologías de ahorro y conservación del agua con la transformación de las zonas de riego por gravedad en las de goteo y aspersión, lo que ha supuesto un aumento de la eficiencia del riego. El efecto de esta política implica un aumento del uso de la energía por un factor de seis en

el período, mientras que la superficie regada se triplica y su uso de agua se duplica en el mismo período. La extracción de agua alcanza su máximo en el año 2004 y disminuye ligeramente como consecuencia de las subvenciones a la inversión. El impacto en el consumo de energía en el bombeo y el tratamiento ilustra el nexo agua-energía en la agricultura española y el cambio en el paradigma de la política del agua desde el aumento de la oferta hacia la gestión de la demanda.

En el Capítulo 4, la investigación se centra en los principales cambios de la estructura y uso de la tierra por el sector agrario español en los últimos años con el objetivo de identificar los motores de dichos cambios y su impacto en la productividad, apuntando algunas reflexiones sobre el futuro del regadío en España. Los resultados muestran que desde los años '70 la apertura del país ha provocado que la baja rentabilidad del secano forzara a los agricultores a intensificar la actividad aumentando la superficie regada hasta llegar a un máximo de extracciones de agua alrededor del año 2004, que marca un fin de ciclo y cambio de tendencia, reduciéndose a partir de esa fecha las extracciones para el riego, aumentando el uso de fuentes no convencionales y acelerando el cambio tecnológico. Todo ello ha incrementado la productividad de los factores (agua, tierra, capital) aumentando el diferencial secano-riego por lo que la presión para aumentar extracciones sigue creciendo y solo una gobernanza firme puede garantizar el uso sostenible de los recursos.

El Capítulo 5 investiga el efecto económico de la sequía hidrológica sobre los diferentes grupos sociales (productores y consumidores) para los cultivos de secano y regadío, empleando como estudio de caso la región de Andalucía (sur de España), utilizando el concepto de excedente económico para estimar el impacto de las sequías en el bienestar social. Los resultados muestran efectos negativos sobre el bienestar social regional, con una pérdida global estimada de 1512 millones de euros, aunque este impacto negativo se distribuye de forma desigual. Existe un efecto cantidad (menor rendimiento de cosechas) y un efecto precio (aumento de precios) debido a la reducción de la oferta. En general, las explotaciones de secano experimentan un impacto negativo en sus ingresos, ya que el aumento de los precios sólo compensa parcialmente la reducción de los rendimientos, aunque, paradójicamente, algunas explotaciones de regadío aumentan sus ingresos cuando el aumento de los precios soporta los menores rendimientos. Los consumidores siempre se ven afectados negativamente por la sequía. Este resultado puede ayudar a diseñar modelos de política agrícola y políticas de recuperación de la sequía.

Finalmente, en el Capítulo 6 se sintetizan las principales conclusiones de esta tesis, y las posibles vías de investigación futura en el ámbito de la gestión de los recursos hídricos en España.

Esta tesis resalta la evolución histórica de la gestión del regadío en España y sus repercusiones en el contexto de la escasez del agua. El impacto del cambio climático, la baja o nula rentabilidad del secano y su vulnerabilidad frente a sequías aumentará la presión por regar más tierras. El regadío solo podrá adaptarse a este escenario mediante múltiples estrategias adecuadas a las condiciones locales, como lo son la mejora de la gobernanza, el aprovechamiento de las sinergias en el nexo agua-energía-alimento, los sistemas de riego de precisión, las fuentes de agua no convencionales, así como nuevos instrumentos económicos para gestión y riesgos.

Abstract

The growing demand for water, energy, and food by the world population in the current context of water scarcity and variability due to climate change, has reinforced greater attention to the quantitative and qualitative status of inland water bodies, underlining the importance and need for sustainable management of water resources. In Spain, agriculture is the sector with the highest water use, incorporating more than 70% of freshwater withdrawals from rivers, reservoirs, and aquifers. The recent modernization of irrigation, stipulated in the 2001 National Irrigation Plan, boosted the adoption of localized irrigation and sprinkler-automated irrigation systems, significantly reducing the area currently irrigated by gravity. The modernization of irrigation and the adoption of more efficient systems brought with it a considerable increase in energy consumption for pumping and distribution of irrigation water, accentuating the water-energy-food nexus. In addition, the availability of water resources affected by droughts increases the need to manage demand in a context of growing complexity in Spanish irrigation.

This thesis is structured in six chapters, focused on the historical evolution of irrigation management in Spain and its repercussions in the field of water scarcity. Chapter 1 is the introduction, placing in context the topic discussed in this thesis; the objectives of this thesis are presented in Chapter 2, which also details the structure of the document, as well as the publications and activities derived from the thesis.

Chapter 3 describes the evolution of the Spanish irrigation sector and focuses on water abstraction, water consumption and energy use in the period 1950-2017. The analysis shows evidence that basins have reached closed status and the impact on energy use of irrigation supply. The response in the context of increasing water demand with limited supply has been investment in water saving and conservation technologies with the transformation of gravity irrigated areas to drip and sprinkler irrigation, leading to increased irrigation efficiency. The effect of this policy implies an increase in energy use by a factor of six in the period, while the irrigated area triples and its water use doubles in the same period. Water withdrawal peaks in 2004 and decreases slightly as a result of

investment subsidies. The impact on energy consumption in pumping and treatment illustrates the water-energy nexus in Spanish agriculture and the shift in the water policy paradigm from supply augmentation to demand management.

In Chapter 4, the research focuses on the main changes in the structure and use of land by the Spanish agricultural sector in recent years with the objective of identifying the drivers of these changes and their impact on productivity, pointing out some reflections on the future of irrigation in Spain. The results show that since the 70's the opening of the country has caused the low profitability of rainfed farming to force farmers to intensify the activity by increasing the irrigated area until reaching a maximum of water withdrawals around 2004, which marks an end of cycle and change of trend, reducing from that date onwards the water withdrawals for irrigation, increasing the use of non-conventional sources and accelerating technological change. All this has increased the productivity of factors (water, land, capital), increasing the dryland-irrigation differential, so that the pressure to increase extractions continues to grow and only strong governance can guarantee the sustainable use of resources.

Chapter 5 investigates the economic effect of hydrological drought on different social groups (producers and consumers) for rainfed and irrigated crops, using as a case study the region of Andalusia (southern Spain), using the concept of economic surplus to estimate the impact of droughts on social welfare. The results show negative effects on regional social welfare, with an estimated overall loss of 1512 million euros, although this negative impact is unevenly distributed. There is a quantity effect (lower yield) and a price effect (increase) due to reduced supply. In general, rainfed farms experience a negative impact on their income, as the increase in prices only partially compensates for the reduction in yields, although, paradoxically, some irrigated farms increase their income when the increase in prices supports the lower yields. Consumers are always negatively affected by drought. This result can help in designing agricultural policy models and drought recovery policies.

Finally, Chapter 6 synthesizes the main conclusions of this thesis, and possible avenues for future research in the field of water resources management in Spain.

This thesis highlights the historical evolution of irrigation management in Spain and its repercussions in the context of water scarcity. The impact of climate change, the low or null profitability of rainfed agriculture and its vulnerability to droughts will increase the pressure to irrigate more land. Irrigation will only be able to adapt to this scenario through multiple strategies adapted to local conditions, such as improved governance, taking advantage of synergies in the water-energy-food nexus, precision irrigation systems, non-conventional water sources, as well as new economic instruments for management and risks.

Capítulo 1
Introducción

1.1. Introducción

1.1.1. El regadío en España: del Medioevo al S.XXI

El regadío ha sido un sistema de adaptación al clima mediterráneo tradicional del que hay pruebas en Mesopotamia desde hace seis milenios, no obstante, en el caso de España, no se conocen restos arqueológicos que nos permitan determinar la existencia de un regadío prerromano. El origen del regadío en España, por tanto, se remonta a la época romana (218 a.C. - siglo V) donde aparecen las primeras obras públicas hidráulicas, con el desarrollo de acueductos, embalses y cisternas. Posteriormente a la caída del imperio romano, durante la época musulmana en España (siglos VIII-XV) se perfecciona y consolida el regadío, siendo la civilización árabe la gran impulsora de los regadíos en el Sur de Europa durante el medioevo. Los árabes aprovecharon al máximo la herencia hidráulica romana, añadiendo una mayor complejidad y perfeccionando los sistemas de conducción de agua para riego, difundiendo el regadío fundamentado en pequeños canales, azudes y norias (Nadal, 1980; Box Amorós, 1992).

Durante la reconquista cristiana, se prestó poca atención al regadío. A principios de la Edad Moderna (siglo XV), los reyes se inclinaron por la ganadería, siendo la lana su fuente de riqueza monopólica. El descubrimiento de América y el aumento de la población hicieron necesaria una mayor extensión y cualificación de la agricultura (Nadal, 1980). Los siglos XVI y XVII figuran una nueva etapa con las presas de planta curva; no obstante, las obras de regadío realizadas por los últimos Austrias en España apenas alcanzaron las cien mil hectáreas (López Gómez, 1992).

En el siglo XIX la Ley de Aguas del 13 de Junio de 1879, marcó un hito en el desarrollo de los regadíos de España, estableciendo las bases de una ordenación de los aprovechamientos colectivos de las aguas superficiales, y de la gestión desconcertada y participativa, fundamentalmente a través de las comunidades de regantes (Pérez, 1992). Durante el primer tercio del siglo XX (1913-1934) se celebran los Congresos Nacionales de Riegos (CNR) mediante los cuales se plantea la importancia, defensa y fomento del regadío español; en ellos se desarrolla el argumento de la colonización en el regadío en relación con la población y el poblamiento del territorio (López Ontiveros, 1992).

Después de la guerra civil española, el cuerpo teórico de los CNR sería aprovechado por el franquismo para el consecutivo desarrollo del regadío (López Ontiveros, 2003). La política agraria en la España del siglo XX se basó en gran medida en la transformación de la economía rural mediante la introducción del regadío y el consiguiente aumento de la productividad. Esto permitió el asentamiento del campesinado autosuficiente en los "pueblos de colonización", y un aumento de la riqueza agrícola del país (Leal, 1969; Gómez, 1978; Bosque, 1984).

La planificación de las obras públicas para la expansión del regadío aumentó la superficie regada de 1,4 a 2,2 millones de hectáreas entre 1940 y 1970, al mismo tiempo que la capacidad de los embalses se multiplicó por diez (García-Mollá et al., 2019). Este impulso al regadío a mediados del S.XX se produjo durante un periodo de crecimiento acelerado y de bonanza económica en España entre 1959 y 1974 conocido como el milagro español (Llopis, 2006).

La transición democrática en España (1975-1978) permitió a la agricultura española incorporarse a la revolución verde mundial y acceder a los mercados exteriores. Durante el periodo en que la revolución verde estaba en su apogeo (1960-1980), España aún no había entrado en la Comunidad Económica Europea (CEE). El sector agrario español experimentó entonces una gran agitación tras su adhesión a la CEE en 1986 (Corbelle-Rico et al., 2015).

Después de la adhesión a la CEE se produjeron muchos más cambios significativos en las tierras agrícolas y forestales de los que se habían aplicado antes. Según Ruiz-Maya y González (2019), la evolución de la agricultura española entre el censo de 1982 y el de 2009 supuso importantes cambios estructurales, tanto en el uso de la tierra como en los tipos de agricultura y ganadería, con una drástica disminución del número de explotaciones y de la superficie total cultivada.

1.1.2. La escasez del agua y la gestión del regadío español

La creación de las Confederaciones Hidrográficas en el año 1926 por Real Decreto Ley (definidas en la Ley de Aguas), y posteriormente en 1939 del Instituto Nacional de Colonización, así como los avances tecnológicos alcanzados después, contribuyeron a un desarrollo espectacular de los regadíos españoles durante el siglo XX (Pérez, 1992; MAPA, 2022a).

La integración de España en el mercado europeo y la aplicación de la Política Agrícola Común (PAC) dieron lugar a intentos de modernización de las estructuras agrarias. Esta opción estratégica recibió un gran impulso cuando la extrema sequía del periodo 1990-1995 convenció al Gobierno de adoptar medidas para afrontar el problema de la escasez de agua, aumentando la eficiencia en el uso del agua mediante el apoyo a proyectos de modernización de regadíos (García-Mollá et al., 2019, Berbel et al., 2019).

En la comunidad internacional desde finales del S. XX, se ha otorgado una mayor atención al estado cuantitativo y cualitativo de las masas de agua continentales debido a la creciente demanda de agua, alimentos y energía por parte de la población mundial en el actual contexto de escasez de agua y variabilidad debido al cambio climático, por lo que la importancia y necesidad de una gestión sostenible del recurso hídrico se hace prioritaria (Postel, 2000; Rosengrant and Cai, 2001). Por otro lado actualmente, existe un creciente reconocimiento del nexo agua-alimentos-energía, en un contexto de escasez de agua, variabilidad y cambio climático (Scott et al., 2014).

En España, la agricultura es el sector con mayor uso de agua, incorporando más del 70% de las extracciones de agua dulce procedente de ríos, embalses y acuíferos. La reciente modernización del regadío, estipulada en el Plan Nacional de Regadíos de 2001, impulsó la adopción de los sistemas de riego localizado y de aspersión-automotriz representando para el año 2017 respectivamente el 51% y 24% del total de la superficie de regadío, disminuyéndose significativamente la superficie de riego por gravedad, representando un 25% en la actualidad (MAPA, 2022b). La modernización del regadío y la adopción de sistemas más eficientes trajo consigo un considerable aumento del consumo de energía para bombeo y distribución del agua de riego (Rodríguez et al., 2011), por lo que existe un fuerte nexo entre agua y energía en el regadío español aumentado cuando las fuentes no convencionales (desalinización y reutilización) se incorporan a la oferta de agua en zonas de elevada escasez.

Además de la mencionada sequía de 1990-1995 como factor catalizador de la modernización, uno de los factores impulsores y decisivos para la modernización ha sido la imposibilidad de aumentar la oferta de agua en muchas cuencas españolas, lo que es conocido como cierre de cuencas (Molle et al., 2010). El paso hacia una economía madura del agua según indica Randall (1981) se caracteriza por una oferta inelástica de nuevos recursos hídricos, la necesidad de una costosa reposición de infraestructura ya amortizada, y el enfoque de la política hacia formas de restringir la demanda de agua y reasignar los recursos existentes.

A nivel de cuencas hidrográficas el cierre y la escasez también pueden ocurrir en subcuencas o pequeñas cuencas, mientras que la cuenca más amplia permanece abierta; de esta manera, el cierre de cuencas incluye casi invariablemente el desarrollo de infraestructura (presas y embalses) con una demanda potencial de agua que supera los recursos de la cuenca (Molle et al. 2010). En este contexto cualquier nueva demanda de agua debe satisfacerse mediante la reducción de otros usos de agua existentes, por lo que el énfasis en los enfoques del lado de la oferta solo intensificaría la presión sobre el recurso agua. En la literatura existen múltiples ejemplos de cómo alcanzar una reasignación más eficiente del recurso agua, empleando instrumentos económicos de la política del agua del lado de la demanda, como son los precios del agua y los mercados del agua (Zilberman & Schoengold, 2005; Lago et al., 2015; Montilla-López et al., 2018).

Para el caso de España, Expósito y Berbel (2017) analizaron cómo el uso del agua para riego agrícola ha afectado el proceso de cierre de la cuenca del río Guadalquivir, observándose durante el periodo 2005-2012 una reducción significativa en las dotaciones de agua por superficie regada, y la tendencia de los agricultores a utilizar el recurso de manera más eficiente a través de la modernización de sus sistemas de riego, la generalización del riego deficitario y las técnicas de alta precisión. Sin embargo, la asignación puede verse afectada por los cambios en el uso de la tierra, los patrones de escorrentía o los valores de la sociedad, por lo que la reasignación de agua entre usuarios y sectores se hace necesaria para aumentar la productividad del agua o mejorar la seguridad alimentaria, corregir las desigualdades o restaurar los caudales naturales de los ríos.

El regadío se puede entender como una respuesta del agricultor a las condiciones del clima mediterráneo con lluvias en invierno y demandas evaporativas en verano, por lo que la existencia de sistemas que permitan trasladar el agua entre estaciones (de otoño-invierno a primavera-verano) o desde zonas de montaña a tierras más fértiles consigue el objetivo de aumentar la producción de alimentos y adaptarse a la escasez estructural de los sistemas mediterráneos donde la evapotranspiración potencial (ETP) es muy superior a los recursos disponibles por la planta. El regadío por tanto se puede considerar como una respuesta a la escasez estructural, pero así mismo supone una reducción del riesgo derivado de la escasez coyuntural, es decir, las sequías que forman parte del clima mediterráneo y que consisten en una reducción de las precipitaciones por debajo de la media que impacta a los cultivos y ecosistemas.

La sequía es un problema frecuente en España, que afecta de manera temporal a la disponibilidad de los recursos hídricos, provocando impactos sociales, económicos y ambientales; situación que aumenta la necesidad de gestionar la demanda de los recursos hídricos en un contexto de creciente complejidad y múltiples visiones del mundo. En diferentes regiones del mundo, los recientes episodios de sequías han actuado como catalizadores de cambios legislativos e institucionales en materia de gestión de agua (Berbel y Esteban, 2019). Asimismo, en el contexto del cambio climático y de la seguridad alimentaria, a medida que los episodios de sequía se vuelven cada vez más frecuentes, sumándose a los crecientes problemas de escasez de agua, es fundamental medir los importantes efectos económicos y sociales que se generan.

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Capítulo 2
Objetivos y estructura de tesis

2.1. Objetivos

Se plantea como objetivo general de la presente investigación de tesis doctoral analizar la evolución histórica de la gestión de los recursos hídricos del regadío en España y sus repercusiones en el contexto de la escasez del agua.

Para lograr este objetivo, se han formulado los siguientes objetivos específicos:

1. Determinar las condiciones e impactos del cierre de cuencas en el uso del agua y el consumo energético asociado al regadío en España.
2. Analizar los principales cambios en la estructura y gestión del regadío español, identificando los motores de estos cambios y su impacto.
3. Determinar el efecto económico de la sequía en España para los productores y consumidores, tanto en los cultivos de secano como en los de regadío.

2.2. Estructura de la tesis

Esta tesis está organizada en seis capítulos. Tras la introducción (**Capítulo 1**) y los objetivos perseguidos en esta tesis (**Capítulo 2**), los consecuentes capítulos considerados son:

El **Capítulo 3** analiza la evolución del consumo del binomio agua-energía en el regadío español durante el período 1950-2017 para comprender el impacto del aumento de la eficiencia en el uso del agua, el consumo de energía y los flujos de retorno. Este capítulo ha sido publicado como artículo con el título "Energized water: Evolution of water-energy nexus in the Spanish irrigated agriculture, 1950–2017" (2020) por Espinosa-Tasón J, Berbel J, Gutiérrez-Martín C en *Agricultural Water Management*.

En el **Capítulo 4**, la investigación se centra en los principales cambios de la estructura y uso de la tierra por el sector agrario español en los últimos años con el objetivo de identificar los motores de dichos cambios y su impacto en la productividad, apuntando algunas reflexiones sobre el futuro del regadío en España. Este capítulo corresponde al artículo publicado con el título “La gestión del regadío ante la escasez del agua” (2020) por Berbel J, Espinosa-Tasón J en *Presupuesto y Gasto Público*.

El **Capítulo 5** investiga el efecto económico de la sequía hidrológica sobre los diferentes grupos sociales (productores y consumidores) para los cultivos de secano y regadío, empleando como estudio de caso la región de Andalucía (sur de España), utilizando el concepto de excedente económico para estimar el impacto de las sequías en el bienestar social. Este capítulo corresponde al artículo publicado con el título "Socioeconomic impact of 2005–2008 drought in Andalusian agriculture" por Espinosa-Tasón J, Berbel J, Gutiérrez-Martín C, Musolino DA en *Science of The Total Environment*.

Finalmente, en el **Capítulo 6** se detallan las conclusiones de esta tesis, y las vías de investigación futura en el ámbito de la gestión de los recursos hídricos en España.

Igualmente, en relación con la estructura de la tesis conviene señalar que, para no alterar el texto original, están redactados en inglés los capítulos 3 y 5.

