UNIVERSIDAD DE CÓRDOBA

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Área de Ingeniería Hidráulica

Gestión sostenible de redes de riego a presión mediante la mejora de la eficiencia en el uso de los recursos agua y energía

"Sustainable management of pressurized irrigation networks by improving the efficiency of water and energy use"

Mª Teresa Carrillo Cobo

TITULO: *Gestión sostenible de redes de riego a presión mediante la mejora de la eficiencia en el uso de los recursos agua y energía*

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"Sustainable management of pressurized irrigation networks by improving the efficiency of water and energy use"

Tesis doctoral presentada por

Mª Teresa Carrillo Cobo

para la obtención del título de

DOCTOR CON MENCIÓN INTERNACIONAL

POR LA UNIVERSIDAD DE CÓRDOBA

Directores

Dr. Juan Antonio Rodríguez Díaz (Ramón y Cajal)
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TÍTULO DE LA TESIS:

Gestión sostenible de redes de riego a presión mediante la mejora de la eficiencia en el uso los recursos agua y energía

DOCTORANDA: Mª Teresa Carrillo Cobo

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

La búsqueda del aumento de la eficiencia en el uso del agua de riego ha derivado en España en la realización de grandes obras de modernización. Gran parte de ellas han consistido principalmente en la sustitución de redes de distribución en canales abiertos por redes a presión. Cuando se acometieron los proyectos de modernización no se contempló en ningún momento la eficiencia energética como criterio de proyecto. Otro inconveniente al que se ha enfrentado el regadío y en particular todo el que depende de redes a presión ha sido la liberalización del mercado de la energía y la desaparición de las tarifas especiales de riego. Resulta por tanto, que los nuevos regadíos modernizados son eficientes en el uso del agua pero ineficientes energéticamente. Los costes energéticos suponen en la actualidad el principal coste del agua y amenazan la productividad del regadío.

Ante esta problemática, son necesarios trabajos de investigación centrados en el uso sostenible de los recursos hídricos conjuntamente con el uso óptimo de los energéticos. Al mismo tiempo, en el contexto actual de cambio climático, también es importante minimizar el impacto ambiental y reducir las emisiones de gases de efecto invernadero ocasionado por el aumento de los requerimientos energéticos. Así, es necesario aplicar la cantidad justa de agua pero con el mínimo coste de energía, lo que permitirá mejorar la renta de los agricultores y, al mismo tiempo, minimizar el impacto ambiental.

Todos estos aspectos son tratados en profundidad en la presente tesis doctoral y se presentan soluciones a los mismos. Inicialmente, en un primer trabajo, se desarrolla y aplica una metodología para la evaluación del uso del agua y de la energía en zonas regables. El conocimiento de la situación actual, es esencial para la realización un correcto diagnóstico de las posibles deficiencias en el uso actual de ambos recursos en una determinada zona regable. Gracias a esto, es posible recomendar las medidas adecuadas que permitan un aumento de la eficiencia global en el suministro del agua.

El segundo trabajo, se centra en la sectorización de las redes de distribución de agua de riego. La sectorización consiste en organizar a los regantes en turnos de riego según su demanda energética y, gracias a ella, obtener importantes ahorros de energía. No obstante, la sectorización es compleja, dado que es necesario considerar una gran cantidad de factores. En esta Tesis Doctoral se desarrolla una nueva metodología para la sectorización de redes de riego a escala mensual, en la cual se tienen en cuenta la topología de la red, las necesidades de agua de los cultivos y las prácticas de riego de los regantes.

Un paso más se da en el tercer trabajo, en donde se combinan objetivos económicos y ambientales. Así, se desarrolla un algoritmo multiobjetivo para la determinación de las láminas de riego óptimas para todos los cultivos de una zona regable en el que, por un lado, se maximiza el beneficio económico de los agricultores y, por otro, se minimizan las emisiones de CO_2. Los resultados obtenidos muestran que es posible disminuir el consumo de agua actual de la zona regable, mejorando al mismo tiempo la renta de los regantes y reduciendo los niveles de emisiones de CO_2.

Por último, en el cuarto trabajo, se analiza el potencial de las energías renovables para el suministro de agua en una zona regable. Dicho trabajo permite concluir que gracias a la energía solar es posible reducir las emisiones de CO_2 y el coste energético asociado al suministro del agua.

Por todo esto, consideramos que la Tesis aborda un problema real, de gran actualidad y con gran aplicabilidad al sector. La Tesis se presenta como un compendio de artículos científicos, publicados en algunas de las revistas más prestigiosas en éste área:

- *Carrillo Cobo, M.T., Rodríguez Díaz, J.A., Camacho Poyato, E. 2010. The role of energy audits in irrigated areas. The case of ‘Fuente Palmera’ irrigation district. Spanish Journal of Agricultural Research. 8 (S2) S152-S161*

- *Carrillo Cobo, M.T., Rodríguez Díaz, J.A., Montesinos, P., López Luque, R., Camacho Poyato, E. 2011. Low energy consumption seasonal calendar for sectoring operation in pressurized irrigation network. Irrigation Science. 29, 157-169.*

- *Carrillo Cobo, M.T., Camacho Poyato, E., Montesinos, P., Rodríguez Díaz, J.A. 2014. New model for sustainable management of pressurized irrigation networks. Application to Bembézar MD irrigation district (Spain). Science of the Total Environment.473-474, 1-8.*

- *Carrillo Cobo, M.T., Camacho Poyato, E., Montesinos, P., Rodríguez Díaz, J.A. Exploring the role of solar energy in pressurized irrigation networks. Spanish Journal of Agricultural Research. Aceptado para publicación.*

Por todo ello, se autoriza la presentación de la tesis doctoral "Gestión sostenible de redes de riego a presión mediante la mejora de la eficiencia en el uso los recursos agua y energía".

Córdoba, 17 de Diciembre de 2013

Firma de los directores

Fdo.: Prof. Dr. Juan Antonio Rodríguez Díaz

Fdo.: Prof. Dr. Emilio Camacho Poyato

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Mariateresa

Mª Teresa Carrillo Cobo

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Note: This current PhD Thesis is written in a bilingual format as a requirement for the International Mention

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List of abbreviations

AC	Alternating current
APV	Agricultural production value
BMD	Bembézar Margen Derecha
BMI	Bembézar Margen Izquierda
CP	Penalty cost
DC	Direct current
DMA	Directiva Marcho del Agua
E4	Strategy for Energy Saving and Efficiency in Spain 2004-2012 Estrategia de Ahorro y Eficiencia energética
EAP 4	Energy Action Plan
EAP4+	Energy Action Plan E4 Plus
ECI	Energy Change Index
EDR	Energy Dependency Rate
EF	Emissions conversion factor
ENMSRH	Estrategia Nacional para la Modernización Sostenible de los Regadíos
ER	Energy Requirement
ESE	Energy supply efficiency
EV	El Villar
FAO	Food and Agriculture Organization of the United Nations
FP	Fuente Palmera
GEN	Generation
GHG	Greenhouse gas
IDAE	Institute for Diversification and Energy Savings of Spain
IE	Initial energy
IPS	Intelligent Power System
IRR	Internal Rate of Return
MOM	Management, Maintenance and Operation
MPPT	Maximum power point tracker
NIP	National Irrigation Plan
NPV	Net Present Value
NSGA-II	Non-dominated Sorting Genetic Algorithm
OEE	Overall energy efficiency
OHPM	Open hydrant probability matrix
P	Profits
PCH	Plan de Choque
PEE	Pumping energy efficiency
PNR	Plan Nacional de Regadíos
PV	Photovoltaic
RIS	Annual Relative Irrigation Supply
S1	Sector 1

S2	Sector 2
SUB	The total subsidies in the irrigation area
WEBSO	Water and Energy Based Sectoring Operation