2.3. Publicaciones y actividades derivadas de la tesis

Durante la realización de las tres publicaciones que forman el cuerpo principal de la tesis, se desarrollaron otras publicaciones procedentes de comunicaciones en congresos científicos. A continuación, se muestran todas las publicaciones que se han derivado de la investigación de tesis.

Artículos en revistas indexadas en el Journal Citation Reports (JCR):

- Espinosa-Tasón, J., Berbel, J. and Gutiérrez-Martín, C. (2020). Energized water: Evolution of water-energy nexus in the Spanish irrigated agriculture, 1950–2017, ***Agricultural Water Management*** 233, 106073. doi.org/10.1016/j.agwat.2020.106073

  Factor de impacto (2020): 4.516
  Categoría y posición: Agronomy 12/91 (Q1); Water Resources 16/98 (Q1)

- Espinosa-Tasón, J., Berbel, J., Gutiérrez-Martín, C., & Musolino, D. A. (2022). Socioeconomic impact of 2005–2008 drought in Andalusian agriculture. ***Science of The Total Environment***, 154148. doi.org/10.1016/j.scitotenv.2022.154148

Factor de impacto (2020): 7.963
Categoría y posición: Environmental Sciences 25/274 (Q1)

Artículos en revistas incluidas en Matriz de Información para el Análisis de Revistas (MIAR):

- Berbel, J., Espinosa-Tasón, J. (2020) La gestión del regadío ante la escasez del agua. ***Presupuesto y gasto público***, ISSN 0210-5977, Nº 101, 2020 (Ejemplar dedicado a: El agua en España: economía y gobernanza), págs. 137-152.

  Índice Compuesto de Difusión Secundaria (ICDS): 6.5

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- Espinosa-Tasón, J; Gutiérrez-Martín, C; Berbel, J. (2019). *La evolución del agua y la energía en el regadío español.* En Congreso Nacional del Agua 2019: Innovación y Sostenibilidad. Orihuela (Alicante), 21 y 22 de febrero de 2019.
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- Espinosa-Tasón, J., Berbel, J. (2021). *Evaluación Ex-Post del impacto económico de la sequía hidrológica en la agricultura andaluza 2005-2008*. III Congreso Nacional del Agua. Fenómenos extremos: sequías e inundaciones. Orihuela (Alicante), del 30 de septiembre al 01 de octubre de 2021.

Capítulo 3

Energized water: Evolution of water-energy nexus in the Spanish irrigated agriculture, 1950-2017

Energized water: Evolution of water-energy nexus in the Spanish irrigated agriculture, 1950-2017

***This chapter has been published entirely in the journal "Agricultural Water Management", Espinosa-Tasón J, Berbel J, Gutiérrez-Martín C** (2020)*

Abstract

This study describes the evolution of the Spanish irrigated sector and focuses on water abstraction, water consumption, and energy use in the period 1950-2017. The analysis shows evidence of the basins reaching closure state and the impact on energy use from irrigation supply. The response in the context of an increasing water demand with a limited supply has been investment in water-saving and conservation technologies (WSCT) with the transformation of furrow-irrigated areas into those of drip and sprinkler, resulting in an increase in irrigation efficiency. The effect of this policy implies an increase in energy use by a factor of six in the period while the irrigated area triples and its water use doubles in the same period. Water abstraction reaches its peak in the year 2004 and decreases slightly as a consequence of subsidies to WSCT. The impact on energy consumption in pumping and treatment illustrates the water-energy nexus in Spain's agriculture and the change in the water policy paradigm from supply augmentation towards demand management.

***Keywords**: Water-energy nexus, Irrigation, Spain, Water accounting, Basin closure, Irrigation Efficiency, Non-conventional water sources.*

3.1. Introduction

Water scarcity constitutes a major concern for both developed and developing countries. Economic development generally involves an increase in water demand and its value since new uses (industry, urban settlements, and/or environmental concerns) or food production cause an increase in the use of the resource. In order to satisfy increased demand, the traditional response has been to increase supply. However, supply-side measures are limited when maximum capacity for water supply is reached and basins or aquifers are defined as 'closed' (Molle et al., 2010). Basin closure implies that any new demand can be satisfied only by reallocating water rights from existing users.

Investment in water-saving and conservation technologies (WSCT) has been a common response to the limited supply in closed basins, as has increasing energy consumption, since they are closely related (Zaman et al., 2012). As a consequence, management of water resources is expected to challenge not only freshwater resources but also energy-source constraints in many countries (Lee et al., 2018).

The water-energy-food (WEF) nexus has recently appeared as a research priority in academic and institutional settings (Zhang et al., 2019b). The framework initially appeared as a way to clarify the physical relationships between components, although more recently, certain specific methodologies have been proposed for the systemic analysis of the WEF nexus with the ultimate goal of reporting on nexus-related responses in terms of strategies, policy measures, planning, and institutional set-ups and/or interventions (Flammini, 2014). Albrecht et al. (2018) systematically reviewed the literature available on the WEF nexus and concluded that a significant share of approaches strive to improve resource-use efficiency between the WEF sectors, while Dargin et al. (2019) analysed how the water-energy-food nexus assessment tools vary in complexity and applications.

The WEF nexus involves various concepts (Huckleberry and Potts, 2019): (a) Water-energy, which refers to the consumption of energy to capture, store, transport, and purify water as well as for wastewater treatment; (b) Energy-water, which measures the use of water for either thermoelectric or hydropower energy production; (c) Energy-food, which measures the use of energy for machinery and equipment for crops and the energy for transport of intermediate and final products; and finally (d) Water-food, as the water needed to grow crops. Additionally, a fifth component involves the analysis of biomass for energy production.

This paper will focus exclusively on the first component, that is, the water-energy (WE) nexus as a subset of the WEF comprehensive framework. This is carried out by describing and estimating the water abstracted and consumed and the energy employed in supplying water for agriculture and by applying a methodology for the analysis of the evolution of irrigation water in Spain which can be considered representative of the adaptation to water scarcity of a semiarid (Mediterranean) developed country. Spain has addressed the issue of water scarcity with an extensive water reservoir network which makes the country the first in the ranking of per capita water reservoirs. Nevertheless, the increase in water storage has reached a limit and the majority of the basins have entered the closure stage (Berbel et al., 2013). As a response to the closure process, in the period 2002-2015, the country carried out an intense irrigation modernization process as an alternative to the limited availability of supply augmentation (Berbel et al., 2019). This investment in water-saving equipment and infrastructure has resulted in a growing consumption of energy by farmers (Fernández García et al., 2014; Rodríguez-Díaz et al., 2011).

This paper aims to illustrate the water-energy nexus in agriculture by conducting an in-depth analysis of a relevant case study with a long time series (1950-2017). The analysis of the evolution of Spanish irrigated agriculture will allow us to gain a perspective regarding not only the trajectories for water resources and the public and private response to scarcity of increasing energy consumption, but also of the effects of these responses.

In Spain, the policy of subsidies for water-saving infrastructure has played a major role and the responses regarding water-saving and increased energy consumption are well documented. This policy shows the water-energy nexus and highlights how water savings have been achieved at the expense of higher energy consumption, and therefore underlines the relevant need to integrate energy and water issues together in all decisions related to energy generation and water abstraction (Hardy and Garrido, 2012; Mayor Rodríguez, 2017; Villamayor-Tomas, 2017).

After describing the state of the art in the analysis of water-use efficiency and energy consumption in following section, we explain how the data gaps in the long-term have been addressed by detailing the methodology that is described in the third section. The results of the methodology that covers the complete series for the relevant water and energy variables are described in the fourth section, while the fifth section discusses the main findings, and the closing section proposes future avenues of research.

3.2. Current state of knowledge on water abstraction efficiency and energy consumption

The water-energy (WE) nexus is an emerging and significant topic in the research agenda worldwide. The role of institution and policies in the United States has been studied by Scott et al. (2011), who highlight the need for improved coordination between water and energy policy. Mercure et al. (2019) analysed the nexus in Brazil, and concluded that energy, water, and food are highly interrelated, and that policy for managing one probably affects the other two factors in often unpredictable ways; they recommend adjusting the scientific approach as an enabling condition for the strengthening of science-policy bridges.

Given the yield benefits from irrigated agriculture relative to rain-fed agriculture, in the future it is likely that society will demand more from irrigated agricultural production. Schwabe et al. (2017) analyse the trends over the past 35 years for the water-energy nexus in irrigated agriculture in the United States and indicate there has been a significant increase in the adoption of irrigation systems of a more efficient nature and show how, between 1950 and the early 1980s, the acreage under irrigation nearly doubled. These changes, plus environmental restrictions and rising energy costs associated with electricity, could be the factors that motivate an overall decline in water application rates.

In the USA, the irrigation withdrawal declined by 9% from 2005 to 2010, which continued the trend from 2000 to 2005 (Barber, 2014). According to Wang (2019), the reduction in water abstraction may be explained by increased technical efficiency supported by government subsidies. Wang (2019) indicates the USDA's Environmental Quality Incentives Program (EQIP) provided $4.2 billion in payments to landowners, and nearly a quarter of these payments were spent on support new irrigation systems in the years 1997 to 2010, and this author estimates the average technical irrigation efficiency as 0.73 for the year 2010; this efficiency is higher than global world average irrigation efficiency, which has been estimated at 65% (Postel et al., 1996). Huckleberry and Potts (2019) estimate the energy consumption for water pumping for the Lower Colorado River Basin to be approximately 88 kWh/hm^3.

In the Murray Darling Basin (Australia), the volume of water diversions (abstractions) for irrigation was in steady decline from 1997-98 to 2017 (with a small increase in the two years after the Millennium drought). This reduction is due both to direct buyouts of water rights by the Government and by a program of 3.5 billion Australian dollars for farmers' infrastructure subsidies (Grafton, 2019).

As mentioned earlier, in addition to USA, Australia, and Spain, several countries provide on-farm and off-farm subsidies to irrigators for water infrastructure (Perry et al., 2017) with the hypothesis that increasing irrigation efficiency will reduce water overexploitation and increase water availability for other uses including those of the environment. The debate of the unintended consequences of this policy, known as the 'rebound effect', will be discussed in the following sections with focus on the Spanish case.

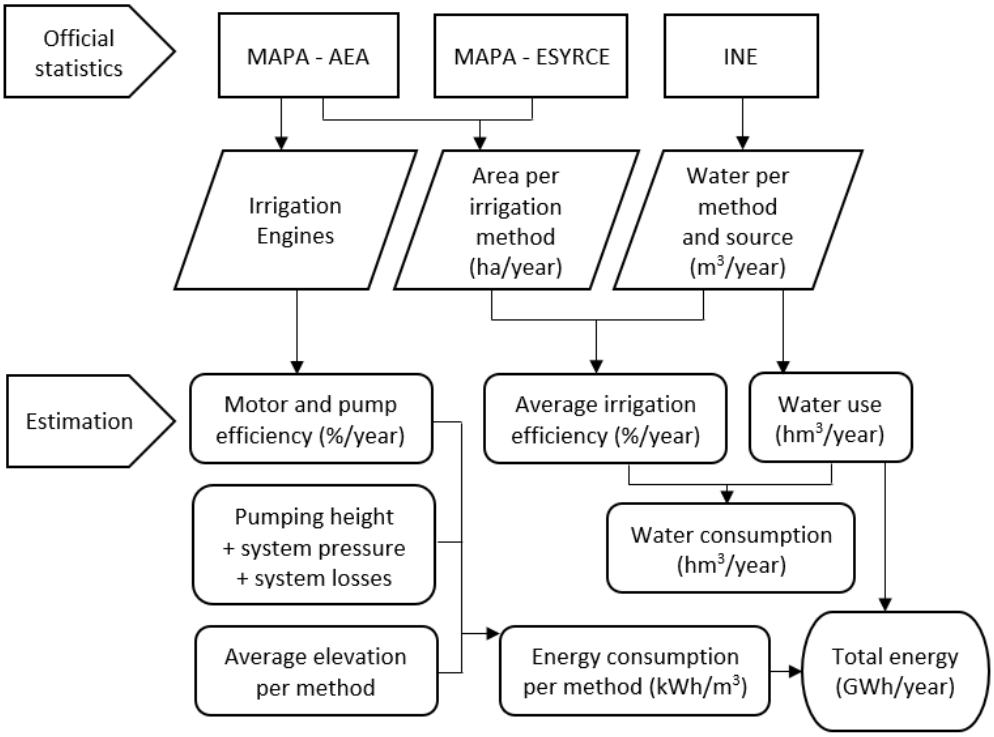
3.3. Methodology and data

The basic material of this research is that of the official published data, although data gaps have been solved with certain estimations when the variable of interest is not directly registered. The objective is the analysis of the long-term evolution of Spanish irrigation water abstraction and of the consumption of energy for irrigation. The methodology is described in Figure 3.1 and shows the data source and the estimation process for the final variables.

Regarding terminology, the definitions proposed by the System of Environmental and Economic Accounting (SEEA) of the United Nations Statistics Division will be used, and specifically those of the SEEA-Water (United Nations, 2012) which define: (a) water abstraction (or withdrawal) is the amount of water that is removed from any source, either permanently or temporarily; (b) water consumed is assumed to be equal to evapotranspiration; and (c) return flow represents the water that returns to the basin after irrigation is performed. Regarding energy variables, the use and consumption of energy are taken as being synonymous.

Official data sources comprised statistical series from various bodies of Spanish government, which included the Ministry of Agriculture, Fisheries and Food (MAPA) for the total irrigated area, and for the area by irrigation method. MAPA also provides the number of engines related to irrigation pumps. The National Statistical Office (INE) provides water abstraction data in terms of irrigation method and source. Hydrological variables, such as water-table level (groundwater use) and efficiency of water distribution systems, was available from the Ministry of Environment (MITECO). The energy use has been estimated with engineering equations related to the volume of pumped water.

Figure 3.1. *Methodological scheme.*



A summary of the methodology, detailing the type of variables and the data source, is shown in Table 3.1.

Table 3.1. *Data source, parameters, and variables (observed and estimated)*

1. Observed variables	**Source**
a) Total irrigated area	MAPA (2019a): 1950-2017
b) Irrigated area by irrigation system	MAPA (2019a), MAPA (2019b): 1972-2017
c) Water abstraction[1] (m^3) by irrigation method	INE (2019a), INE (2019b): 1999-2016
d) Water use (hm^3) by source: surface water, groundwater, desalinated and reclaimed water	INE (2019b): 2000-2016
e) Number of diesel and electric engines for irrigation	MAPA (2019a): 1955-1996
f) Groundwater depth average	MITECO (2019b): 2000-2011
2. Parameters required for the model based on values found in the literature	**Source**
a) Irrigation efficiency by system: furrow 60%; sprinkler 80%; and drip 90	Berbel et al. (2018), Brouwer et al. (1989), Daccache et al. (2014), Zhang et al. (2019a)
b) Efficiencies of conveyance and distribution for irrigation were assumed: 90% and 90%	CHG (2012), Junta de Andalucía (2011)
3. Estimated variables	**Source**
a) Water consumption	Water abstraction multiplied by irrigation system efficiency
b) Return flow	Water abstraction minus water consumption
c) Energy consumption for pumping	Based on the equation [1] (Daccache et al., 2014)
d) Energy consumption required for desalinated water and reclaimed water	IDAE (2010), Lapuente (2012), López Unzu (2018), Martínez Álvarez et al. (2019)

(1) INE statistics refer to the water used, which is equivalent to water abstracted.

3.3.1. Irrigated area by irrigation method

The total irrigated area is probably the data known with the greatest reliability. The report "Survey on Areas, Yields and Crops" (ESYRCE in Spanish), published by MAPA, is the source for the years 2002-2017; while for the remaining years we use the Statistical Yearbook (AEA in Spanish), published by MAPA for the period 1950-2001. Data on irrigation systems by method (furrow, drip, and sprinkler) has been available since 1972 (MAPA-AEA). From 2002, a more detailed ESYRCE survey has been available.

The missing data per time period is shown in Table 3.2. A first analysis consisted of a preview of sequence charts. Missing values in the input data were subsequently replaced with imputed values, using a linear interpolation replacement method executed in time-series forecasting software from IBM® SPSS®. The following criteria were assumed: a) sprinkler irrigation was introduced in the late 1960s, whereby year 1967 is assumed as the initial year; and b) drip irrigation was introduced at the beginning of the 1980s, whereby year 1981 is assumed as the initial year.

Table 3.2. *Missing data in the time series per period.*

Method	Missing Data per time period	Missing values	(%)
Furrow	1967-1971, 1980-1988, 1990-1996, 2000-2001	23	34
Sprinkler	1967-1971, 2000-2001	7	10
Drip	1980-1988, 1990, 1992-1996, 2000-2001	17	25

The total irrigation area continuously grew in the period by approximately 1% annually with a smaller growth rate in the period 1998-2006 although growth rates returned to above 1% in 2007-2017. The lower growth rate in 1998-2006 may be due to the period of intense modernization where investment was largely directed inside the already existing irrigable areas[1]. It should be noted that drip irrigation at present occupies the largest share nationwide, amounting to 51% of the total irrigated land. Figure 3.2 shows the evolution of the irrigated area in terms of total area and irrigation methods.

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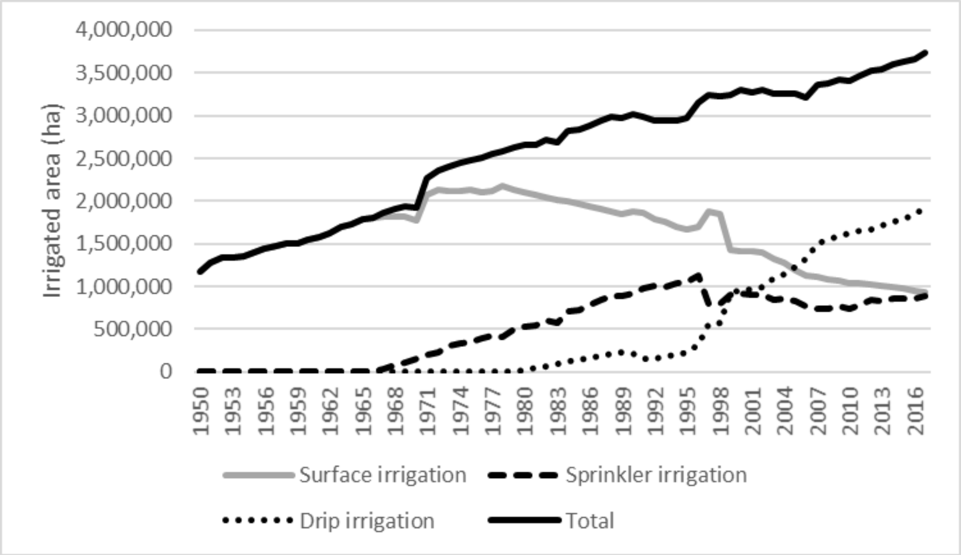
[1] Areas with water rights but not necessarily irrigated

Figure 3.2. *Irrigation area in Spain, 1950-2017. Source: Own elaboration based on data from MAPA.*



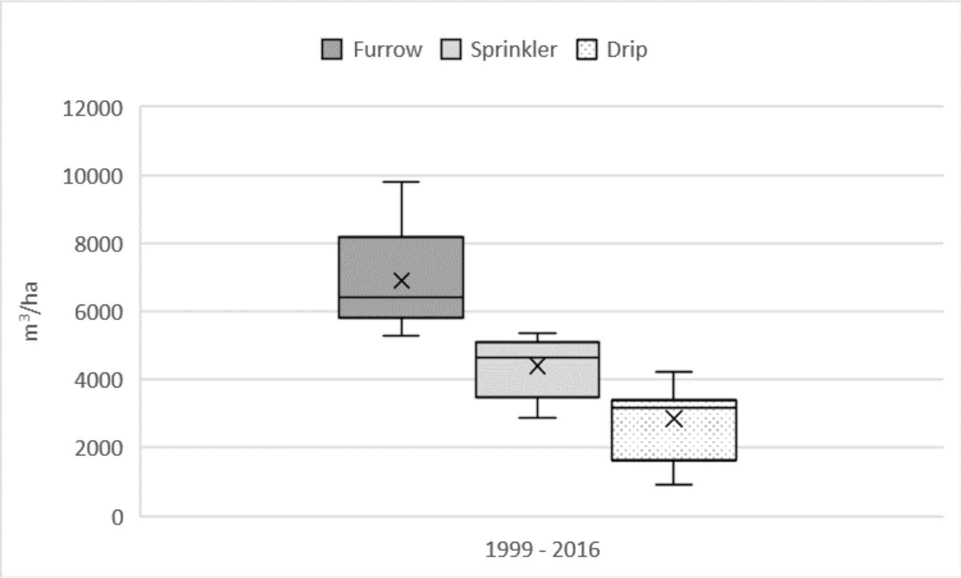
3.3.2. Water abstraction and water consumption per irrigation method

Since 1999, the National Statistical Office (INE) has recorded the volume of water abstracted by different sectors of the economy. In the agricultural sector, the statistics include volume of annual water abstracted in terms of irrigation methods and resource origin. As shown in Figure 3.3, the annual water abstracted differs significantly in accordance with the method of irrigation.

In order to complete the gap in the data regarding water abstraction from 1950-1998, medians from the available years of 1999-2016 were used as the most robust measure of central tendency for a retrospective extrapolation. To this end, the median of annual water allocated per hectare (m^3/ha) in accordance with the irrigation method was multiplied by the irrigation area in accordance with the system for the estimation of the water abstracted by each system in the period 1950-1998.

The variable water abstracted per system is essential for the computation of the energy consumed by each irrigation method and is subsequently aggregated (see the following section).

Figure 3.3. *Water applied (m³/ha) per irrigation method, 1999-2016. Source: Own elaboration based on data from INE.*

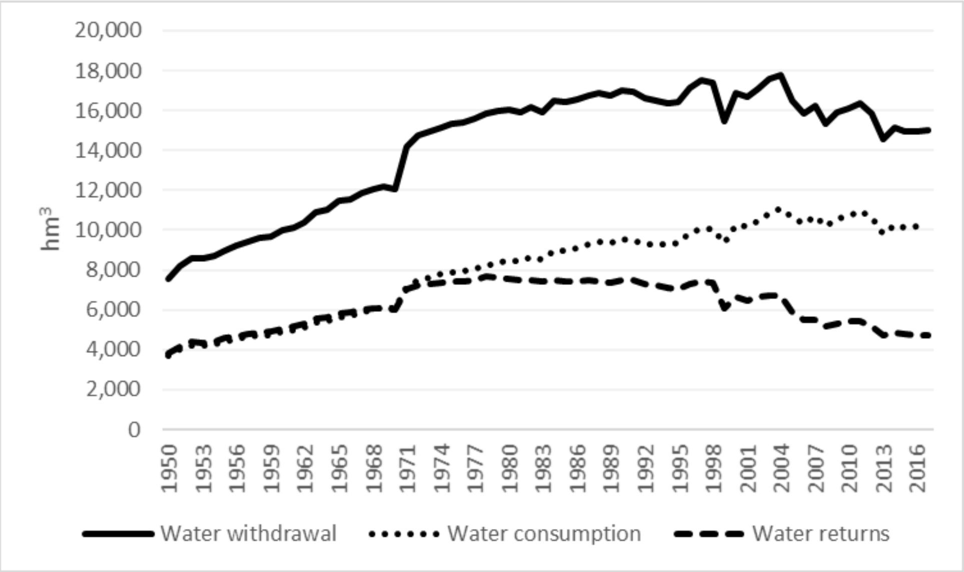


The irrigation method determines the efficiency in the use of water, which we considered as the ratio of evapotranspiration (water consumed by the crops) with water abstraction. Although there are several estimates of the average application efficiency of each irrigation method, our approach considered indicative standard values of the same. These values are the same assumed in several irrigation water management literature (Berbel et al., 2018; Brouwer et al., 1989; Daccache et al., 2014; Zhang et al., 2019a). The application efficiencies that were used in this work are 60% for surface irrigation, 80% for sprinkler irrigation, and 90% for drip irrigation.

For conveyance and distribution efficiency values we relied on the irrigation and hydrological plans 2000s, considering as a representative sample of agricultural irrigation in the north and south of Spain the Guadalquivir and Duero river Basin. Considering the proportion of pipelines, covered canal, grounded canal, drained and ground ditches, in the south the conveyance and distribution efficiencies have a weighted average of 92% and 92% respectively (CHG, 2012; Junta de Andalucía, 2011). In the Duero river basin, conveyance and distribution efficiency approximate 94% and 88% respectively (CHD, 2019). In our analysis the efficiency of conveyance and distribution for irrigation were assumed at 90% and 90%, respectively, for surface water source and 100% for groundwater. By applying these efficiencies to the irrigated areas per system, the parameter of irrigation efficiency can be estimated.

The determination of real crop evapotranspiration presents a complex agronomic research task and no data is available at the regional or national scale, therefore the proposed approach constitutes a step in the direction of quantifying water abstraction and water consumption, whose importance is highlighted below. The estimated global system average efficiency for all irrigation of the national territory increases from 0.49 in 1950 to 0.69 in 2017 (including conveyance losses), while farm application efficiency increases from 0.60 in 1950 to 0.80 in 2017. Figure 3.4 shows the values of water abstraction, consumption, and returns, the latter having been measured as the difference thereof.

Figure 3.4. *Volume of water abstracted, consumption, and return flows in Spain, 1950-2017. Source: Own elaboration based on data from INE.*



The volume of water abstracted has increased in parallel to the irrigated area (see Fig. 3.2) 1950-2004, reaching a maximum at 17,808 hm3. The water consumed is estimated by multiplying water abstractions by conveyance and distribution efficiency. Irrigation returns are defined as the differences between abstraction and consumption; Figure 3.4 shows that return flows decrease from 1980 although the return flows decrease faster from 2004 according to our estimation.

3.3.3. Energy consumption

The energy consumed in irrigation depends directly on the volume pumped, the irrigation system, the efficiency of the pump, and the motor's source of fuel. As shown in Figure 1, the proposed methodology for the estimation of energy consumption of Spanish irrigation is related to the volume of water used by each system, either from official data or from our own estimation for those years prior to the availability of the series. Equation [1] estimates energy use as a function of water abstracted (m3) and total pressure head (TH), which is in turn estimated in equation [2].

$$Energy\ (kWh) = \frac{Volume\ (m^3) \cdot TH\ (m)}{367 \cdot \mu_{pump} \cdot \mu_{motor}} \qquad [1]$$

TH is the sum of: Lift (depth to groundwater); and H min which is the typical working pressure of the different systems (surface irrigation = 0, sprinkler = 3 bars, and drip = 1 bar). Additional pressure is normally added at the head of these systems to guarantee uniformity, pressure losses of around 20% are assumed from friction in the irrigation system.

$$\mathrm{TH}_{(m)} = Lift_{(m)} + H_{\min(m)} + f_{Losses(m)} \qquad [2]$$

An additional pumping energy (lift) was considered for water abstracted from groundwater when compared to direct abstraction from surface water sources. The pumping lift data were derived from the groundwater depth average from 2000-2011 (MITECO, 2019b) and weighted depending on the mix of abstraction sources (surface and groundwater) each year. The groundwater depth average was approximately 60 m;

the global water table depth dataset (Fan et al., 2013) indicates for Spain a range essentially between 20-80 m below land surface.

Once the necessary pressure is determined, the energy consumed by the pumping systems is calculated with eq. [1], which is widely used in irrigation engineering (see Daccache et al., 2014). This equation relates the volume extracted (m^3) with the work pressure contributed height (m) and is divided by a factor that relates the water volume with energy (kWh) and two factors. These factors are the efficiency of the pump in converting the motor energy into hydrodynamic pressure with µ_pump = 0.8 regardless of the power source used, and the efficiency of the motor, taken as µ_motor = 0.4 for diesel engines, where there is a large loss of energy in the form of heat, and 0.9 for electric motors, which are more efficient. The number of pumps powered by electric power have been increasing progressively since the 1980s in Spain, and the evolution of electric vs. diesel pumps is also considered in the model.

Data for engines were available for years 1955-1996. We estimated the missing data by regression from period 1980-1996 to fit a trendline curve to compute forecasts giving 3% of cumulative increase for electric motors that showed a similar annual growth rate (≈ 3%), that increased the electricity use by farms.

Regarding the use of energy for furrow irrigation, some of the farms may not use any energy (pumping height =0) however, others use water from a lake, or a river and need a certain level of pumping. As a proxy for the energy required for transport of surface water to the field, we used 5 meters of pressure as energy required for all surface irrigation (conveyance and transport). In the case of sprinkler and drip irrigation systems at farm plot, there would be a need for additional pressure.

Data on annual water supply by alternative water sources (reclaimed and desalination) is available from Statistical Office (INE). During the period 2000-2017, reclaimed water was regularly around 1.48% of the total irrigation water supply. Desalinated water has been steadily growing from near zero in the year 2000 to 0.94% of water supply in 2017. Energy consumed by reclaimed water account for a stable share on average of 14% of the total energy consumption (2000-2017 period), while desalinated water has grown from almost zero (2000) to 22% of total energy in (2017). It should be noted the enormous impact of desalination and reclaimed water in the energy consumption of the irrigated sector as deduced from the abovementioned figures.

3.4. Results

The water-energy nexus trajectory for irrigation in Spain yields several interesting results, where the annual water abstraction and energy consumption is plotted for the series 1950-2017 (Fig. 3.5). On the left, Figure 3.5 all annual data are shown, whereas the right of the figure focuses on critical years, to show a clearer presentation of the evolution avoiding temporal fluctuations (e.g. droughts or very humid years). Also, the right of the figure is linked to Table 3.3 proposing some historical phases in the period under analysis. The curve becomes gradually more vertical as the water abstracted reaches the available volume (this event is called 'basin closure') and the increased area causes an increase in energy consumption (Fig 3.2).

The evolution of water abstractions and energy consumption can be categorized into different periods, which illustrate the changes in the contexts: a) transition from open basins (new demand can be satisfied with additional supply) to closed basins (new demand requires re-allocation from already existing uses); b) conversion from traditional (furrow, open channels) to pressurized and precision irrigation; and c) introduction of alternative supply sources in the form of desalination and wastewater reclamation. The combination of these three changes in context provides the explanation of the behaviour of the WE nexus in the period 1950-2017 (Fig. 3.5).

The selected years on the right in Figure 3.5 and Table 3.3 indicate milestones in the series for water withdrawal with the estimated water consumption that follows a related trajectory. We propose four stages in the evolution of the water-energy nexus in Spanish irrigation as summarized in Table 3.3, illustrated for variables per volume, energy use and per area water use in Figure 3.6.

Figure 3.5. Evolution of water abstracted and consumed vs. energy used for irrigation in Spain.

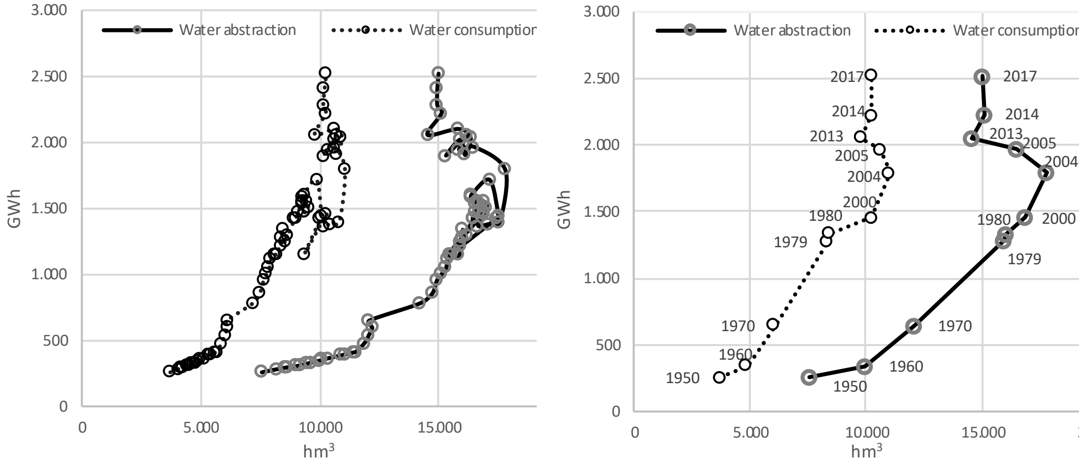
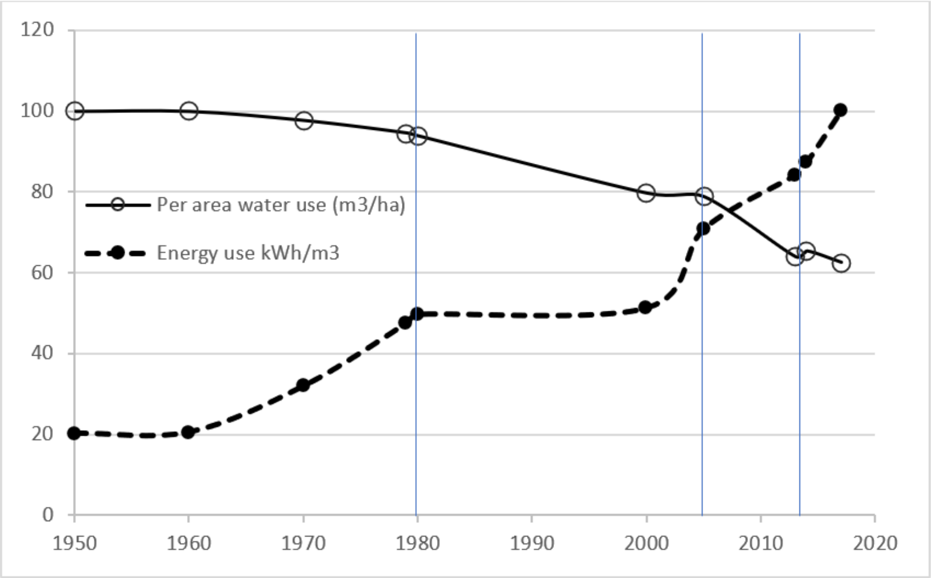


Table 3.3. Estimated water withdrawal, water consumption, irrigated area, and energy consumption in Spain in selected years.

Indicator	Year						Annual growth (%)			
	1950	**1960**	**1980**	**2004**	**2013**	**2017**	*1950-1979*	*1980-2004*	*2005-2013*	*2014-2017*
Irrigated area (10^3 ha)	1179	1555	2656	3264	3541	3734	*2.8%*	*0.9%*	*1.0%*	*1.2%*
Water abstraction (hm^3)	7568	9984	16016	17808	14535	14998	*2.6%*	*0.4%*	*-1.6%*	*-0.3%*
Water consumption (hm^3)	3721	4909	8436	11065	9794	10277	*2.8%*	*1.1%*	*-1.0%*	*0.1%*
Energy consumption (GWh)	258	345	1336	1788	2056	2520	*5.5%*	*0.5%*	*-1.4%*	*1.1%*
Per area water abstraction (m^3/ha)	6419	6419	6031	5456	4105	4017	*-0.2%*	*-0.4%*	*-2.6%*	*-1.5%*
Application Efficiency	0.60	0.60	0.64	0.76	0.79	0.80	*0.2%*	*0.7%*	*0.4%*	*0.3%*
Energy use kWh/m^3	0.03	0.03	0.08	0.10	0.14	0.17	*2.9%*	*0.8%*	*2.2%*	*4.5%*

Source: Own elaboration from various sources.

Figure 3.6. *Evolution of per hectare water abstracted and per volume energy use in Spain.*



The main indicators from Table 3.3 and Figure 3.6 can serve as a basis for the definition of four transforming stages of development in the WE nexus, and these are:

Area expansion (1950-1979): There is a strong positive correlation between the water abstraction and the irrigated area. The milestone that signals the end of the phase may be the transition of the Franco regime to democracy (1975-1978), the economic crisis during 1975-1982, and the existence of a severe long drought (1978-1984). The increase in the volume of water abstraction gradually forced a greater use of energy, although the slope is moderate, since in the 1970s, the adoption of sprinkle irrigation systems boosted the WE dependence. The water scarcity is not evident in this stage since the water allocation is stable and the area and abstracted volume follow parallel trends.

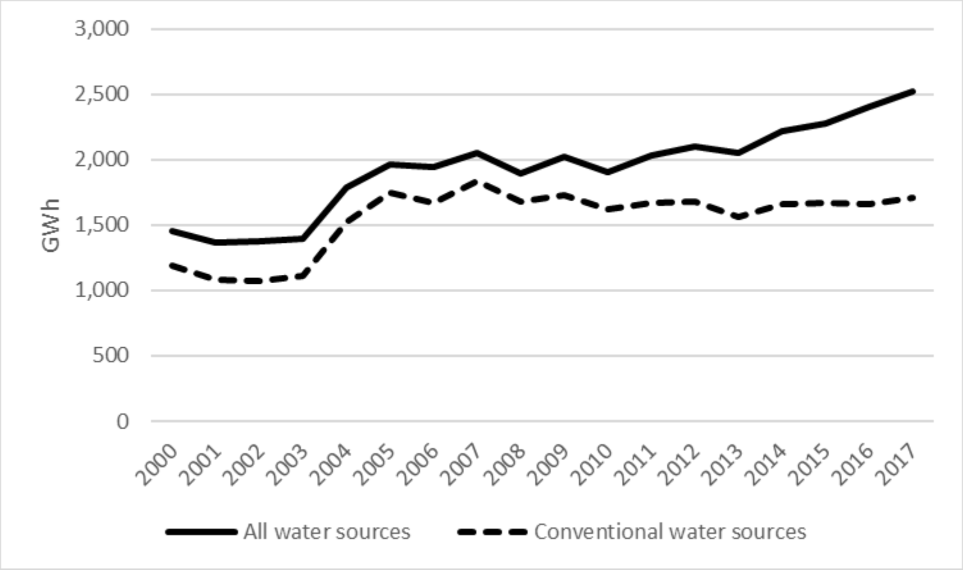
Closure (1980-2004): During the 1980s, Spain developed its agriculture with the opening of European markets and its adhesion to the European Community (in the year 1986). Drip irrigation was introduced at the beginning of the 1980s in Spain, thereby progressively increasing the energy dependency and opening the door to a new competitive horticulture and export-oriented fruticulture (mainly EU markets). The farmers responded to the extreme drought in 1992-1995 with an increase in the area irrigated. In this phase, water abstraction reached the maximum volume in the year 2004, which indicated the arrival of basin closure. The water abstraction and water consumption curves in Figure 5 gradually increase their slope into vertical lines, thereby illustrating a clear water-energy trade-off and basin closure.

Modernization (2005-2013): The milestone herein could be the drought of 2004-2008 and the Royal Decree 10/2005 which created the legal framework for subsidizing water-saving investments ('modernization') (Berbel et al., 2019). In this phase, there is a 16% reduction in water withdrawals, and water consumption stabilizes, while energy consumption and irrigated area continue to grow. There is a widespread implementation of volumetric pricing systems that forced farmers to move from the flat rate per hectare (generalized up to 2010) to a binomial system where the variable part, which is around 30% of the total water cost, is determined volumetrically. The rate of energy use during that period decreased due to the substitution of fuel pumps with electric pumps. Along with the rising cost of energy and the generalization of the binomial tariff, the modernizations imply a reduction in the entitlements of irrigators of 25% for the basins where scarcity is more extreme (in south and southeast Spain), and explain the reduction in volume abstracted as a direct result.

Present and outlook for the future (2014 onwards): The milestone for this stage may be the ending of modernization policy (subsidies to water-saving infrastructure) due to the economic crisis. During the previous phase, modernization transformed 1.7 million hectares, whereby the water saving was greater, and the remaining irrigated areas were either less productive or more expensive to transform. This period shows significant changes in almost all variables: a) water abstraction decreases slightly (-0.3%); b) water consumption increases slightly (+0.1%); c) per-area water application is reduced by -1.5% yearly; d) there is an abrupt increase in energy consumption per volume. Water abstraction per type of crop in 2016 was: herbaceous (56%), citrus and fruit trees (16%), vegetables (11%), olive grove and vineyard (8%), and other crops (9%). The drought in the Eastern basins reduced surface supply and stimulated the use of desalination and reclaimed wastewater for irrigation which explained the steep vertical growth of the last segment of the WE curve.

The short period of the last four years may be considered irrelevant, but, in our opinion, it initiates a new paradigm with high water efficiency and use of alternative water supply that should be monitored closely. The last stage has seen a significant increase in energy consumption for irrigation nationally and especially per unit (kWh/m^3), which can be explained by the use of alternative water sources in the form of desalinated and reclaimed water. Figure 3.7 shows the difference between the total energy consumption in Spanish irrigation including alternative water sources and the consumption calculated by only considering conventional water sources (surface and groundwater).