List of symbols

A_c	Area devoted to crop [ha]
A	Excess pressure [m]
C	Crop index
C_f	Fixed costs [€]
cos φ	Pump power-factor
C_v	Variable costs [€]
d_m	Days of each month
E	Daily energy demanded by the pumping station in the peak demand month [kWh]
e_a	Application efficiency
e_c	Conveyance efficiency
ECI	Average pressure head [m]
EF	Emissions conversion factor [kg CO_2 kWh^{-1}]
E_{mjl}	Energy demand at the pumping station in month (m), management scenario (j) and operating sector (l) [kWh]
E_T	Annual energy consumed in the pumping station [kWh]
ET_a	Ratio actual evapotranspiration [mm day^{-1}]
ET_m	Evapotranspiration in no water stress conditions [mm day^{-1}]
F	Demanded flow rate [m^3s^{-1}]
F_{mjl}	Pumped flow per month (m), management scenario (j) and operating sector (l) [m^3s^{-1}]
G	Global irradiation on the PV array plane for the peak energy demand day [kWh m^{-2}]
G*	Reference irradiation [1 kWm^{-2}]
H	Pressure head at the pumping station [m]
H_{ei}	Hydrant elevation measured from the water source elevation [m]
H_i	Pressure head supplied per hydrant (i) [m]
H_j	Pressure in the most restrictive hydrant in each management scenario (j) [m]
H_{jl}	Pressure head in each management scenario (j) and operating sector (l) [m]
H_{li}	Friction losses in pipes) [m]
H_{max}	Maximum theoretical pressure head [m]
H_{mjl}	Minimum pressure head required at the pumping station [m]
H_p	Energy requirement at a pumping station to supply water to a certain hydrant [m]
H_{pmjl}	Lowest pressure head at the pumping station per month (m), management scenario (j) and operating sector (l) [m]
H_{reqi}	Pressure head required at hydrant

I	Intensity [A]
IN_{im}	Daily irrigation need per hydrant (i) and month (m) [L ha^{-1} day^{-1}]
K	Montecarlo iterations
k_y	Yield response factor
l_i	Distances from the pumping station to hydrant (i) along the distribution network [m]
l_i^*	Dimensionless coordinate
l_{max}	Distance to the furthest hydrant [m]
M	Month index
N_c	Number of crops
N_m	Number of months of the irrigation season
P	Electric power of the PV array [kW]
P_e	Effective rainfall [mm day^{-1}]
p_{imj}	Open hydrant probability per hydrant (i), month (m) and management scenario (j)
$Power_{mj}$	Power requirements at the pumping station in month (m) and management scenario (j) [kW]
$Power_{mjl}$	Power requirements per hydrant (i), month (m) and management scenario (j) [kW]
Pr_c	Average market price of each crop [€ kg^{-1}]
q_i	Base demand [L s^{-1}]
q_{max}	The network's design flow [L $s^{-1}ha^{-1}$]
R_{imjl}	Random number for every hydrant (i), month (m), management scenario (j) and operating sector (l)
R_{imjl}	Random number for every hydrant
RIS_c	Crop Annual Relative Irrigation Supply
S_i	Irrigation area associated to each hydrant (i) [ha]
t_{aj}	Time available [hour]
t_{im}	Irrigation time in hours per hydrant (i) and month (m) [hour]
V	Voltage of each pump [v]
V_i	Volume supplied per hydrant (i) [m^3]
V_m	Volume of water pumped each month (m) [m^3]
W	Power consumption [kW]
w_a	Electrical power consumed [kW]
w_s	Power given to the water flow [kW]
Y_a	Yield under actual conditions [kg]
Y_m	Potential yield [kg]
z_i	Hydrant elevation [m]
z_i^*	Dimensionless hydrant elevation
z_{ps}	Pumping station elevation [m]
A	Excess pressure [m]

Γ	Water specific weight [N m^{-3}]
H	Pumping system efficiency
η_{pv}	PV array efficiency under the operation conditions

Summary

In the last decades, irrigated agriculture has undergone a significant expansion, increasing the requirements of a natural and essential resource for the activity development, such as water. This resource is increasingly precious and competition for its use tends to be more intense in the economic sectors. This competition intensifies the need to submit to irrigation, especially in arid and semi-arid areas, a process of modernization by improving their technological level and ensure sustainability of the agricultural sector as a whole. The Spanish government has approved two plans for improving irrigation, National Irrigation Plan (NIP) horizon 2005 and NIP horizon 2008, both of them mainly consisted of promoting the canal lining, pressurized irrigation networks and new automation technologies to improve management in the irrigated areas. This plan has improved water use efficiency, but the new pressurized irrigation networks require large amounts of energy for pumping water. Therefore, energy costs have risen sharply after the modernization, being aggravated by an exponential increment of energy unit prize and compromising the profitability of the sector. In the interests of sustainability and in a context of climate change, where evapotranspiration rate increases water resources decreases, due to the increase of the greenhouse gas (GHG) directly emissions or indirectly caused by the combustion of non-renewable resources, have increased the need to improve efficiency of both resources.