Figure 3.7. *Evolution of the energy consumption in Spanish irrigation. Source: Own elaboration based on data from INE and IDAE.*



The energy requirements are significantly higher for desalinated water in comparison to reclaimed water. Throughout 2014-2017, there is a trend showing an increase in the use of desalinated water, which explains the higher energy consumption at national level, although the use of desalinated water is concentrated in southeast Spain.

3.5. Discussion

Overall, the trend of Spanish irrigated agriculture in the period 1950-2017 shows an average annual growth of irrigated area of 1.72%, whereas water abstractions increase annually by 1.02%, and energy consumption increases by 3.40% per year. During this period, certain basins became fully allocated in the 1990s and the government responded by subsidizing investments into infrastructure and water-saving equipment during the early 2000s, with a fivefold increase in energy consumption per water abstraction between 1960 and 2017. The increase in the ratio of energy to water is due to the introduction of pressurized systems as a response to water scarcity and, in more recent years, due to the introduction of alternative supply sources. As expected, although water withdrawal has been reduced since its maximum in 2004, this reduction does not lead to savings in water consumption but does lead to its stabilization.

The reaching of the system boundary (or basin closure) in Spain has already been described for the case of the Guadalquivir basin (Berbel et al., 2013), and this underlines the increase in irrigated area accompanied with the introduction of water-saving technologies, and the increase in water costs. The economic consequences of this closure in terms of productivity of the resource (also in the case of the Guadalquivir) are shown in Expósito and Berbel (2017), whereby productivity gains seem to have reached a ceiling due to technological innovations having reached the limits of their capacity in creating new value. The present work shows that a phenomenon such as that described for this basin is occurring on a national scale. Southern and Mediterranean irrigated agriculture accounts for 85% of groundwater, 88% of desalinated and reclaimed water, and 61% of surface water used in Spain, as well as 92% of the water used by drip irrigation systems, which currently represents more than 50% of the irrigated area (INE, 2019b; MAPA, 2019b). Also, the highest added value is in the southern and Mediterranean irrigation sector, so citations explaining the events in this area have relevance at national level.

Our methodology is relatively simple and supported by reliable data from official statistics: the irrigated area per method and the volumes used by the irrigation methods where some gaps in the time series have been completed with estimates that probably reflect reality. The efficiency estimates for the approximation of water consumed from water abstraction are based on typical values that are frequently found in the literature. All parameters have been selected as the most frequent according to the literature and they have been assumed constant for the whole period 1950-2017 (a simplifying assumption as some parameters may have improved such as pumping motor efficiency). We have performed some sensitivity analysis to the parameters assumed in the model (system efficiency, motors efficiency) such as that developed by Zhang et al. (2019a) and finally decided to avoid the presentation of the different results as the parameters that have been finally chosen are the most frequent values quoted in the literature. In our opinion, the model illustrates the evolution of water use, consumption and energy use in Spanish irrigated systems with a good degree of realism. Nevertheless, readers can access and use the original data and parameters in the 'Supplementary material' for free use.

Based on our estimation, as efficiency grows (from 0.49 in the 60s to 0.69 in 2017) and consequently, as water abstraction stabilizes in around 2004 (or are even reduced slightly from 2004 to 2017), the water consumption continues to grow and consequently return flows (fraction not consumed) are reduced. This has consequences for the management of watersheds, which have already been analysed elsewhere (Berbel et al., 2018).

Our model shows an increasing share of the evapotranspiration fraction and reduced return flows so that smaller abstraction volume does not reduce water consumption. Also, our estimation has not detected increased consumption after 2004 even as the irrigated area keeps growing. Therefore, our model does not confirm the existence of the 'rebound effect' due to modernization (Gutiérrez-Martín and Gomez-Gomez, 2011; Perry et al., 2017). The increased irrigated area has been coupled with reduced water dose as water use per hectare (from 6419 to 4017, i.e. 38%) decreased. This reduction has been possible due to the combination of two techniques, by one hand, increase in water efficiency (reduced losses) and on the other hand, the growing importance of deficit irrigation. Deficit irrigation applies irrigation during crop sensitive growth stages periods, this results in plant stress and yields below technical maximum and increases water productivity. Deficit irrigation is generalized in some crops such as olive groves, vineyards or almond leading to some basins such as Guadalquivir to reach an average relative irrigation supply (RIS) of 0.60 (Berbel et al., 2011).

National information on the energy consumption by Spanish irrigation remains scarce. Hardy et al. (2012), from various secondary sources, estimated a value of 2469 GWh (year 2008) for the energy consumption required for the distribution and water abstraction in Spanish agriculture (including livestock). Our estimation for the energy consumption in irrigation nationwide in 2008 accounted for 1900 GWh. Another estimation of this parameter is provided by Corominas (2010), who based the value on several secondary sources and indicated that between 1950 and 2007 the consumption of energy for irrigation increased from 309 to 5866 GWh, which is much higher than our estimation, although the methodology is not explicit.

The gap with the data produced by Corominas (2010) is very significant, yet we have not been able to access neither the methodology nor, the materials used for the mentioned work. Our opinion is that there is some erroneous information in the report such as water use in the agricultural sector that according INE was 16,897 hm^3 for year 2000 while Corominas report 23,870 hm^3. We have contacted the author, but the material and methodology are not available currently so that we cannot find the source of these previous estimations.

The increase in energy consumption is an undesired effect of technical change, although it should be noted that a global analysis of the impact of the modernization policy is complex since, according to the work of Borrego-Marín and Berbel (2019), on the one hand CO_2 is emitted when pumping water, but on the other hand there are savings of greenhouse gases due to a lower use of fertilizers and the area of fruit trees that increase carbon capture, partially or totally compensating for (depending on each basin and each case) the increase in energy consumption.

When reviewing the contribution of the emission sources, crop management is responsible for 25% of CO_2-eq emissions in Spanish agriculture with the remaining 75% due to livestock production; main emissions of rainfed and irrigated agriculture comes from synthetic fertilizers and soil management (FAOSTAT, 2019; MITECO, 2019a). On farm pumping for irrigation represents 23% of the on-farm energy use for crop production (Sloggett, 1992). The analysis of the emissions by water pumping and infrastructure isolated from land use changes and rest of inputs maybe misleading (Aguilera et al., 2015a, b) nevertheless, some authors have conducted this simplified analysis converting GWh to CO_2-eq.

In addition, the integration of unconventional water resources as a means of adaptation to face the risk of drought, is estimated to be more intense and frequent in the future due to climate change (Morote et al., 2019). In the United States, Schwabe et al. (2017) indicate that, as groundwater levels become more depleted, we can expect energy costs to rise, a quicker and wider adoption of highly efficient irrigation systems, and greater incentives to utilize surface water supplies. Furthermore, it has been discussed that extreme extraction of groundwater represents a serious threat to sustainable development (Yannopoulos et al., 2015).

Regarding increased use of energy, Mushtaq et al. (2013) analyse the climate-change impact of irrigation modernization in Australia, although the analysis was limited to financial effects and emissions of CO_2-eq due to the change from previous open channels to pressurized networks and it fails to include the positive impact of increased CO_2-eq storage in both soil and trees. This latest indicator was included by Borrego-Marín and Berbel (2019) in a cost-benefit analysis of modernization policy. In response to the increasing cost of energy, solar-powered systems have been implemented. Although the promotion of solar-based pumping for irrigation may present advantages for energy policies, it may also have potentially negative impacts on the environment caused by excessive resource abstraction (Closas and Rap, 2017).

There are examples of regional case analysis, such as that provided by Siddiqi and Anadon (2011), who describe the water-energy nexus in the Middle East and North Africa and quote that the consumption of electricity used for desalination in Arabian Gulf countries lies between 5% and 12%. In Israel, the adoption of seawater desalination technology remains the leading policy strategy to deal with the Israel water crisis, thus advancing the creation of a new water regime (Bismuth et al., 2016; Teschner et al., 2012). In California, for current conditions, the production cost and regulatory hurdles form the limiting factors of desalination. Nevertheless, emerging innovative technologies, such as the combination of the reduction of pre-treatment and efficient membrane technology, energy recovery systems, and efficient brine management, boost the likelihood of seeing California become a leader in desalination (Rocha, 2017).

Soto-García et al. (2013) analysed the energy consumption for crop irrigation in the southeast of Spain for period 2002–2011 and showed that desalinated brackish water is the highest energy consumption source. Desalination and wastewater strategies should be considered in water policies. However, due to the high costs of the water produced, it is not advisable to use these technologies as the only solution (Molina and Melgarejo, 2016). Correspondingly, there is an increasing need to find and incorporate methods for the energy requirements of irrigation pumps that do not depend on imported oil and electricity (Yannopoulos et al., 2015).

Finally, in Spain, the demand for alternative water sources for irrigation is concentrated along the Mediterranean coast, where water availability is restricted. As Martinez-Granados and Calatrava (2014) indicate, the over-exploitation of aquifers constitutes a major problem in southeast Spain, although in some areas, the availability of desalinated seawater resources is expanding. The trend of increased use of desalinated water has been shown in our analyses and therefore must be considered for the future planning and policy design of water and energy in Spain's irrigation.

According to the European Environmental Agency, total water abstraction in Europe has decreased by more than 20% over the last 15 years[2]. Unfortunately, the Agency report provides data on trends in terms of the amount of water abstraction for irrigation in Europe and use the land area subject to irrigation as a 'proxy'; however, as we can see in the case of Spain and also for USA 2000-2010, this assumption is obviously wrong and misleading (Wang, 2019).

We need to point out that we have not focused in any specific location as the analysis aims to be nationwide. Obviously, the different national polices and external events (EU accession) have been national country policies promoted at national level affecting the whole country, although with regional differences, but we believe that country level analysis reflect the global evolution and is a better indicator of the changes in the WEF nexus that focusing in a specific area. The application of the model at river basins level is

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[2] EEA, 2018. Water abstraction; https://www.eea.europa.eu/archived/archived-content-water-topic/water-resources/water-abstraction

a relevant issue but the available data at river basin level has a short time span (since 2005) and the number of variables is reduced to perform this long-term analysis at basin level.

3.6. Conclusions and policy implications

The present study is the first carried out nationwide for a long-term series (1950-2017) with a detailed analysis of the joint evolution of irrigation efficiency and irrigation energy consumption. The main results illustrate the closure of the main basins characterized by the reduction of supply-augmenting measures and the emphasis on water conservation equipment that increases the efficiency of water abstraction and reduces return flows. The change of paradigm from supply policy to demand management as defined by the intense modernization with a strong presence of public subsidies has resulted in increased energy use per unit of water and, more recently, in the introduction of alternative supply sources. Regarding the data quality and reliability, in our research, we have witnessed major improvement in data quality since 1999, including water abstraction statistics (related to the implementation of the Water Framework Directive), while data gaps from 1950-1998 have required from our expertise and estimation, Nevertheless, the most significant changes have occurred in the last 20 years (increases in basin closures, energy consumption, and water consumption).

The data used paints a coherent picture of the process and presents several relevant questions for the future of water management in water-scarce regions. It remains convenient, however, that analysis based on official statistical data is supplemented by data on actual evapotranspiration, return flows, and the status of water bodies. The estimation of water consumption could be complemented with remote sensing to measure or estimate evapotranspiration. In general, the use of water accounting at basin or aquifer level must be improved in order to more closely control and measure water abstraction, water consumption, and energy use, especially under growing uncertainty derived from climate-change impacts on water resources. Nevertheless, the analysis of currently existing European Union policies whose specific focus is on nexus thinking, reflects the fact that cross-sectorial effects, especially across all three nexus resources, have only recently been accounted for and predominantly, exist in the form of non-formalized statements of intent (Venghaus and Hake, 2018).

In our opinion, the WEF nexus should consider both the positive effects (CO_2-eq capture) and negative effects (CO2-eq generation) of water-saving investment and alternative supply sources regarding climate-change mitigation and greenhouse gas emission. This, in our opinion, constitutes a critical point to be addressed in future research.

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Capítulo 4

La gestión del regadío ante la escasez del agua

La gestión del regadío ante la escasez del agua

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***Berbel J, Espinosa-Tasón J** (2020)*

Resumen

El regadío ha surgido históricamente en España como una adaptación al clima Mediterráneo con el fin de garantizar alimentos para la población. Desde los años 70' la apertura del país ha provocado que la baja rentabilidad (incluso negativa) del secano forzara a los agricultores a intensificar la actividad aumentando la superficie regada hasta llegar a un máximo de extracciones de agua alrededor del año 2004, que marca un fin de ciclo y cambio de tendencia, reduciéndose a partir de esa fecha las extracciones para el riego, aumentando el uso de fuentes no convencionales y acelerando el cambio tecnológico. Todo ello ha incrementado la productividad de los factores (agua, tierra, capital) aumentando el diferencial secano-riego por lo que la presión para aumentar extracciones sigue creciendo y solo una gobernanza firme puede garantizar el uso sostenible de los recursos.

Palabras clave: regadío, agricultura, agua, productividad de los factores, cambio, cambio tecnológico, nexo agua-energía.

4.1. Introducción

El sector del agua en general en España ha experimentado una fuerte modernización en los últimos 25 años. Entre el año 2000 y 2008 el PIB español creció un 25% mientras el uso del agua se redujo en un 34% situándose en 25,2 km^3 (año 2018, estimación propia de varias fuentes[1]). Debe hacerse notar que en el mismo periodo en la UE la reducción del uso del agua ha sido de un 17% (EEA 2019). Estos valores tan destacables de reducción del uso de agua han sido posible por la contribución de todos los sectores, en especial el agrario que con el 62% de las extracciones tiene un gran peso en el sector.

La reducción del consumo de agua por la agricultura es el resultado de la combinación de factores a) internos: escasez de agua, mejora de competitividad y b) externos: Directiva Marco de Aguas (Dir. 2000/60) y cambios políticos y sociales, han sido los motores que explican la reducción del uso del agua y el aumento de su productividad. No obstante, la percepción de escasez se hizo dramática con la gran sequía de 1992-95 que fue el catalizador de cambios importantes en todos los sectores en general y del riego en particular. No obstante, aunque la situación ha mejorado sensiblemente, siguen existiendo muchos problemas de sobreexplotación, falta de garantías, y contaminación que necesitan ser atendidos.

En este trabajo analizaremos los motores de la transformación del regadío español, su pasado reciente, su presente y la evolución esperada del sector. Veremos que la escasez y la productividad del recurso son las claves que explican las luces y las sombras del sector, su debilidad y su fortaleza.

4.2. El cambio en la agricultura española (1965-2018)

El riego surge en nuestro clima mediterráneo como una adaptación a los veranos secos, de modo que se trasladan las lluvias invernales para nutrir la planta durante el estiaje. Esto se consigue mediante sistemas de almacenamiento natural (acuíferos) o

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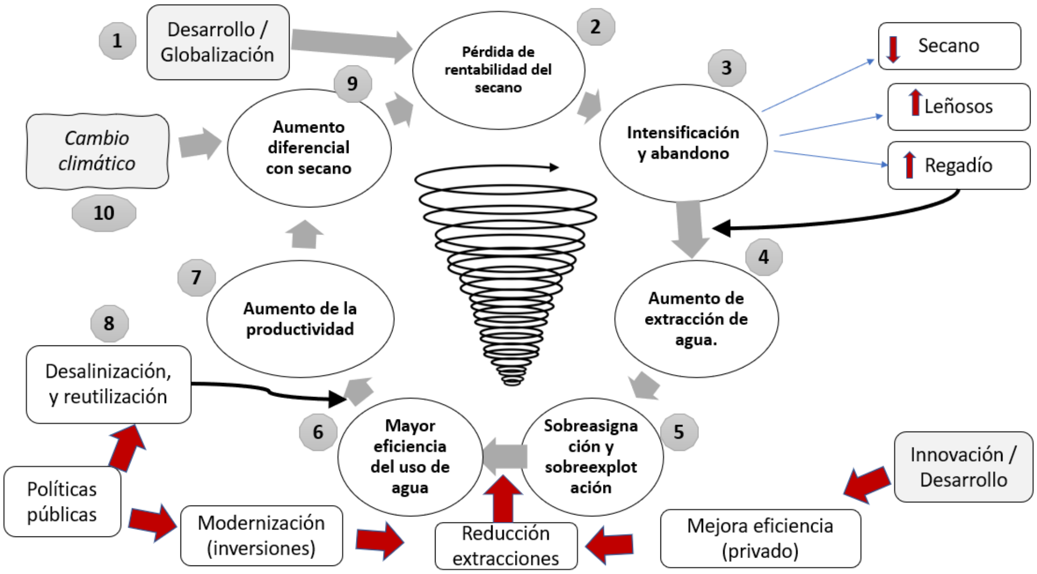
[1] El sector agrario que empleó 15,5 km3 (62%) (año 2018, INE), el sector urbano utilizó 4,3 km3 (año 2016, INE), mientras el resto de la economía (principalmente la generación de energía) emplea alrededor de 5,4 km3 MIMAM (2008).

artificial (embalses) y recientemente mediante sistemas no convencionales (depuración y desalinización). La necesidad de regar estuvo justificada históricamente por la necesidad de alimentar la población mediante esta técnica tan vieja como la propia agricultura. Mas recientemente, la justificación del riego deja de ser por razones de subsistencia y pasa a ser por una cuestión de competitividad ya que el secano cada vez es menos rentable y sufre un abandono creciente o se transforma cuando es posible en riego. La figura 1, trata de hacer un esquema de las fuerzas, presiones y respuestas que se configuran entorno al regadío español.

La evolución del regadío se refleja de manera esquemática en la figura 4.1, que indica de manera aproximada unos hitos y fases de evolución donde las fuerzas externas e internas han provocado un cambio que en la tabla 4.1 a continuación podemos ver reflejados en la evolución de indicadores seleccionados. La figura está inspirada en el análisis de los procesos que se han venido observando en otras regiones del mundo que tienen un clima y condiciones socioeconómicas semejantes a España como son California o Australia (Berbel y Esteban 2019).

Figura 4.1. *Esquema de fuerzas, presiones y respuestas en la evolución del regadío español.*



Fuente: Elaboración propia.

El análisis comienza en los años 70' donde la superficie cultivada alcanza un máximo alrededor del año 1975, fecha a partir de la cual empieza decrecer lentamente y de manera más acelerada a partir de nuestra entrada en la Comunidad Europea (año 1986). Hemos representado la apertura económica de España como catalizador de los cambios ([1] en esquema), el impacto diferencial que esto tiene en los secanos menos competitivos y el regadío es diferente ([2] en esquema). La tabla 4.1, muestra la evolución de los indicadores y de la tasa de cambio.

Tabla 4.1. *Evolución de indicadores de secano y regadío en España.*

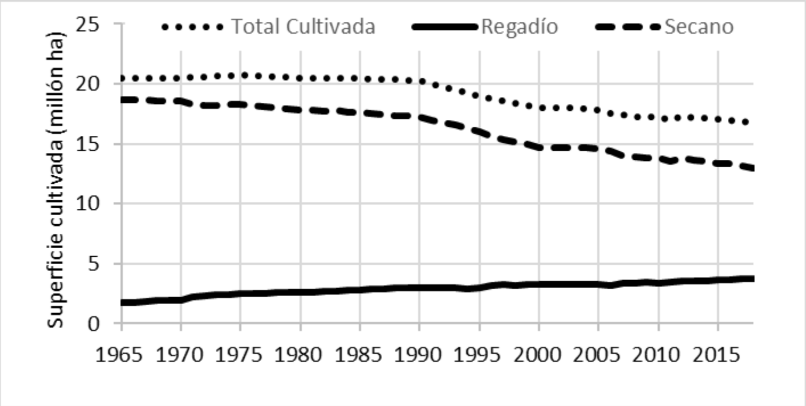
Indicador						**Crecimiento anual**			
	1965	**1980**	**2004**	**2013**	**2018**	***1965-1979***	***1980-2004***	***2005-2013***	***2014-2017***
Secano (10^6 ha)	18,7	17,9	14,7	13,6	13,0	*-0.3%*	*-0.8%*	*-0.9%*	*-0.9%*
Regadío (10^6 ha)	1,8	2,7	3,3	3,5	3,8	*2.7%*	*0.9%*	*0.9%*	*1.4%*
Agua riego (hm^3)	9.984	16.016	17.808	14.535	15.495	*3.2%*	*0.4%*	*-2.3%*	*1.3%*
Energía riego (GWh)	345	1.336	1.788	2.056	2.520	*9.0%*	*1.2%*	*1.6%*	*4.1%*
Dotación m^3 / ha	6.419	6.031	5.456	4.105	4.017	*-0.4%*	*-0.4%*	*-3.2%*	*-0.4%*
% Leñoso riego	23%	23%	37%	41%	43%	*0.0%*	*2.0%*	*1.0%*	*1.2%*
Eficiencia	0,6	0,6	0,8	0,8	0,8	*0.4%*	*0.7%*	*0.4%*	*0.3%*
Energía kWh / m^3	0,03	0,08	0,1	0,14	0,17	*6.5%*	*0.9%*	*3.7%*	*3.9%*

Fuente: elaboración propia basado en Espinosa-Tasón, Berbel et al. (2020), MAPA (2020)

La evolución del secano y del riego en España es muy reveladora al respecto tal como muestra la figura 4.2, el secano ha perdido en el periodo 1965-2018 una superficie de 5,7 millones de hectáreas (31%) mientras el riego ha ganado 2,0 millones de ha (210%), reduciéndose la superficie total cultivada en 3,7 millones ha (18%).