This document consists of seven sections. The first one provides an introduction and frame work in which the present PhD thesis is developed. The specific objectives to achieve the main objective of improving the sustainable management of water and energy use are defined in sections 2. Studies to achieve the proposed objectives are developed in sections 3, 4, 5 and 6 correspond to publications in scientific journals included in the database of the Science Citation Index (SCI)

Section 3 contains a first study in which the water and energy use was evaluated in Fuente Palmera irrigation district. To this end, the protocol for energy audits, proposed by IDAE, was adopted and applied and which concluded that this irrigation district is high energy consumer. The impact of organizing farmers in irrigation turns, as improvement measure, was outlined and evaluated resulting a potential energy savings of 12 %.

Section 4 designs, develops and optimizes WEBSO, which sets up the low energy consumption monthly calendars for sectoring operation in pressurized irrigation networks. The methodology was applied to two irrigation districts in Andalusia, Fuente Palmera and El Villar, evaluating the potential energy savings when theoretical irrigation needs were covered (8% and 5 % respectively) and when local practices were considered (27 % and 9% respectively). This study confirms the need for optimizing the water and energy use together.

Section 5 proposes a methodology to improve the irrigation pattern in irrigation districts using multi-objective optimization techniques, considering environmental and economic criteria. The methodology was applied to a sector of the BMD irrigation district, identifying the optimum irrigation pattern which not only increases the current benefit of the study area by 14.56 % but also reduces the carbon footprint generated by energy consumption in the pumping station at 8.56 %. This methodology highlights the relation among water, energy, environment and crop productivity in the irrigated agriculture.

The feasibility of incorporating renewable energy in irrigation districts is approached in section 6. This study was applied to the BMI irrigation district. The WEBSO model developed in section 4, was applied to this irrigation district achieving potential energy savings by a 30.8 %. In addition, the technical and economic feasibility of photovoltaic system on the pumping station was studied. The result obtained shows that an environmental (the carbon footprint is reduced by 70.5 %) and economic (reduction of energy costs by 77.7 %) benefits are possible in the irrigation area by installing a photovoltaic system of 2.15 MW with a payback of 8 years.

Section 7 comprises the general conclusions of this PhD thesis and supplies recommendations for future research in the field of sustainable management of irrigation networks are provided.

This PhD thesis highlights the need for improving the management of irrigation district from a sustainable viewpoint. Deep knowledge of the real water and energy use in irrigation district identifies weaknesses and consequently, designs, develops, evaluates and optimizes specific improvement measures. These measures also allow maximizing profit, the main objective of any economic activity, mitigating the environmental impact, through reductions in GHG emissions and conservation of natural resources for future generations.

Resumen

La agricultura de regadío ha sufrido una importante expansión en las últimas décadas, incrementándose así los requerimientos de un recurso natural y esencial para el desarrollo de la actividad, como es el agua. Este recurso es cada vez más preciado y la competencia en los diferentes sectores económicos por su uso tiende a ser más intensa. Esta competencia agudiza la necesidad de someter a los regadíos, principalmente en zonas áridas y semiáridas, a un proceso de modernización que mediante la mejora de su nivel tecnológico asegure su sostenibilidad y la del sector agrario en su conjunto. El Gobierno español ha aprobado varios planes para la mejora del regadío, Plan Nacional de Regadíos (PNR) horizonte 2005 y PNR horizonte 2008 que consistieron principalmente en la instalación de redes a presión en las zonas regables y la incorporación de nuevas tecnologías de automatización para mejorar su gestión. Dichos planes han conseguido mejorar la eficiencia en el uso del agua, sin embargo las nuevas redes a presión requieren elevados consumos de energía. Los costes energéticos que debe soportar el sector han crecido bruscamente tras la modernización, siendo agravados por un contexto de incremento exponencial del precio unitario de la energía y comprometiendo la rentabilidad del sector. En aras de la sostenibilidad y en un contexto de cambio climático, donde aumentan las tasas de evapotranspiración y disminuyen los recursos hídricos motivados por el incremento de las emisiones de gases de efecto invernadero, causados directa o indirectamente por la combustión de recursos no renovables, surge la necesidad de mejorar la eficiencia del uso de ambos recursos.

Este documento consta de siete apartados. El primero de ellos proporciona una introducción y define el marco en el que se desarrolla la tesis doctoral. Los objetivos específicos para alcanzar el objetivo principal de mejorar la gestión sostenible de los recursos agua y energía, son definidos en el apartado 2. Los estudios realizados para la consecución de los objetivos propuestos se desarrollan en los apartados 3, 4, 5 y 6 y corresponden con publicaciones íntegras en revistas científicas incluidas en la base de datos del Science Citation Index (SCI)

El apartado 3 contiene un primer estudio en el que se caracteriza el uso del agua y la energía en la zona regable de Fuente Palmera. Con este fin,

se adaptó y aplicó el protocolo de auditorías energéticas, propuesto por el IDAE, concluyendo que es una comunidad de regantes catalogada como gran consumidora energética. Se desarrolló y evaluó el impacto de implementar la organización del riego en turnos como medida de mejora, obteniendo como resultado un ahorro potencial de energía del 12 %.

En el apartado 4 se diseña, desarrolla y optimiza el modelo WEBSO, el cual establece un calendario mensual de sectorización óptima de una zona regable. La metodología fue aplicada a dos zonas regables de Andalucía, Fuente Palmera y El Villar, evaluando los ahorros potenciales de energía cuando se cubren las necesidades teóricas de los cultivos (8 % y 5 % respectivamente) y cuando se consideran las prácticas locales de riego deficitario (27 % y 9 % respectivamente). Este estudio confirma la necesidad de optimizar conjuntamente la eficiencia en el uso del agua y la energía.

En el apartado 5 se propone una metodología para mejorar el patrón de riego de una zona regable mediante técnicas de optimización multiobjetivo, considerando criterios ambientales y económicos. La metodología fue aplicada a un sector de la comunidad de regantes BMD permitiendo identificar su patrón de riego óptimo, que no solo incrementa el beneficio actual de la zona de estudio en un 14.56 % sino que reduce la huella de carbono generada por el consumo energético del bombeo en 8.56 %. Esta metodología pone de manifiesto la relación en la agricultura de regadío entre agua, energía, medio ambiente y productividad de los cultivos.

La viabilidad de incorporar energías renovables en el regadío es abordada en el apartado 6. En este estudio se aplicó a la comunidad de regantes de BMI. El modelo WEBSO, desarrollado en el apartado 4, es aplicado a esta zona regable obteniendo ahorros potenciales de energía del 30.8 %. Además, se estudia la viabilidad técnica y económica de instalar un sistema fotovoltaico en la estación de bombeo. Los resultado obtenidos muestran que es posible una mejora ambiental (la huella de carbono es reducida un 70.5 %) y económica (reducción de costes energéticos en un 77.7 %) en la zona regable mediante la instalación de un sistema fotovoltaico de 2.15 MW, amortizable en 8 años.

En el apartado 7, se recogen las conclusiones generales de esta tesis doctoral y se aportan recomendaciones para las investigaciones futuras en el ámbito de la gestión sostenible de las redes de riego.

Esta tesis doctoral pone de manifiesto la necesidad de mejorar la gestión de las zonas regables desde un punto de vista sostenible. El conocimiento profundo del uso real del agua y la energía en una zona regable permite identificar sus debilidades y consecuentemente, diseñar, desarrollar, evaluar y optimizar medidas de mejora específicas. Estas medidas permitirán además de maximizar el beneficio, como objetivo principal de cualquier actividad económica, mitigar el impacto ambiental de la actividad, mediante reducciones de emisiones de gases de efecto invernadero, y la conservación de recursos naturales para generaciones futuras.