El análisis de la evolución de los sistemas cultivados (figura 4.2) refleja la crisis del secano español. Gran parte del secano español tiene pérdidas en su cuenta de explotación que a veces (pero no siempre) es compensada con las ayudas de la PAC. A esta situación de falta de rentabilidad generalizada se escapan la viña y el olivar en determinadas regiones y algunos secanos muy productivos (p. ej. norte de España, partes de Andalucía), con una conversión de los cultivos herbáceos a leñosos tanto en secano como en riego. En el periodo 2000-2018 la superficie cultivada se ha reducido un 7% (ver fig. 4.2).

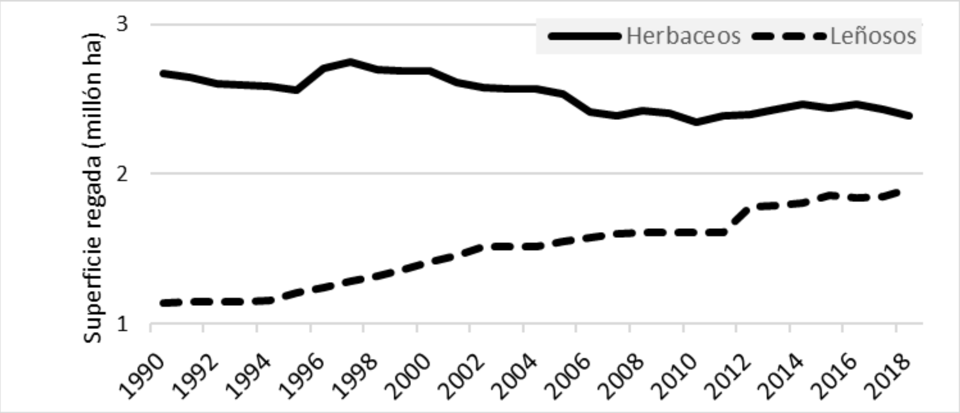
***Figura* 4.2.** *Evolución de la superficie cultivada de secano y regadío en España, 1965-2018.*



Fuente: Elaboración propia a partir de datos del MAPA (2020).

La respuesta a la evolución de los mercados ha sido el aumento de cultivos leñosos (olivar, almendro, viña) que han soportado mejor la competencia exterior y el aumento del regadío ([3] en esquema). La figura 4.3, muestra la evolución de los cultivos leñosos y herbáceos en España de manera conjunta.

***Figura* 4.3.** *Evolución del área de regadío de leñosos y herbáceos en España, 1990-2018.*



Fuente: Elaboración propia a partir de datos del MAPA (2020).

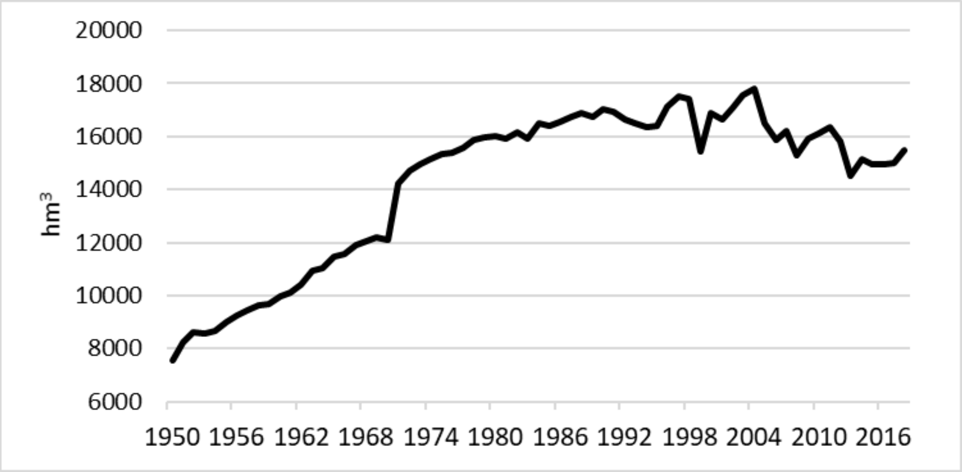
La baja rentabilidad de la agricultura es corresponsable del despoblamiento de buena parte del mundo rural, lo que se ha venido llamando 'la España vaciada'. El contraste con el regadío es extraordinario, mientras un sistema no deja de reducir su importancia lastrado por unas pérdidas económicas insostenibles, hay orientaciones de regadío que siguen creciendo, estas son: a) horticultura y fruticultura especializada (sureste español con frutos rojos, subtropicales, fruticultura del Ebro, y hortícolas extensivos en el interior), b) cultivos leñosos tradicionales reconvertidos con riego deficitario (olivar, viña y recientemente almendro y pistacho), c) finalmente cultivos herbáceos tradicionales (cereales, etc.) muchos de ellos con apoyo de la PAC (arroz, algodón, y otros). En la próxima sección trataremos de ver con detalle los indicadores y fuerzas motoras de esta transformación.

4.3. La respuesta a la escasez: la modernización y la tecnificación del regadío

Como vemos, el proceso de intensificación de la agricultura se manifiesta en un abandono de terrenos marginales (en secano), a una intensificación de los secanos más productivos (plantaciones de cultivos leñosos) y a una transformación de secano a riego. La superficie regada en España ha pasado de ser 9% del total cultivado (1965) al 23% (2018) y como consecuencia la aportación del riego al valor de la producción agraria no ha dejado de crecer. Según Rodríguez-Chaparro (2013) el regadío es responsable del 65% de la producción final agraria (año 2012). La figura 4.4, muestra el impacto que el aumento de regadío tiene del proceso desde el punto de vista de la intensificación y el aumento de valor por superficie. Siguiendo la evolución de las extracciones totales del regadío, podemos ver que se alcanza un máximo entorno al año 2004, año que vino marcado por ser el inicio de una sequía después de años relativamente lluviosos, lo que posibilitó unas extracciones generosas.

Desde el año 2004 como hemos comentado la superficie regada ha crecido en 500.000 ha, y sin embargo las extracciones se reducen significativamente. Los mecanismos correctores que han compensado el aumento de superficie regada han consistido en dos respuestas técnicas y económicas: a) por un lado, la modernización de regadíos, entendida como el aumento de la eficiencia de los sistemas de transporte, distribución y aplicación en parcela del agua de riego, y por otro b) la expansión del riego deficitario como técnica agronómica aplicada a cultivos mediterráneos como vid, olivar y más recientemente almendro o pistacho.

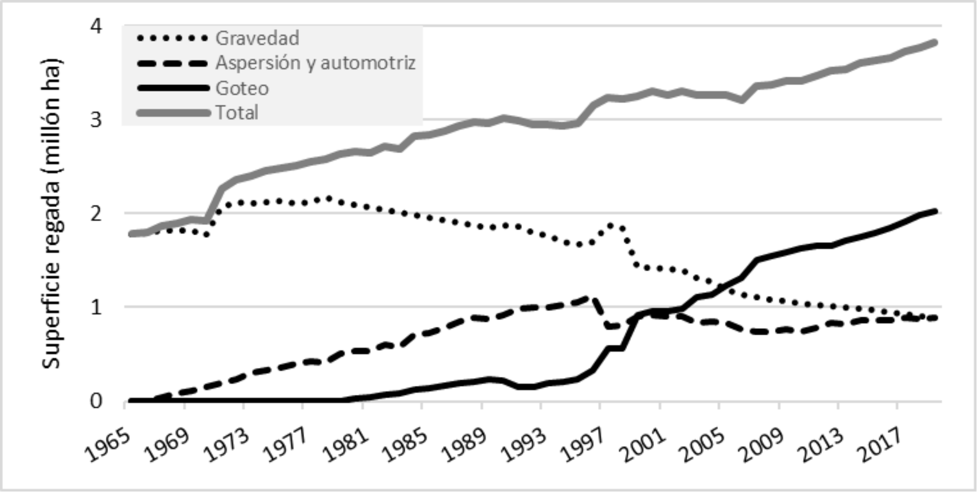
Figura 4.4. *Volumen de extracciones de agua del regadío en España, 1950-2018.*



Fuente: Espinosa-Tasón, Berbel et al. (2020), INE (2020)

El aumento de la eficiencia y el riego deficitario no serían posible sin la entrada en el sistema de los riegos de precisión. La Figura 4.5, muestra la evolución de los distintos sistemas de riego y muestra el aumento del goteo que ya supone el sistema predominante en muchas regiones y comarcas españolas.

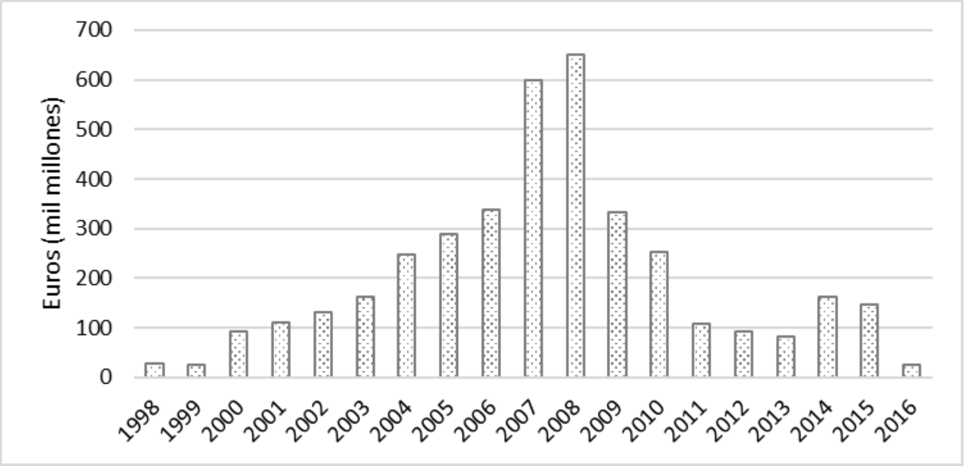
Figura 4.5. *Superficie regada por sistemas de riego en España 1965-2019.*



Fuente: MAPA (2019), Espinosa-Tasón, Berbel et al. (2020).

El Estado (Central y autonómico) ha sido un impulsor fundamental en la modernización de las grandes zonas regables. La Figura 4.6 muestra el esfuerzo inversor del estado en esta política. Dado que las subvenciones a la modernización vienen a ser un porcentaje (próximo al 50%) del total invertido, podemos ver que el esfuerzo público ha venido acompañado de un esfuerzo paralelo del sector privado.

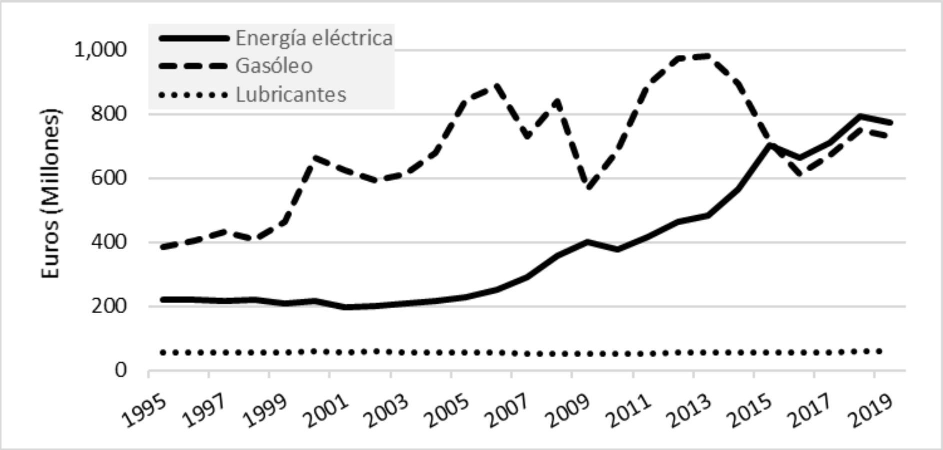
Figura 4.6. *Inversiones del Estado en modernización (mil millones EUR constantes 2016).*



Fuente: Elaboración propia a partir de la Dirección General del Agua.

El capital invertido por unidad de superficie trae consigo unos costes anuales de amortización y gastos financieros asociados que en muchos casos ronda los 300 EUR/ha. Estos costes fijos suponen un riesgo financiero cuando vienen años malos y la necesidad de intensificar la producción para poder hacer frente a los pagos. Por otra parte, junto al coste fijo, hay un aumento de los costes variables derivados del aumento de la energía consumida. La Figura 4.7, muestra la evolución del gasto en combustibles y energía eléctrica en las explotaciones agrarias de España y se observa, como desde el año 2006 (entrada en funcionamiento de las modernizaciones) el gasto en energía eléctrica se incrementa muy sustancialmente.

***Figura 4.7.** Evolución del gasto en combustibles y energía eléctrica de la agricultura en España, 1995-2019 (año base 1990).*



Fuente: Elaboración propia a partir de MAPA (2020).

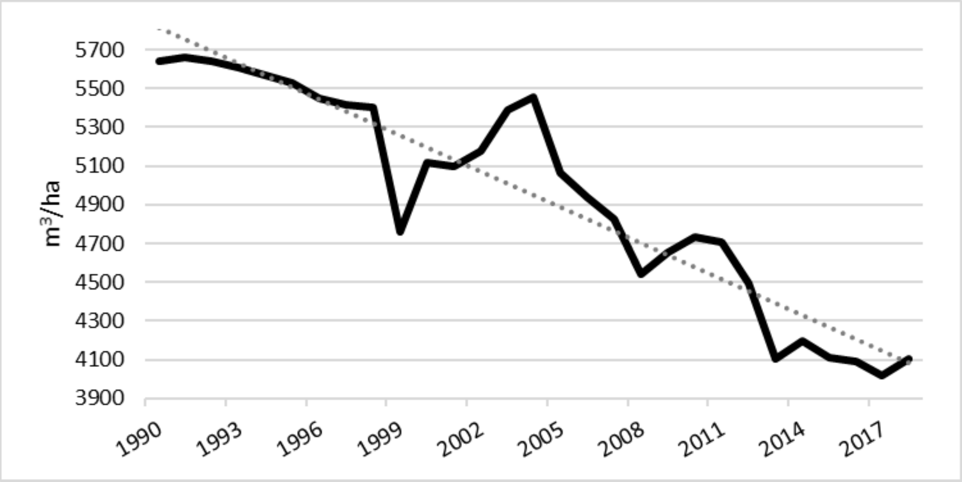
En resumen, las inversiones de capital en el sector han sido enormes en muchas actuaciones: a) aumento de superficie regada por los costes de transformación del secano al riego; b) modernización en zonas ya regadas previamente ya que los costes se estiman en unos 6000 EUR/ha (Berbel and Gutiérrez Martín 2017); c) incremento del capital biológico como son las plantaciones de frutales y d) riego de precisión.

4.4. El impacto de la mejora de la eficiencia

Siguiendo el esquema que planteamos en la figura 4.1, las actuaciones anteriores conducen a un aumento de la productividad del agua ([8] en el esquema), que supone un mayor incentivo al regadío y un aumento del diferencial de productividad con el secano.

El uso creciente del riego deficitario requiere de una capacidad de gestión del riego con cierto nivel de precisión (goteo generalmente) que ha sido posible precisamente por la modernización. Un análisis detallado de los efectos de la modernización puede consultarse en Berbel, Expósito et al. (2019). La mejora en la gestión del agua en parcela y la reducción de pérdidas en transporte explican las menores dotaciones por hectárea que pueden observarse en la Figura 4.8.

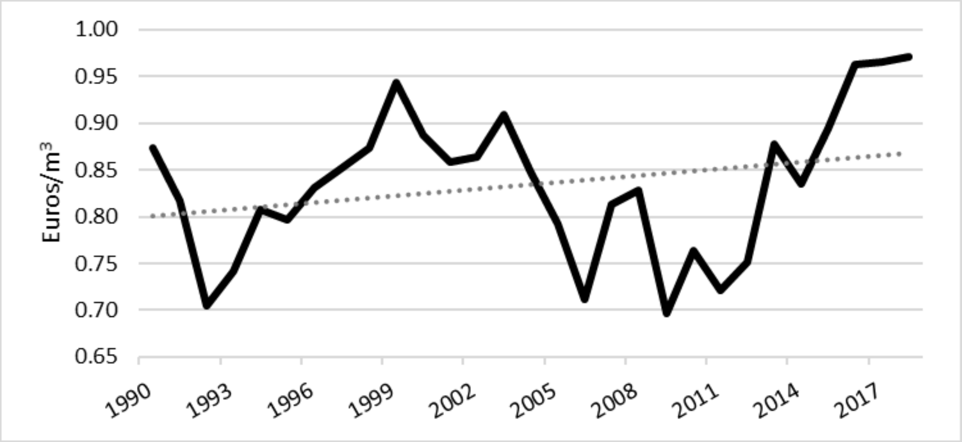
Figura 4.8. *Volumen aplicado por hectárea de riego, España 1990-2018 (m^3/ha)*



Fuente: Elaboración propia a partir de INE (2020), MAPA (2020).

La reducción del uso de agua por unidad de superficie mientras que se mantiene o aumenta la producción tiene como consecuencia la mejora de la productividad del agua definida como la ratio [PFA (vegetal)/agua extraída] que tiene una tendencia al aumento de la productividad (EUR/m^3) como refleja la figura 4.9.

Figura 4.9. *Productividad aparente del agua EUR/m^3 1990-2018 (año base 1990).*



Fuente: Elaboración propia a partir de datos del MAPA (2020).

En resumen, a lo largo de esta sección hemos visto una transformación del regadío español hacia una reducción del uso del agua, aumento de la eficiencia y mejora de la productividad. Estos cambios han traído consigo necesidades de financiación importantes y un aumento del consumo de energía que ya comentaremos en la sección precedente.

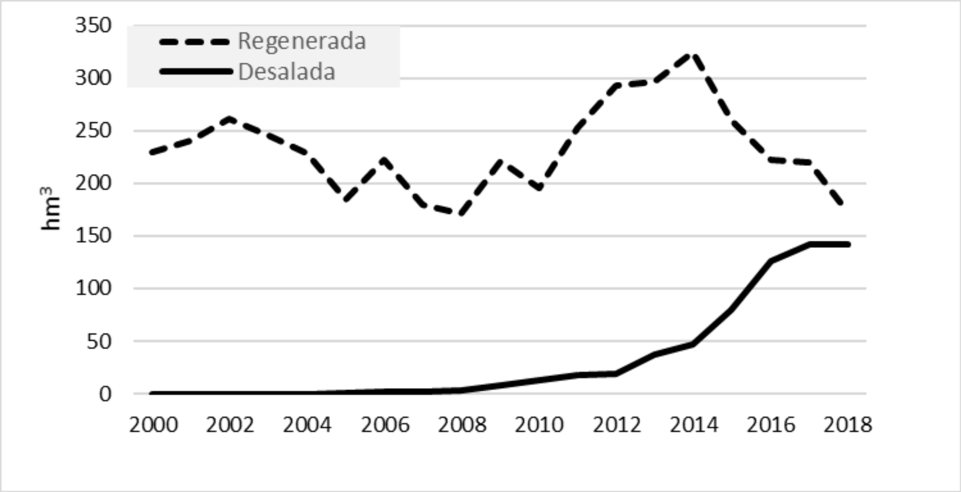
4.5. El impacto de la mayor eficiencia: mayor consumo de energía y uso de fuentes no convencionales

Al analizar la trayectoria reciente del regadío español hemos visto que la modernización explica gran parte de la evolución reciente. La política de modernización se enmarca en la política de aguas y simultáneamente en la política de desarrollo rural de manera que ambas se entremezclan en esta medida de manera indisociable. Podría parecer en principio que la medida es una consecuencia de la aplicación de la Ley de Aguas en el sentido de dar cumplimiento al Artículo 40. Objetivos de la planificación hidrológica que plantea la necesidad de satisfacer las demandas de agua manteniendo el buen estado ecológico de las masas de agua, incluyendo para ello el método de 'economizar su empleo'.