Introduction

1. Introducción

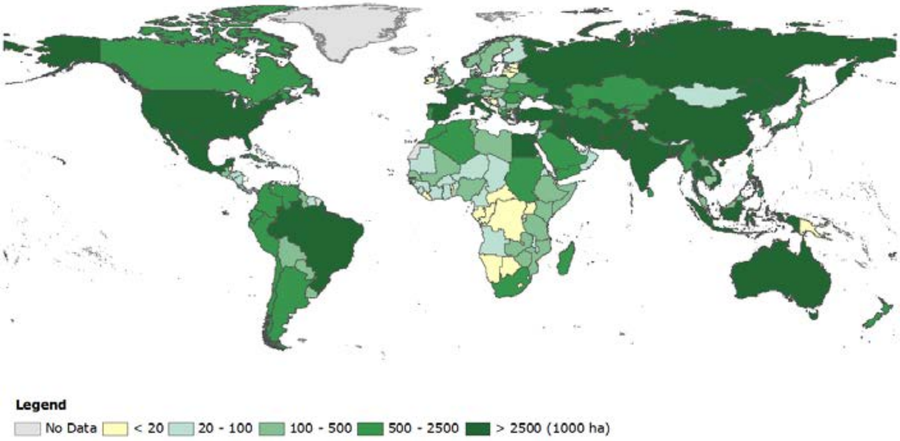
1.1 Introducción general

El agua es un recurso natural fundamental para el desarrollo económico y social, así como del mantenimiento de la integridad del entorno natural actual y futuro, de cualquier país. Existe una gran incertidumbre en cuanto a la disponibilidad de este recurso para satisfacer las demandas de agua requeridas para producir alimentos, energía, usos humanos y a su vez mantener el ecosistema. La población mundial está en continuo crecimiento y por tanto, la perspectiva mundial de consumos de alimentos también sufrirá una importante progresión. Este hecho es agravado con el impacto del cambio climático en la disponibilidad de recursos hídricos. La población mundial actual es de unos 7200 millones de personas y se prevé un crecimiento exponencial hasta 8300 millones de personas en el año 2030, 9600 millones en 2050 y 10900 para 2100 (UNDESA, 2013). Así mismo, la demanda de alimentos experimentará un incremento importante, estimado en un 50 % para el 2030 y en un 70 % en 2050 (FAO, 2003).

Dadas las necesidades de intensificación de la producción de alimentos, es necesaria una mejora tanto a nivel tecnológico como en la gestión integral de la agricultura, que permita abastecer las necesidades de esta población creciente y le proporcione la calidad y la seguridad alimentaria necesaria.

A nivel mundial, la agricultura de regadío es la responsable del 70% del uso de agua dulce. Este sector ocupa el 20 % del total de superficie cultivada, sin embargo genera el 40 % de la producción total de alimentos. Existen grandes diferencias entre la productividad de los cultivos de secano y los de regadío, mejorando el rendimiento de éstos últimos el doble con respecto a los cultivos de secano (FAO, 2011). La Organización de las Naciones Unidas para la Alimentación la Agricultura (FAO) estima que existe una superficie equipada para el riego de 307.6 millones de hectáreas (Figura 1.1), de las cuales 255.2 millones son regadas (Siebert *et al.*, 2013).

Lo expuesto anteriormente pone de manifiesto el papel fundamental, a nivel mundial, de la agricultura de regadío.



**Fuente: FAO-AQUASTAT, 2013*

Figura 1. 1. *Superficie mundial equipada para el riego.*

Se estima que hasta el horizonte 2050 casi la mitad de la superficie de regadío a nivel mundial (Bruinsma, 2009) habrá sido modernizada. La modernización en el regadío permite mejorar la productividad del agua de riego, incrementando la producción de alimentos por volumen de agua aplicado, así como mejorar las condiciones de vida en el mundo rural y contribuir a la conservación de los recursos naturales, garantizando un uso más sostenible de los mismos.

El concepto de modernización ha ido evolucionando. Inicialmente, la modernización del regadío se entendía como la ejecución y mejora de infraestructuras y equipamientos de las zonas regables. Posteriormente, se ha puesto de manifiesto la necesidad ligar la modernización de un regadío con la mejora de su gestión. Para ello, se han implementado sistemas de control, automatización y servicios de asesoramiento técnico.

1.2 La modernización del regadío en España

La gestión de los recursos hídricos en las zonas semiáridas, como es el caso de España, es especialmente importante a la vez que conflictiva, desde un punto de vista económico, político, ambiental y cultural.

La Directiva Marco del Agua (DMA) (2000/60/EC) condiciona la gestión de los recursos hídricos en los países de la Unión Europea. Esta directiva establece como objetivo principal un buen estado ecológico y un uso sostenible para todas las aguas en el horizonte 2015. Además, la DMA instaura la importancia de la gestión del agua menos orientada a la creación de infraestructuras hidráulicas y más a la protección del dominio público hidráulico y de la calidad de las aguas, además del el fomento de la eficiencia en la participación social y la transparencia.