El consumo de energía es responsable de que se haya implementado una tarifa volumétrica (fijo más variable) en todas las áreas modernizadas. La implantación de una tarifa volumétrica es clave para inducir a un ahorro del uso de agua ya que con el sistema tradicional de pago por superficie (tarifa plana) aunque se recuperen los costes del servicio, no hay un incentivo al ahorro que es clave para fomentar la racionalización del uso. Finalmente, la escasez ha obligado a los regantes a recurrir a fuentes no convencionales (Figura 4.10), mucho más caras que las tradicionales.

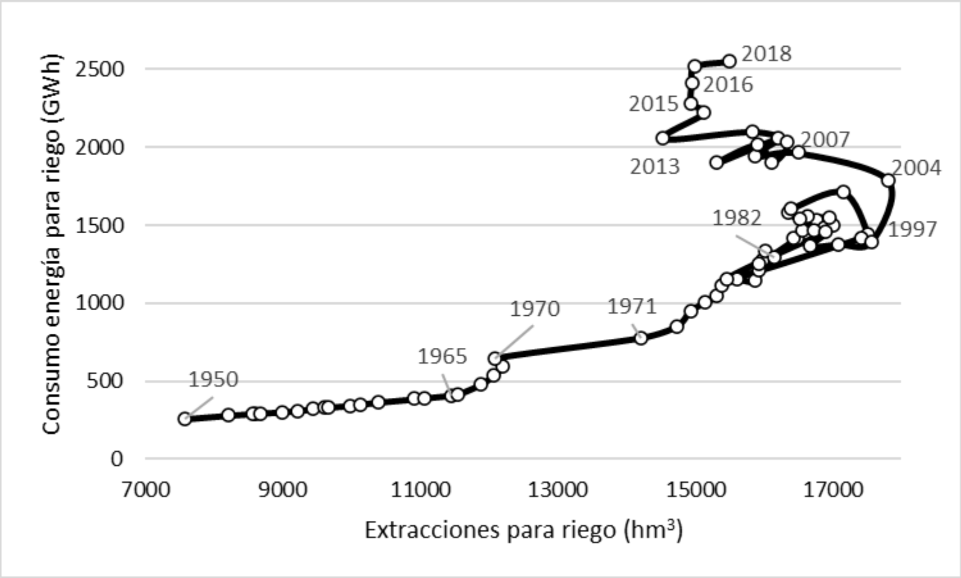
La combinación de menos agua y más energía, tanto por la modernización como por el aumento de porcentaje que proviene de fuentes no convencionales lleva a una vinculación de lo que se conoce como Nexo Agua-energía-Alimentos que puede verse de manifiesto en la Figura 4.11. Vemos en la figura que el agua extraída ha tocado techo el año 2004 como ya hemos visto en la Tabla 4.1 y a lo largo del texto mientras que el consumo de energía no deja de crecer.

Figura 4.10. *Uso de agua regenerada y desalinizada en España (hm^3).*



Fuente: Elaboración propia a partir de (INE 2020).

Figura 4.11. *Nexo Agua-energía en el riego en España, 1950-2018.*



Fuente: Espinosa-Tasón, Berbel et al. (2020), INE (2020).

En resumen, esta sección ha tratado de analizar las consecuencias del cambio tecnológico que ha sido el motor del aumento de productividad del regadío y de todos los sus factores productivos (tierra, agua, trabajo). Junto a este cambio positivo: ahorro de agua, racionalización del consumo, mejora de la productividad de los factores, aparece el aumento de la vulnerabilidad del sistema a impactos externos (sequías, crisis económicas).

En la próxima sección trataremos de dar unas ideas sobre el futuro del sector y su adaptación a la creciente escasez.

4.6. ¿Qué futuro para el regadío?

El futuro del regadío español es el futuro de la agricultura española. El sector agroalimentario ha crecido más que el conjunto de la economía española durante el último lustro y genera 62.000 millones de euros de valor añadido (Maudos and Salamanca 2020). El regadío es uno de los pilares básicos del desarrollo rural y desarrollo regional creando empleo directo e indirecto y mejorando la calidad de vida. El regadío dinamiza un territorio, lo que se observa a partir de los diversos efectos que provoca tanto económicos, como sociales y antrópicos. La distribución de la población en las zonas en regadío hombre-mujer es más equilibrada que las de secano y tiene una mayor proporción de jóvenes (Valiente Palma 2019).

Hemos visto como el porcentaje de la producción agraria española que depende del regadío no ha dejado de crecer históricamente y cómo esta tendencia sigue manifiesta. En el futuro, con el impacto del cambio climático, la baja o nula rentabilidad del secano y su vulnerabilidad frente a eventos climáticos (sequia, golpes de calor) seguirá en aumento la presión por regar más tierras. A esto hay que unirle la competencia cada vez mayor en los mercados de 'commodities' por la apertura de mercados que hace que los secanos cada vez sean menos viables económicamente. La respuesta del agricultor será intentar acceder al riego dentro de sus posibilidades.

Las demandas de agua prioritarias en nuestro ordenamiento jurídico son las urbanas (abastecimiento a poblaciones) y las ambientales (caudal ecológico), y estas no van a reducirse a medio plazo ya que se encuentran en unos niveles razonables que no parecen que vayan a bajar a medio plazo. Frente a unas demandas prioritarias nos encontramos con escenarios de cambio climático que plantean un futuro muy complicado para el medioambiente español y para su agricultura.

El reciente informe de AEMET (2020) recoge un contexto mucho más cálido que hace 50 años combinado con un incremento de 0,3ºC por década desde los años 60 lo que implica un aumento de la evapotranspiración. Para empeorar las cosas, este aumento de las temperaturas se aprecia especialmente en el verano y aunque no se observa una reducción de la precipitación media sí que es evidente un aumento de la varianza de la precipitación. En resumen: lluvias más imprevisibles, mayores temperaturas y mayor evaporación.

En consecuencia, si el riego va a tener que soportar mayor evapotranspiración tenderá a aumentar su demanda, aunque se mantuvieran estables los cultivos y la superficie actual. Dado que podría existir menos recursos y que el riego se encuentra en una jerarquía inferior a los usos ambiental y urbano, está claro que los recursos convencionales destinados al regadío podrían mantenerse o en todo caso reducirse a largo plazo.

Asumiendo que el uso de fuentes convencionales de agua alcanzó su máximo a principios de este siglo y que en el futuro seguirá un descenso paulatino e imparable de las extracciones de fuentes convencionales, el regadío solo puede adaptarse a este escenario mediante múltiples estrategias que tendrán que adaptarse a las condiciones locales.

- Aprovechamiento de las sinergias en el nexo agua-energía, incremento de la altura de bombeo en aguas subterráneas, etc. El consumo medio de energía del regadío español se encuentra en la horquilla de 0,3 a 0,4 kWh/m^3 de agua. Muchos de los embalses tienen un uso múltiple hidroeléctrico y de regadíos, las Comunidades de Regantes gestionan aprovechamientos energéticos en sus canales, existe un gran volumen de balsas de regulación privadas, las instalaciones fotovoltaicas para elevación de agua pueden usarse no solamente en temporada de riego (primavera-verano) sino durante todo el año, contribuyendo al suministro energético nacional, especialmente si se pueden aprovechar infraestructuras de almacenamiento de agua en elevación. Hay proyectos para hacer compatible las placas solares elevadas con el cultivo agrícola sin afectar al rendimiento agronómico, en India hay iniciativas muy innovadoras apoyadas por el Banco Mundial de las que se puede aprender.

- Integración de las fuentes no convencionales, que requieren de una flexibilidad en el sistema concesional y de la gestión integrada de fuentes convencionales (más baratas y menos seguras) con las procedentes de desalinización y regeneración (más caras y seguras). El nuevo Reglamento EU-2020/741 es una oportunidad, pero requiere de un nuevo sistema de gobernanza y control de riesgos (Mesa-Pérez and Berbel 2020).

- Implantación de sistemas de riego de precisión, la mejora y abaratamiento del precio de los sensores, la teledetección y otras herramientas harán posible de manera cada vez más sencilla y económica una agricultura de precisión (herbicidas y abonos localizados, etc.,) y un riego cada vez mejor gestionado.

- Una agricultura más sostenible y biológica, el crecimiento de los bioestimulantes y de la agricultura orgánica es constante, favorecido por ayudas públicas o simplemente por la demanda creciente del mercado. Pero la agricultura que minimiza el uso de agroquímicos requiere de una mayor tecnificación y precisión, y la sensibilidad a sequía y enfermedades hace que el riego sea una herramienta clave para la gestión de los cultivos.
- Mejora genética y mayor integración con el sistema de innovación, que debe estar orientado hacia las necesidades locales, de un país seco como España e integrado en un mercado muy poderoso como el europeo y con una especialización y competitividad que requiere de semillas y técnicas adaptadas a las condiciones locales.
- Mejora de gobernanza, la sobreexplotación de acuíferos o la contaminación de las masas de agua normalmente son una herencia envenenada a la siguiente generación, y requiere de una política más dinámica y eficaz por parte de las administraciones y de una corresponsabilidad de los regantes. Hay ejemplos en España de que una gestión participada y sostenible de aguas subterráneas es posible (ver Berbel et al. 2019).
- Nuevos instrumentos económicos para gestión y riesgos como en especial bancos de agua (públicos y privados), seguros de sequía, entre otros.

Estas son algunas de las ideas que sin duda irán configurando el regadío del S. XXI, no queda tiempo para comentar que algunas de las tendencias apuntadas como la tecnificación, inversión en capital humano y tecnológico, instituciones y gobernanza traen consigo unas economías de escala que pueden cambiar la agricultura del futuro acelerando cambios que ya se están observando en el sector como la aparición de fondos de inversión, aumento de la mecanización, intensificación, robotización, por ejemplo. Estos cambios son medidas de adaptación a un mundo más globalizado donde las consecuencias de la revolución tecnológica que está viviendo el regadío pueden impactar de manera diferencial a territorios y grupos sociales por lo que necesitamos lideres que sean capaces de equilibrar los objetivos en conflicto económicos, sociales, territoriales y ambientales buscando un consenso y evitando de populismos (de derechas y de izquierdas) que destruyen la cohesión actual y el futuro de todos.

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Capítulo 5
Socioeconomic impact of 2005–2008 drought in Andalusian agriculture

Socioeconomic impact of 2005–2008 drought in Andalusian agriculture

This chapter has been published entirely in the journal "Science of the Total Environment",
Espinosa-Tasón J, Berbel J, Gutiérrez-Martín C, Musolino DA (2022)

Abstract

Meteorological drought is defined as the event that arises when precipitation is lower than average and initially affects rainfed crops; this is transformed into hydrological drought when persistent drought affects water storage. We have studied the economic impact of multiyear droughts by applying the economic surplus to the last severe drought (2005-2008) in Andalusia. The method is applied to both rainfed and irrigated agriculture. The results show negative effects on regional social welfare, with an estimated global loss of EUR 1,512 million, although this negative impact is unequally distributed. There is a quantity effect (lower yields) and higher prices due to shorter supply. Overall, rainfed farms experience a negative impact on their income since higher prices only partially compensate for yield reduction, although, paradoxically, certain irrigation farms increase their income when higher prices overcorrect lower yields. Consumers are always negatively affected by drought. This result may aid in the design of agricultural policy models and drought-recovery policies.

Keywords: Economic surplus, hydrological drought, impact assessment, irrigation, rainfed.

5.1. Introduction

Drought is a recurring problem in Mediterranean regions such as Spain, and temporarily affects the availability of water resources, which causes a wide spectrum of economic, social, and environmental impacts (Stahl et al., 2016); these hit not only vulnerable sectors, such as agriculture (Mendelsohn and Dinar, 2009), but also the quality of life and well-being of the local population (Berlemann and Eurich, 2021).

In the context of climate change and food security, drought events are becoming increasingly frequent, and it is essential to measure the economic and social effects generated. In numerous regions of the world, recent drought episodes have acted as catalysts for legislative and institutional changes in water management (Berbel and Esteban, 2019; Kampragou et al., 2015).

Meteorological drought (low precipitation compared to that of the year average) affects the whole cultivated agricultural area (both rainfed and irrigated crops). Hydrological drought occurs when circulating flows through the watercourses and reservoir storage drop below normal (Cantos, 2001), which mainly affects irrigated agriculture, since its water supply depends principally on the water available in the regulated reservoirs for, and the Spanish normative prioritises urban supply and the maintenance of environmental flow. Agriculture is located at a lower level in the user hierarchy; it is therefore the main sector affected by water supply restrictions. Obviously, reduced rainfall translates into a greater impact for rainfed systems, where rainfall provides the only source of water.

In regions of a Mediterranean climate, rainfed agriculture is exposed to meteorological droughts and productivity is closely linked to effective rain meanwhile irrigated agriculture is vulnerable to the risk of hydrological drought: a phenomenon that concerns irrigators mainly due to the negative effects of water supply failures. It should be noted that in the future due to climate change drought conditions may worsen making them more frequent and widespread (Gomez-Gomez et al., 2022), as well the probability of propagation from meteorological drought to hydrological drought will tend to increase under climate change scenarios (Jehanzaib et al., 2020).

Gómez-Limón and Guerrero-Baena (2019 study the design of an insurance index for hydrological-drought risk coverage; their simulation results show that irrigated agriculture in southern Spain is expected to become more vulnerable to hydrological droughts. Montilla-López et al. (2018 propose the implementation of water banks in the Guadalquivir River Basin during droughts as an effective tool for the mitigation of the negative effects of droughts in agriculture. However, these approaches only consider the effect regarding the quantity produced, and therefore they only partially capture the effects of drought.

For the case of Spain, the various studies in the scientific literature that assess the impacts caused by drought in the agricultural sector differ in scope and methodology. Certain research has focused on the economic analysis of drought risk for irrigated agriculture in Spain (Gil et al., 2011; Gómez-Limón, 2020), while other studies analyse the performance of water policies in the face of drought events in Spain (Berbel and Esteban, 2019; Kahil et al., 2016a; Kahil et al., 2016b).

The above-mentioned literature focus in agricultural sector, with some works enlarging the scope to a regional economic impact such as Pérez and Hurlé (2009 who estimated the direct and indirect economic impacts of a drought episode in the Ebro basin, and Borrego-Marín et al. (2015 analysed meteorological and hydrological droughts and their relationship with agricultural water use in the Guadalquivir River basin. According to Sanz-Hernández et al. (2019, despite the significant importance of the bioeconomy transition, studies from a social science perspective are largely lacking. We have not found analysis of drought impact on the bioeconomy sector as a wider and more inclusive concept, at the same time probably because is relatively new and socioeconomic perspectives are lower than technological and there is a need for improved analysis and indicators in line with the proposed by (D'Adamo et al., 2020).

Assessment of the economic impact of drought events can be made using any of a variety of methodologies, ranging from econometric approaches (Connor et al., 2014; Gil et al., 2013; Lopez-Nicolas et al., 2017), mathematical programming methods (Qureshi et al., 2014; Salami et al., 2009; Ward, 2014), and methods based on the economic surplus theory (Garcia Valiñas, 2006; Grafton and Ward, 2008; Musolino et al., 2017; Musolino et al., 2018; Pattanayak and Kramer, 2001). All three approaches are in widespread use, however, the application of economic surplus theory to drought impact estimation has the advantage that it requires a minimal amount of data and can be applied to the widest range of sectors and different types of drought events.

The present research applies the economic surplus theory with two goals: a) to measure the total economic effect of drought on society; and b) to show whether, under hydrological drought conditions, the same economic effects, in terms of sign (negative or positive) and magnitude, are caused in different social groups (producers and consumers) of both rainfed and irrigated crops in the region of Andalusia.

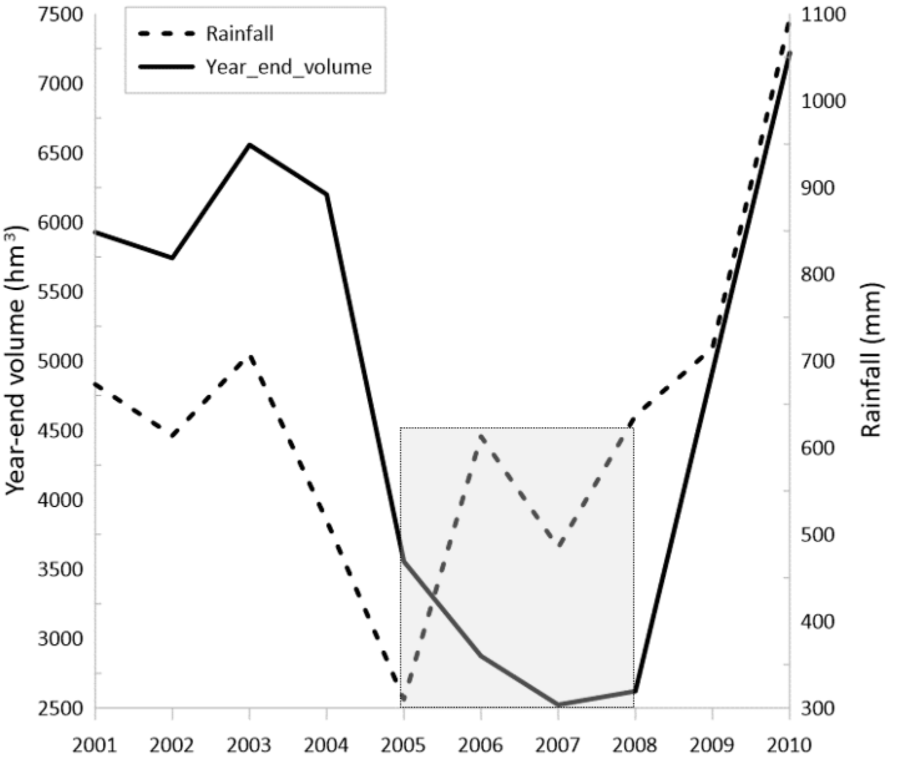
This paper adds empirical evidence to this line of research by focusing on a relevant case study area, which is extremely vulnerable to drought and strongly specialised in the primary sector (agriculture). Its innovation and relevance also lies in the unusually high level of detail in the analysis of the economic impacts, which hitherto has not been achieved in these studies, in particular concerning the type of crops (and not only disaggregated into rainfed and irrigated cultivations). This allows us to better reflect on the economic effects of drought on agriculture and society.

The remainder of this paper is organised as follows. The second section explains the theoretical approach of the economic surplus in addressing the assessment of the impact of droughts on social welfare, and describes the data needed for its estimation, as well as the methodological steps of the calculation. The results and their discussion are presented in the third section, whereby the evolution of production and prices during hydrological drought is addressed first, followed by the effects of drought on farmers and consumers, and finally, the effects of drought per crop are considered. The main conclusions are outlined in the last section.

5.2. Material and Methods

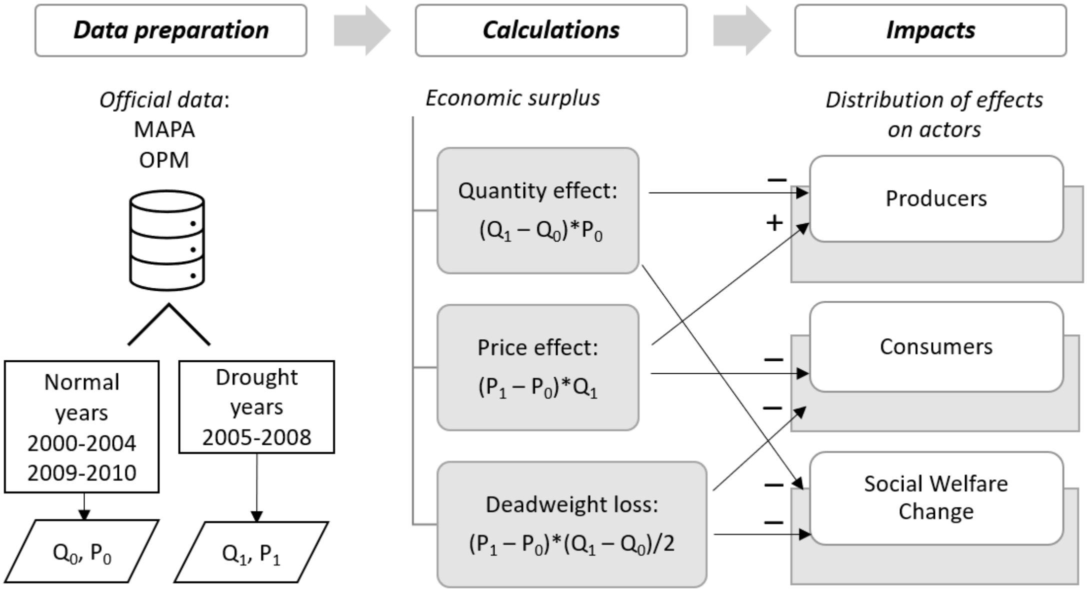
This study has been conducted at the territorial level of the Andalusian region and covers the 2005-2008 hydrological drought which was the last relevant drought event in the Andalusian territory (IMA, 2009). For the analysis, the period from 2000 to 2010 was considered. The period presented a significant decrease in precipitation, from an average of 590 mm (1940-2004) to 310 mm in 2005, thereby reducing the volume of water stored in the reservoirs during these years (shaded in Figure 5.1), which resulted in water volumes in the reservoirs being significantly lower than the average for normal years.

Figure 5.1. *Volume of water stored at the end of the year and annual rainfall in the Guadalquivir River basin, 2001-2010. Source: Authors' own based on MAPA (2020).*



The diagram in Figure 5.2 summarises the methodology developed to assess the effects of drought on the economic surplus. Data sources comprised statistical series from bodies of Spanish government, which included the Ministry of Agriculture, Fisheries and Food (MAPA) of Spain and the Observatory of Prices and Markets (OPM) of Andalusia.

Figure 5.2. *Schematic of the methodology for assessing the effects of drought on the economic surplus.*



The analysis has focused on the socioeconomic impact on rainfed and irrigated agriculture due to the scarcity of water resources caused by a declared hydrological drought, which is significantly related to the problems of meeting demands (streams, reservoirs, and groundwater levels). Since not all the agricultural sector has to lose and can mitigate its losses, this methodology helps us to assess the mitigation of the economic loss from drought that is due to the price effect. The potential for disaggregated analysis allows for a more in-depth analysis and comparison of the effects on different crops according to irrigated and rainfed systems.

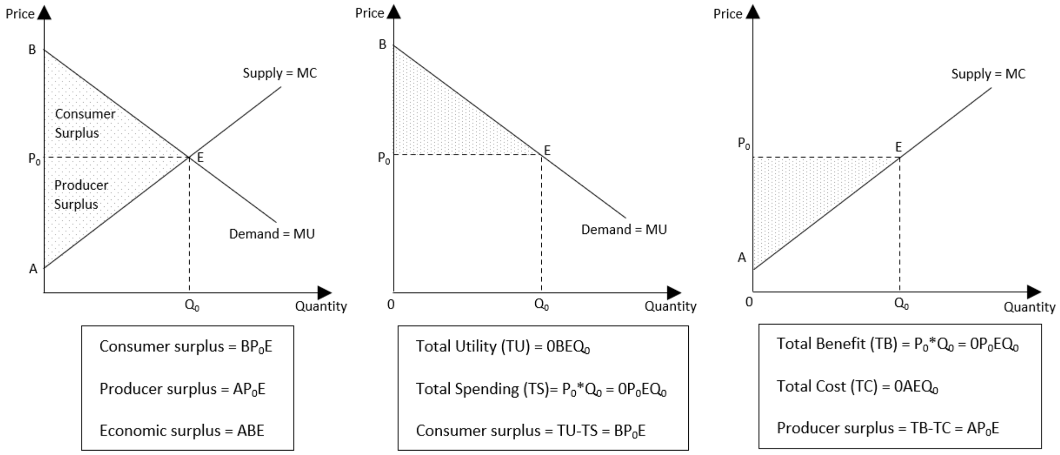
Regarding the limitations of the methodology, considering that drought does not affect all farms equally, we have that the estimated effect is an overall average per crop and the effects on different farmers are not differentiated. As we will see below, our model assumes that price variation is not influenced by external factors, which is a limitation of the methodology, as the price could be influenced by the international market for some products. Another limitation is the influence of the CAP, we cannot control for the effects that the CAP had on the price effect and the quantity effect. These limitations will be discussed in more detail in the discussion.

The concept and theory of the economic surplus is now presented, together with its estimation on the economic impacts of the hydrological drought in Andalusia.

5.2.1. Economic surplus method for the assessment of the impact of droughts

The economic surplus, a well-established theory in the context of welfare economics in microeconomics, is intended to measure aggregate social benefits; it represents the welfare of consumers and producers throughout the economy. The social value of a given level of production and consumption can be estimated using the concept of economic surplus, defined as the area between the supply and demand curves, measured in terms of money (price on the vertical axis, times quantity on the horizontal axis). Economic surplus is composed of two parts: consumer surplus and producer surplus. Both these surpluses are derived from marginal utility (MU) in the case of the consumer, and from marginal cost (MC) in the case of the producer (Figure 5.3).

Figure 5.3. *Supply, demand, and economic surplus. Source: Authors' own.*



Consumer surplus = BP_0E
Producer surplus = AP_0E
Economic surplus = ABE

Total Utility (TU) = $0BEQ_0$
Total Spending (TS)= $P_0 * Q_0 = 0P_0EQ_0$
Consumer surplus = TU-TS = BP_0E

Total Benefit (TB) = $P_0 * Q_0 = 0P_0EQ_0$
Total Cost (TC) = $0AEQ_0$
Producer surplus = TB-TC = AP_0E

For the consumer, decreasing demand (marginal utility) generates an excess utility that the consumer derives from the consumption of Q_0 units of the commodity. In the case of the producer, as long as the supply curve (marginal costs) is increasing, there is a difference between revenue received from the sale of Q_0 units and the total cost of production of Q_0. Economic surplus is thus the welfare or net utility gain from production and consumption of a commodity; it is equal to the consumer surplus plus the producer surplus. It is the monetary value that consumers would have paid for each unit consumed, plus the monetary value that producers would have paid for each unit produced, up to the actual market price and quantity (Kolmar, 2017; Pindyck and Rubinfeld, 2014).

The quantity produced of most agricultural and other primary products cannot change until the subsequent growing season. Farmers may not be able to increase their amount of land, labour, and capital in a short period of time following a price rise, and hence the short-term supply curve may be perfectly inelastic (Pindyck and Rubinfeld, 2014). For example, the amount of water available for irrigation cannot be adjusted, due to technological constraints, such as a low degree of flexibility in water supply and distribution networks. Therefore, to simplify our model, we can consider a perfectly inelastic supply curve for every agricultural product in the short-term.

Additionally, the analysis is based on the following assumptions (Musolino et al., 2018):

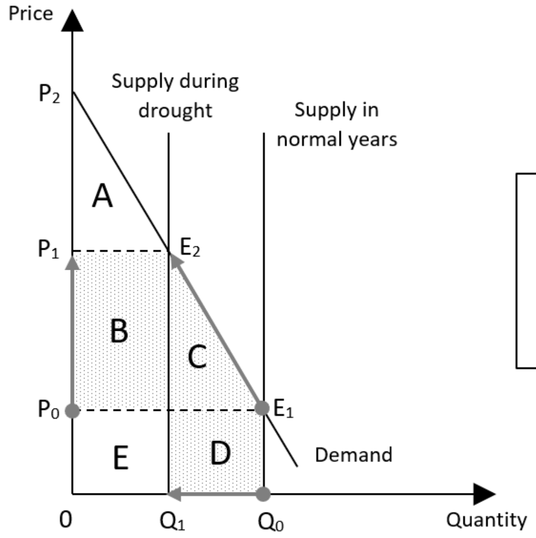
a) Economic losses in terms of crop production are entirely due to drought.

b) This microeconomic system is closed, in that production and the local variation in crop prices that can be observed are not influenced by external factors (e.g., the price of oranges depends on the drought suffered in the region and not on a shortage or abundance in the international markets).

c) Price increases are passed on in full to final consumers and are not absorbed by any intermediate stage of the value chain.

In this simplified model, the economic consequences in the agricultural sector caused by a drought are represented in Figure 5.4. When the availability of water for crop production (rainfed and irrigated) is at normal levels, then the equilibrium point is at the intersection between the demand curve and the supply curve (E_1). In this situation, the consumer surplus corresponds to the area ABC ($P_2P_0E_1$), which is equal to the difference between the total amount of money consumers are willing to pay for every purchased unit from 0 to Q_0, as shown in the area ABCDE ($P_20Q_0E_1$) below the demand, and the total amount they actually pay for it, as identified by the area ED ($P_00Q_0E_1$). On the other hand, producer surplus is represented by this area ED. Total economic welfare, as the sum of consumer and producer surplus, is the area ABCDE.

Figure 5.4. *Short-term effects of the drought on the agricultural sector. Source: Authors' own.*



When a drought event occurs, water availability and crop production decreases and the supply curve shifts to the left, as production is now strictly limited by the drought. Due to the lower supply of agricultural product and excess market demand, the market price increases from P_0 to P_1, and the equilibrium point shifts from E_1 to E_2. The effects on the various groups of economic factors involved in crop production and the market can differ widely. If the structure of the value chain is simplified, it can be assumed that it is composed of only two groups: producers (farmers) and consumers.

The first effect from the drought that farmers suffer is the fall in agricultural production (Q_0-Q_1). Thus, farmers lose a part of the income they could have obtained normally. This quantity effect can be represented graphically by the area D. On the other hand, due to the price increase, farmers will be able to sell the (remaining) crop production (Q_1) at a higher price (P_1), thereby earning an additional profit corresponding to the area B. Thus, while the quantity effect causes them a loss, the price effect can determine an extra profit.

The final economic impact on farmers is given by the difference between these two effects. Seldom are all farmers affected to the same extent: some farmers lose only a small part of their production, and therefore only gain from the combination of these effects, as they can take full advantage of the price effect to increase their income and profits, compared to normal years. Other farmers may lose a great amount of crop production, whereby the quantity effect exceeds the price effect, causing a net loss. Therefore, droughts not only raise the price of crops, but also tend to raise the incomes of the most resilient farmers, that is, those who have the capacity to adapt and keep their production relatively stable when confronted with a drought event.

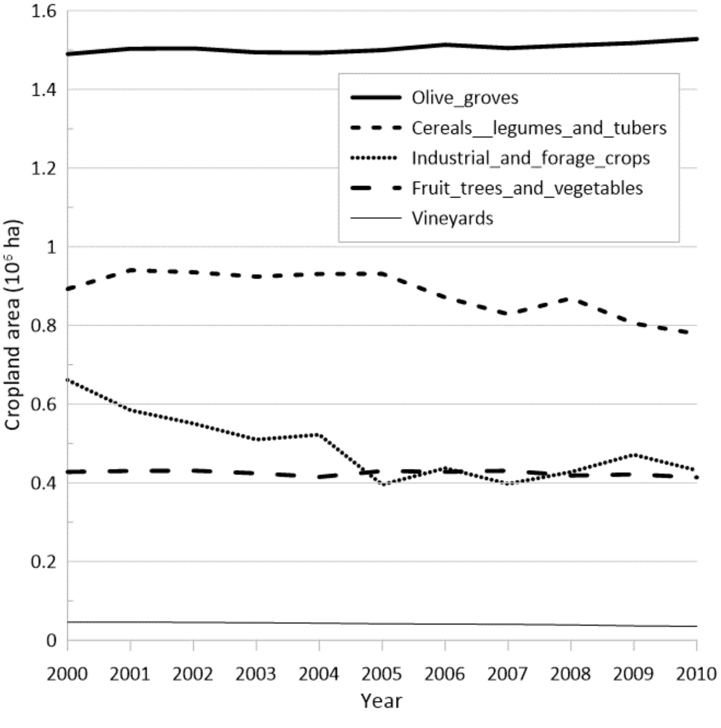
As for consumers, due to changes in production and price, the consumer surplus also changes and diminishes; in fact, it is now represented by the area A ($P_2P_1E_2$), which is smaller than the previous area ABC ($P_2P_0E_1$). For consumers, it is evident that the drought event causes an economic loss, equal to the area BC ($P_1P_0E_1E_2$), which is the sum of the deadweight loss or irrecoverable loss of efficiency (shaded area C) due to the welfare loss related to the lower consumption of agricultural products, and the price effect (shaded area B) associated with the higher price paid for consuming the agricultural products still produced in the drought year.

Considering all the effects on farmers and consumers, the change in social welfare caused by the drought related to agriculture is assumed to be negative because the community suffers a loss equal to the area CD ($E_2Q_1Q_0E_1$), which is the total of the losses suffered by consumers and the two effects observed on farmers. In this context, the elasticity of demand plays a major role in determining the impact: the more inelastic the demand becomes, the greater is the impact of supply constraints passed on to prices and thus away from producers.

5.2.2. Data and procedure for economic surplus calculations

Annual time series were prepared for crop production (tons/year) and prices (€/ton/year) of the main crops produced in Andalusia (Figure 5.5). The crop price series was valued in constant 2015 prices using the GDP deflator. For the estimation of the effects on the economic surplus caused by the drought, the procedure of Musolino et al. (2018) was adapted. In their research, the analysis was performed at the aggregate level by total crop groups (cereals, industrial, fruit trees, etc.) without distinguishing between rainfed and irrigated crops or between crops of the same group, while our analysis is more detailed at the crop level, in that it specifies whether the crops are rainfed or irrigated, which enables a more in-depth understanding and interpretation of the differences in impacts between crops.

Figure 5.5. *Area dedicated to the main crops in Andalusia, 2000-2010.*
Source: Authors' own based on data from IECA (2020).



For each rainfed and irrigated crop, the following economic surplus effects were estimated:

1) The quantity effect, which was calculated as the difference between production in hydrological drought years and average production in normal years (Q_1-Q_0), multiplied by the average price in normal years (P_0).

2) The price effect, obtained by multiplying the difference between prices in drought years (P_1) and the average price in normal years (P_0) by the average agricultural production in the drought year (Q_1).

3) The deadweight loss effect (irrecoverable loss of efficiency) was calculated as the multiplication of the price variation by the production variation divided by two ($(P_1\text{-}P_0 * Q_1\text{-}Q_0) / 2$).

Finally, the total change in social welfare was obtained by adding algebraically the three effects on the two groups seen above (producers and consumers). Based on the model in Figure 5.4, the effects, and signs (negative or positive) of the expected impacts can be summarised (table 5.1).

Table 5.1. *Effects of drought in terms of social welfare according to the economic surplus theory.*

	Quantity Effect	**Price effect**	**Irrecoverable Loss**
Producers (farmers)	D (–)	B (+)	
Consumers		B (–)	C (–)
Change in Social Welfare	D (–)		C (–)

Source: Authors' own, adapted from Musolino et al. 2018.

The quantity effect is associated with a loss for farmers since they are negatively affected by the decrease in production. However, the price effect, due to the increase in price caused by the reduction in agricultural production, affects both farmers and consumers: for the farmer it represents a benefit and for the consumer a loss. Both effects cancel each other out at the societal level. The irrecoverable loss of efficiency negatively affects consumers, while society as a whole (consumers and farmers) experience a negative change in overall welfare.

5.3. Results

5.3.1. Changes in production and prices during the hydrological drought

The main changes in crop production and prices are presented in tables 5.2 and 5.3. It is shown that during the hydrological drought (years 2005-2008) there was a general decrease in crop production, while the increase in prices was generalised for most crops. In relative values, the total reduction in production was greater in the case of rainfed crops (140%). It should be noted that share of the rainfed area represents 74% of the total cultivated land in Andalusia (2000-2010) while the irrigated area is only 26% thereof. As can be observed below, the differences are clearly evident in the impacts of the drought on rainfed and irrigated crops.

As shown in Table 5.2, during the drought there was a decrease in rainfed and irrigated agricultural production in all crop groups; however, certain irrigated crops, namely wheat, oranges and mandarins, and wine grapes, showed a significant increase, while lemon, olive oil, and table olives showed a slight decrease in production. The reason is that, in the period 2005-2008, an increase in these irrigated crops was due to the expansion off production; even in the case of citrus orchards, new trees had entered into production since their area had been under expansion since 2000.

Table 5.2. *Impact of drought on crop production (2005-2008 vs. 2000-2010 averages) in Andalusia.*

Group	Crop	Relative change (%)	
		Rainfed	Irrigated
Cereals	Wheat	–15.2	25.3
	Rice	—	–34.0
	Corn	0.9	–29.6
Industrials	Cotton	–21.5	–32.4

	Sunflower	−19.3	−16.6
Woody	Orange	—	14.2
	Tangerine	—	32.1
	Lemon	—	−1.3
	Almond	−20.1	−41.2
	Grapes (table)	−12.6	−17.5
	Grapes (wine)	−13.6	10.5
	Olive (table)	−17.3	−2.4
	Olive (oil)	−21.6	−2.4
Total		−140.2	−95.2

Source: Authors' own based on MAPA data.

In terms of productivity, yield evolution shows a statistically significant difference between irrigated and rainfed crops (Figure 5.6). Table 5.3 shows how during the drought period the decline in agricultural production generated upward pressure on agricultural commodity prices.

Figure 5.6. *Comparison of yields of rainfed and irrigated crops in Andalusia, 2000-2018.*
Source: Authors' own based on data from MAPA (2020).

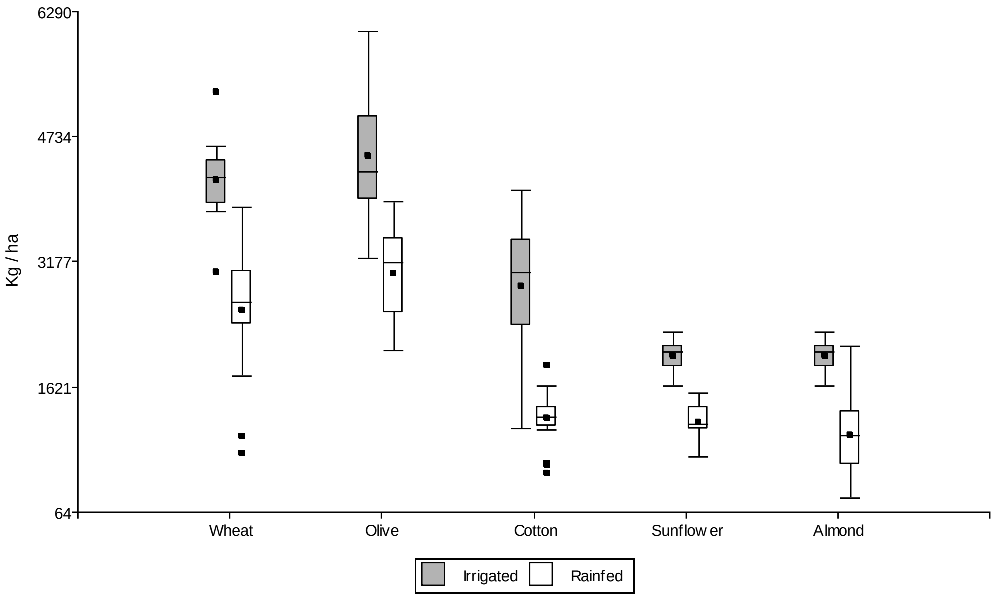


Table 5.3. *Changes in prices received by farmers (2005-2008 vs. 2000-2004 averages) in Andalusia.*

Group	**Crop**	**Relative change** (%)
Cereals	Wheat	21.4
	Rice	–2.6
	Corn	16.5
Industrials	Cotton	–57.7
	Sunflower	49.5
Woody	Orange	7.3
	Tangerine	–10.1
	Lemon	33.5
	Almond	29.7
	Grapes (wine)	20.5
	Olive (table)	33.8
	Olive (oil)	28.1

Source: Authors' own based on OPM data.