En España, el uso de agua en la agricultura supone un 80 % de la demanda total de agua, la mayor parte destinada a la agricultura de regadío. A nivel nacional, la superficie de riego ocupa el 20 % de la superficie agraria útil (FAO-AQUASTAT, 2013) y sin embargo aporta más del 50 % del producto bruto agrícola, lo que supone 6 veces más que la producción unitaria de secano. Las comunidades autónomas con mayor superficie de regadío son Andalucía, Castilla-La Mancha, Castilla León y Aragón, las cuales representan más del 70 % del regadío español (MAGRAMA, 2012).

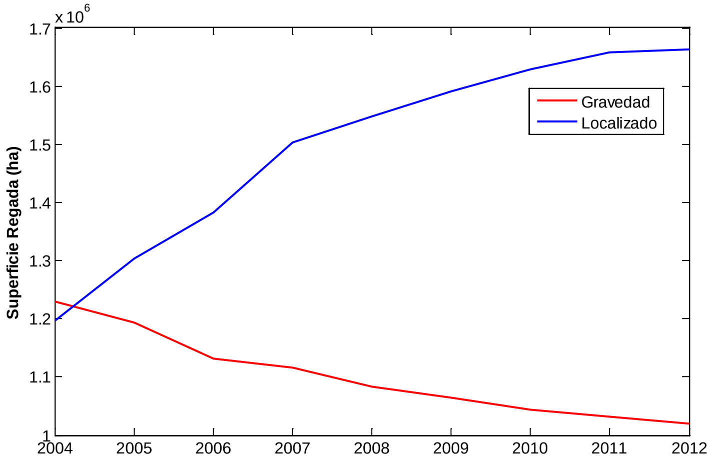
Como consecuencia del elevado volumen de agua requerido por el sector, sus externalidades comerciales y las exigencias internacionales en cuanto a la sostenibilidad de la agricultura en general, y del regadío en particular, obliga a emprender un proceso de modernización en los regadíos españoles.

El gobierno español aprobó el Plan Nacional de Regadíos (PNR) hasta el horizonte 2005 por Real Orden del 14 de Marzo de 1996 (BOE, 1996), "*como instrumento de consolidación del sistema agroalimentario español y factor básico para un uso eficiente de los recursos hídricos y de equilibrio interterritoral*".

Posteriormente, fue aprobado el PNR horizonte 2008 en el Real Decreto 329/2002 (BOE, 2002a). El objetivo principal de este PNR fue aumentar la competitividad de las explotaciones de regadío y el ahorro de agua. Este PNR fue reforzado con un Plan de Choque (PCH) de Modernización de Regadíos 2006-2008 (BOE, 2006). El PCH tenía como objetivo "*garantizar una mejor gestión de los recursos hídricos y a paliar los daños producidos por la sequía padecida en los años 2004 y 2005. Este Plan, refuerzo del PNR, consiguió la mejora y consolidación de una* *superficie de 866898 hectáreas y supuso un ahorro anual de 1162 hm^3 en el consumo de agua"*

En su conjunto, el proceso de modernización consistió en la mejora de la eficiencia técnica del riego mediante actuaciones sobre las infraestructuras y la gestión de las zonas regables. Las actuaciones más generalizadas consistieron principalmente en la sustitución de los canales abiertos por redes de riego a presión, construcción de balsas de regulación que flexibilicen el riego, adecuación de estaciones de bombeo y filtrado, así como la automatización y control del agua de riego, de forma que permitiera una mejora en la gestión sostenible de los recursos.

Como consecuencia de ello, se ha producido una mejora de la eficiencia en el uso del agua, reduciéndose su uso en un 23 % desde 1950 (Corominas, 2009), así como una mejora en los principios de fiabilidad, equidad y flexibilidad de los sistemas de riego. Asimismo, con la modernización se han implementado sistemas de riego a presión, incrementándose el uso de riego localizado y disminuyendo la superficie regada por gravedad (Figura 1.2). Este hecho ha desencadenado un nuevo problema en la agricultura de regadío, al incrementarse los requerimientos energéticos, también desde 1950, en un 670 % (Corominas, 2009).