Hence, there are not only social groups that lose, as is usually expected, but also groups that gain. It is therefore reasonable to state that drought does not always generate negative effects. Having reviewed the trends and changes in crop production and prices during the drought, we can now examine how these changes affected farmers and consumers during the drought.

5.3.2. The effects of drought on farmers and consumers

The total effect of drought on producers, consumers, and on society was calculated (Table 5.4), whereby the negative effects on the social welfare of the agricultural sector in Andalusia are shown and represent an estimated loss of EUR 1,512 million, of which 94% (EUR 1,426 million) corresponded to rainfed crops. As for consumers, the impact was negative (EUR 2,324 million) with 79% (EUR 1,842 million) corresponding to rainfed crops. As can be observed, the negative impacts of the drought were mainly concentrated on rainfed crops. On the other hand, according to the consumer surplus theory, the estimates reveal not only losses, but also gains in the case of producers. The gains obtained by producers are explained by the price effect, which in most rainfed and irrigated crops was positive; in absolute terms, this effect greatly exceeded the quantity effect, which was as expected negative.

Table 5.4. *Impacts on producers, consumers, and total social welfare during the 2005-2008 drought (Millions of constant EUR 2015).*

		Quantity effect $(\Delta q * p)$	**Price effect $(\Delta p * q)$**	**Deadweight loss $(\Delta p * \Delta q) / 2$**	**Total impacts**	**Sign of impacts**
Rainfed	Producers	-1,261.0	1,677.5		416.5	+
	Consumers		-1,677.5	-165.1	-1,842.6	–
	Social Welfare	-1,261.0		-165.1	-1,426.1	–
Irrigated	Producers	-191.4	586.8		395.4	+
	Consumers		-586.8	104.9	-481.9	–
	Social Welfare	-191.4		104.9	-86.5	–
Total	Producers	-1,452.4	2,264.3		811.9	+
	Consumers		-2,264.3	-60.2	-2,324.4	–
	Social Welfare	-1,452.4		-60.2	-1,512.6	–

Source: Authors' own.

Therefore, in most cases, farmers, taken as a whole, although they lost part of their crop production due to the drought ("quantity effect"), were able to benefit from the higher prices that the drought created in agricultural markets (“price effect”), by selling their remaining agricultural production at higher prices. The positive impact of the drought on producers is estimated at 811 million Euros, 51% of which was distributed among rainfed crops and 49% among irrigated crops. It should be noted that in the case of irrigated crops, the price effect in absolute terms was triple the quantity effect, while in rainfed crops both effects were close in absolute terms. Comparatively, this lower quantity effect in irrigated crops explains the low (6%) negative impact that irrigated crops exerted on social welfare in Andalusia. Irrigated crops take advantage of the increase in the price effect due to the yield loss of rainfed crops, while the quantity effect is reduced by agricultural water.

Despite the presence of negative and positive effects (losses and gains), it must be reiterated that, in Andalusia, the total impact of the 2005-2008 drought in terms of social welfare was negative, that is, society (including all social groups) underwent a negative socio-economic impact. However, as we will see below, depending on the crop, the magnitude of the impacts varies significantly.

5.3.3. The effects of drought on crops

When estimations are made at the crop level, the results show that within each of the two social groups (producers and consumers) the impacts differ. It is shown that not all farmers obtain positive effects, that not all farmers who achieve positive effects achieve them to the same extent, and that not all consumers experience losses to the same extent. The estimated effects show that most farmers overall gain (Table 5.5), although certain farmers may still make a loss. Moreover, those making a profit differ greatly in terms of the magnitude of the benefit they stand to gain from the drought.

Table 5.5. *Impacts on producers (farmers) in terms of rainfed and irrigated crops during the 2005-2008 drought (Millions of constant EUR 2015).*

Group		Crop	Quantity effect $(\Delta q * p)$	Price effect $(\Delta p * q)$	Annual average	Total	Magnitude of impacts[1]
Rainfed	Cereals	Wheat	-114.9	159.1	11.1	44.2	+
		Corn	0.0	0.2	0.1	0.3	+
	Industrial	Cotton	-1.9	-7.6	-2.4	-9.5	-
		Sunflower	-51.5	119.1	16.9	67.6	+
	Woody	Almond	-14.8	32.0	4.3	17.2	+
		Grapes (table)	-0.9	2.7	0.5	1.9	+
		Grapes (wine)	-48.0	77.2	7.3	29.2	+
		Olive (table)	-51.1	101.2	12.5	50.2	+
		Olive (oil)	-978.0	1,193.4	53.9	215.4	++
	Total		**-1,261.0**	**1,677.5**	**104.1**	**416.5**	
Irrigated	Cereals	Wheat	31.2	37.8	17.3	69.1	+
		Rice	-100.9	-19.4	-30.1	-120.3	-
		Corn	-74.4	25.2	-12.3	-49.3	-
	Industrial	Cotton	-134.8	-248.2	-95.7	-383.0	--
		Sunflower	-12.8	30.8	4.5	18.0	+
	Woody	Orange	105.4	78.7	46.0	184.1	+
		Tangerine	54.0	-24.8	7.3	29.2	+
		Lemon	-0.7	29.3	7.1	28.6	+
		Almond	-9.1	5.8	-0.8	-3.3	-
		Grapes (table)	-6.9	8.0	0.3	1.1	+
		Grapes (wine)	0.1	2.3	0.6	2.4	+
		Olive (table)	-5.4	115.4	27.5	110.0	+
		Olive (oil)	-37.2	546.0	127.2	508.8	++
	Total		**-191.4**	**586.8**	**98.8**	**395.4**	

[1] Percentage of the total sum of the impact (in absolute values) of each crop grouped in terms of rainfed and irrigated crops (more than 50%: +++ / - - -; from 25% to 50%: ++ / - -; from 0% to 25%: +/-)

Source: Authors' own.

For farmers, the main loss-making crop during the drought was that of cotton, where the impact of the negative price effect coupled with the negative quantity effect was significant. The other crops that represented losses for farmers included that of rice, which was also affected by a negative price effect, and irrigated corn, which, although it had a positive price effect, remained insufficient to offset the loss derived from the (negative) quantity effect.

On the other hand, the winning crops for farmers differed greatly in terms of the magnitude of the benefit farmers could obtain from the drought. Note that for the main profit-making crop, which was olives for oil milling (olive oil), the positive impact was higher in irrigated than in rainfed crops, because the production loss (negative quantity effect) was lower for irrigated crops (EUR -37.2 million) and was compensated by a positive price effect; this is contrary to the situation of rainfed crops, whose production loss was significant (EUR -978.0 million), despite being compensated by the price effect.

Furthermore, farmers who grew irrigated wheat obtained an increase in production (positive quantity effect) together with the positive price effect, while farmers who grew rainfed wheat obtained a loss of production compensated by a significant price increase. Citrus crops (mainly oranges) also obtained a positive quantity effect together with a positive price effect, resulting in large benefits for producers.

While most crops during the drought represented benefits for producers, consumers (Table 5.6) suffered losses in almost all types of agricultural products, although the magnitude of the reduction in their welfare was not always the same.

Table 5.6. *Impacts on consumers in terms of rainfed and irrigated crops during the 2005-2008 drought (Millions of constant EUR 2015).*

Group		**Crop**	**Price effect** $(\Delta p * q)$	**Deadweight loss** $(\Delta p * \Delta q)/2$	**Annual average**	**Total**	**Magnitude of impacts**[1]
Rainfed	Cereals	Wheat	-159.1	-1.6	-40.2	-160.7	-
		Corn	-0.2	0.0	-0.1	-0.2	-
	Industrial	Cotton	7.6	0.7	2.1	8.3	+
		Sunflower	-119.1	-4.5	-30.9	-123.7	-
	Woody	Almond	-32.0	-3.3	-8.8	-35.3	-

		Grapes (table)	-2.7	-0.3	-0.8	-3.0	-
		Grapes (wine)	-77.2	-5.9	-20.8	-83.1	-
		Olive (table)	-101.2	-8.7	-27.5	-110.0	-
		Olive (oil)	-1,193.4	-141.4	-333.7	-1,334.9	- - -
	Total		**-1,677.5**	**-165.1**	**-460.6**	**-1,842.6**	
Irrigated	Cereals	Wheat	-37.8	5.7	-8.0	-32.2	-
		Rice	19.4	-5.0	3.6	14.4	+
		Corn	-25.2	-7.9	-8.3	-33.1	-
	Industrial	Cotton	248.2	115.7	91.0	363.9	++
		Sunflower	-30.8	-1.4	-8.1	-32.2	-
	Woody	Orange	-78.7	8.4	-17.6	-70.3	-
		Tangerine	24.8	-2.0	5.7	22.8	+
		Lemon	-29.3	-3.6	-8.2	-32.9	-
		Almond	-5.8	-2.0	-1.9	-7.8	-
		Grapes (table)	-8.0	-0.8	-2.2	-8.7	-
		Grapes (wine)	-2.3	0.1	-0.5	-2.2	-
		Olive (table)	-115.4	-1.5	-29.2	-116.9	-
		Olive (oil)	-546.0	-0.8	-136.7	-546.8	- -
	Total		**-586.8**	**104.9**	**-120.5**	**-481.9**	

[1] Percentage of the total sum of the impact (in absolute values) of each crop grouped in terms of rainfed and irrigated crops (more than 50%: +++ / - - -; from 25% to 50%: ++ / - -; from 0% to 25%: +/-)

Source: Authors' own.

The largest losses were observed in the consumption of olive products for oil and table olive production, wheat, and sunflower products. These losses corresponded to the magnitude of the price effect. At the same time, three crops (cotton, rice, and mandarins) had a positive effect on consumers.

5.4. Discussion

The dichotomy between irrigated and rainfed agriculture in Spain has been growing since the mid-20th century. During the period 1965-2018 in Spain as a whole, rainfed crops lost an area of 5.7 million hectares (31%) while irrigated crops gained 2.0 million hectares (210%), thereby reducing the total cultivated area by 18%, equivalent to 3.7 million hectares (Berbel and Espinosa-Tasón, 2020); a similar behaviour has been observed in Andalusia (Gil et al., 2000). Likewise, modernisation policy at the beginning of the 21st century has exerted a significant influence on the recent evolution of irrigated areas and on the productive orientation of irrigated land (Berbel et al., 2019). The trend towards intensification has continued up to the present day, in a scenario where precipitation and temperatures are expected to become more variable with climate change, leading to a higher incidence of droughts; this will have particularly severe effects on agriculture.

Our results can be compared with the findings in other regions of southern Europe by Musolino et al. (2017 in the Po River basin in Italy for the droughts of the years 2003, 2005-2007; and with those of Musolino et al. (2018 which included Italy, Portugal, and the Júcar basin in Spain. In the aforementioned studies, the authors estimate that not all farmers incur losses from the quantity effect, as some may even make money in times of drought, due to the price effect caused by the scarcity of agricultural products. Consumers, however, always lose, due to the sum of the quantity effect and the price effect. The impacts on the farmers themselves also differ in terms of sign and magnitude, particularly when distinguished by crop category and geographical area.

Another comparison can be made with California, characterised by its Mediterranean climate, which experienced one of its deepest and longest historic droughts in the 5-year drought from 2012 to 2016. The most severe economic impacts from the effects of the drought were suffered by much of Californian agriculture, although local groundwater buffered the majority of the agricultural impacts. In 2014-2015, the two deepest years of the drought, state-wide crop revenue losses reached approximately US $1,700 million. These losses primarily affected annual crops and were concentrated in areas without access to good groundwater (Howitt et al., 2014; Lund et al., 2018).

During the California drought, farmers tended to allocate water to perennial higher-value crops, which have a large share of national and global production (Sumner, 2015). Agricultural areas were adapted to the drought by fallowing significant acres of annual crops, reducing irrigation applications to only certain crops, and shifting a number of annual crops to new orchards, such as almonds, grapes, and pistachios (CFWC, 2016; Lund et al., 2018). Market prices and production of these perennial crops (especially almonds) were high during the drought, which bolstered farm income and employment (Medellín-Azuara et al., 2015).

According to our results, the quantity effect caused by drought significantly decreased production revealing the scarcity of water resources during the period 2005-2008, and its impact on the agricultural sector, which affected especially rainfed crops. In the case of irrigated crops, the effects of the drought were mitigated by the use of groundwater and the use of non-conventional resources (Estrela Monreal and Rodríguez Fontal, 2008).

The analysis assumes that the price effect is only due to reduced production. Given the nature of some crops in Spain, such as olive groves, citrus fruits, and cotton, among others, their prices will not be influenced by the international market, but this is not the case for wheat which coincides with a price rise due to the global food commodities crisis of 2007-2008; therefore, the rise in wheat prices is not only due to the drought in Andalusia.

During the drought, cotton (rainfed and irrigated) had a negative impact on its production and prices. In addition to the drought, a strong change in the economic framework contributed to the observed reduction in yields. After a very stable production in the period 1995-2004, a drastic reform of the CAP regime for cotton came into force in 2005, resulting in a sharp reduction of input use and, consequently, a 60% decrease in crop production (Arriaza & Capellán, 2009).

On the other hand, agricultural insurance may play an important role in mitigating the economic impact of drought. Crop insurance programs cover approximately 20% of the cultivated area in the EU (Santeramo and Ford Ramsey, 2017), although agricultural insurance in Spain is above the EU average in rainfed arable crops, where the most frequent insured risks are "drought and hail", covering around 80% of the insured arable area (MAPA, 2021). This implies that producers are usually compensated by the insurance system with an income in addition to the estimated values. This applies mainly to rainfed crops, since irrigated crops cannot be insured against drought under the current insurance policy norms and therefore cannot claim compensation, even if the water quota is reduced below normal years.

5.5. Conclusions and policy implications

Regarding agriculture in Andalusia, the magnitude of the economic impacts of hydrological drought on social welfare is considerable. Differences are clearly evident between rainfed and irrigated crops; the negative impacts of the hydrological drought were mainly concentrated on rainfed crops. At the same time, as assumed by the economic surplus theory approach, the negative impacts are socially differentiated between consumers and producers. This analysis contradicts the usual depiction, according to which drought causes only economic loss or damage. As noted above, the elasticity of supply and demand plays a key role in determining and distributing the impact. The more inelastic demand becomes, the greater the negative impact of supply constraints is passed on to prices and, therefore, the greater the negative impact on consumers and the greater the benefit to farmers. Since elasticity depends on the availability of substitutes, our analysis implicitly predicts that farms producing crops that have closer substitutes suffer more acutely, while those producing less substitutable crops (e.g., olives for oil production, wheat for bread making, etc.) will be able to increase prices, and possibly even benefit from the drought.

Our study contributes to the analysis of the economic impact of hydrological drought on agriculture with an interesting case study, since Andalusia is the Spanish region with the largest irrigated surface area (29% of the total national irrigated area), with a majority presence of drip irrigation. Due to the aggregation of the whole of Andalusia of different provinces in terms of geographical scale, demographic, and economic characteristics, it would be convenient that this analysis be repeated using a smaller territorial unit, which would enable the conclusions provided by our analysis to be contrasted. Consequently, the analysis can be employed to guide support and recovery policies for farmers (in terms of subsidies, insurance schemes, etc.), while taking into consideration that not all farmers are affected to the same extent and that some farmers may even profit from droughts. Therefore, a thorough characterisation of winners and losers among farmers, differentiated by geographic region, crop type, and farm size, among other possible criteria, would be necessary, and an in-depth analysis of the value chain would be required to investigate whether farmers or other actors, such as wholesalers, maintain these benefits.

Among future lines of research, we aim to expand the economic analysis presented here with wider research on the impact of drought in the whole bioeconomy sector, possibly expanding the territorial scope to other EU areas and when possible, in a more recent intense drought, that unfortunately will come soon or later. As far as policy implications are concerned, it is clear that investing in drought preparedness and resilience, taking into consideration both water supply and demand management measures (Kampragou et al., 2015), is the first implication to draw from our study, as it prevents from suffering the overall net economic caused by droughts. Moreover, considering that not all farmers are hit to the same extent by drought, policies should support only “losers” from drought. That means first identifying them correctly, enhancing monitoring systems and data management; second, it means designing appropriate financial tools aimed at compensating them for the damages suffered (for example, through mutual insurance schemes). In this respect, also the use of the instruments increasingly used for funding sustainable projects (e.g., green bonds emission) (ICMA, 2018), should be explored better, in particular with reference to drought resilience and preparedness of the most vulnerable agricultural sectors.

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Capítulo 6
Conclusiones

6.1. Conclusiones

6.1.1. Conclusiones generales

- La integración de España en la Comunidad Económica Europea lograda en 1986 y la globalización de los mercados, ha favorecido especializarse a la agricultura española en cultivos en los que posee una ventaja competitiva, iniciando un proceso de innovación y cambio que ha transformado radicalmente su agricultura en los últimos 40 años.

- La evolución conjunta de la eficiencia del regadío y su consumo energético a nivel nacional indican el efecto de una economía del agua madura y el consecutivo cierre de las principales cuencas caracterizado por la reducción de las medidas de aumento de la oferta y el énfasis en los sistemas de ahorro del agua que aumentan la eficiencia del uso y reducen los caudales de retorno.

- El cambio de paradigma de la política de oferta a la gestión de la demanda, en los últimos 20 años definido por la intensa modernización con fuerte presencia de subvenciones públicas, ha dado lugar a un mayor uso de energía por unidad de agua y, más recientemente, a la introducción de fuentes alternativas de suministro como la desalación y reutilización.

- Con el impacto del cambio climático, la baja o nula rentabilidad del secano y su vulnerabilidad frente a sequías, se aumentará la presión por regar más tierras. En este contexto, el regadío solo podrá adaptarse a este escenario mediante múltiples estrategias adecuadas a las condiciones locales: mejora de gobernanza, de las sinergias en el nexo agua-energía, de sistemas de riego de precisión, de las fuentes de agua no convencionales, así como nuevos instrumentos económicos para gestión y riesgos.

- Los impactos socioeconómicos de la sequía hidrológica muestran diferencias claramente evidentes entre los cultivos de secano y los de regadío; los impactos negativos de la sequía hidrológica se concentran principalmente en los cultivos de secano. Al mismo tiempo, los impactos negativos están socialmente diferenciados entre consumidores y productores. Cuanto más inelástica sea la demanda, mayor será el impacto negativo de las limitaciones de la oferta que se traslada a los precios y, por tanto, mayor será el impacto negativo sobre los consumidores y mayor el beneficio del efecto precio para los agricultores.

- Teniendo en cuenta que no todos los agricultores se ven afectados en la misma medida por la sequía, las políticas deberían apoyar solo a los "perdedores" de la sequía. Esto significa, en primer lugar, identificarlos correctamente, mejorando los sistemas de seguimiento y la gestión de datos; en segundo lugar, significa diseñar herramientas financieras adecuadas destinadas a los sectores agrícolas más vulnerables para compensarles por los daños sufridos.

6.1.2. Nuevas líneas de investigación

A partir de los resultados presentados en esta tesis, las nuevas líneas de investigación se pueden enfocar de acuerdo con lo recogido en los siguientes puntos:

- La sustitución de agua por energía que se observa con la modernización a nivel nacional debe analizarse a nivel de cuenca, al menos en las grandes cuencas intercomunitarias, lo que arrojaría diferencias significativas entre cuencas en el nexo agua-energía-alimentos.

- El análisis de la extracción y consumo de agua a nivel de cuenca o acuífero basado en datos estadísticos oficiales debe complementarse con datos sobre la evapotranspiración real, los caudales de retorno y el estado de las masas de agua. La estimación del consumo de agua podría complementarse con la teledetección para medir o estimar la evapotranspiración.

- El análisis del nexo agua-energía-alimentos se debe realizar considerando tanto los efectos positivos como los negativos de la inversión en ahorro de agua y las fuentes de suministro alternativas en relación con la mitigación del cambio climático y la emisión de gases de efecto invernadero.

- El análisis del impacto socioeconómico de la sequía hidrológica en la agricultura se debe repetir utilizando una unidad territorial menor, lo que permitiría contrastar las conclusiones aportadas por nuestro análisis.
- Teniendo en cuenta que no todos los agricultores se ven afectados en la misma medida, sería necesaria una caracterización exhaustiva de los ganadores y perdedores entre los agricultores, diferenciada por región geográfica, tipo de cultivo y tamaño de la explotación, entre otros posibles criterios, y un análisis en profundidad de la cadena de valor para investigar si los agricultores u otros agentes, como los mayoristas, mantienen estos beneficios.