**Fuente: Elaboración propia con datos de la "Encuesta sobre superficies y rendimientos". MAGRAMA, 2012*

Figura 1. 2. *Evolución de los sistemas de riego en España. Año 2004-2012*

Este incremento importante de la demanda energética implica dos inconvenientes significativos para el sector, ambientales y económicos, este último agravado por el encarecimiento del precio unitario de la energía en los últimos años.

Partiendo de los logros y debilidades alcanzados con los diferentes planes de actuación y con el propósito de alcanzar el objetivo ecológico demandado por la DMA (horizonte 2015), se desarrolló el borrador de la "Estrategia Nacional para la Modernización Sostenible de los Regadíos horizonte 2015" (ENMSRH 2015), sin embargo esta estrategia aún no ha sido aprobada. El objetivo principal de esta estrategia sería el fomento de la sostenibilidad del regadío español, mediante el ahorro del agua, la transferencia de tecnología, el fomento de la utilización de los recursos hídricos alternativos, la eficiencia energética, la mejora de la renta agraria y la creación de puestos de trabajo adicionales (MAGRAMA, 2013).

Por tanto, las actuaciones ejecutadas dentro del PNR horizonte 2005 y PNR horizonte 2008, junto con el PCH, están marcando el presente y futuro del regadío, pero siempre tratando de mejorar la competitividad de sus explotaciones.

1.3 Nexo agua–energía en el regadío

Existe una fuerte relación entre los recursos agua y energía. Desde tiempos inmemorables se ha utilizado las corrientes de los ríos para aprovechar la energía y ésta, entre otras cosas, para el transporte del propio recurso. Esta relación se ha ido intensificando a medida que la tecnología ha ido evolucionando, hasta el punto que en la sociedad actual el agua es necesaria para la generación de energía, y ésta última imprescindible para tratar, calentar y transportar el agua. El empleo intensivo de agua y energía se da en cualquier actividad urbana, industrial o agrícola (Jebaraj e Iniyan, 2006). Consecuentemente, entre los sectores del agua y la energía, existen grandes sinergias y también importantes conflictos.

A nivel mundial, el 8 % de las extracciones de agua dulce tienen como finalidad la producción de energía (petróleo, carbón, centrales nucleares, hidroeléctricas, termosolares, etc.). En la Unión Europea este valor se eleva a 44 % de las extracciones de agua dulce. Se estima que la demanda mundial de energía primaria se incrementará en un 70 % hasta

2030 (IEA, 2010) sufriendo un complementario y significativo aumento de la demanda de agua. Por su parte, los procesos relacionados con el uso del agua, como la captación, tratamiento y transporte requiere de importantes cantidades de energía. Este hecho pone de manifiesto la necesidad de mejorar la eficiencia en el nexo agua-energía, siendo esencial para el desarrollo económico, social y ambiental de cualquier sector.

Aunque el incremento de la demanda en ambos recursos parezca imparable, existen importantes oportunidades para mitigar los aspectos negativos. En primera instancia, es prioritario considerar la conservación del agua y la conservación de la energía conjuntamente (Hardy y Garrido, 2010). Además, hay una necesidad importante de identificar y optimizar las políticas, prácticas y percepciones para optimizar el uso de dichos recursos.

La relación agua y energía es muy compleja y existe diversas escalas de análisis. En España, más del 10 % del consumo total de energía está ligada al agua (Cabrera, 2011). La agricultura es el sector con mayores demandas de agua (80 %), principalmente debidos a la actividad del riego y cuyas demandas energéticas se han incrementado considerablemente en los últimos años.

En la agricultura de regadío, el nexo agua-energía es considerada en términos de la energía requerida para la captación, transporte, y aplicación del agua para abastecer las necesidades de los cultivos e incrementar la productividad de los mismos. Por tanto, la demanda energética del sistema varía en función de la energía requerida en cada uno de esos procesos. La fuente principal de agua es superficial y supone el 68 % del total de agua extraída, seguida con un 28 % las aguas subterráneas y en menor porcentaje el agua procedente de trasvases, desalación y aguas depuradas. La energía requerida en la captación varía significativamente en función de la fuente de agua siendo el agua superficial la que tiene menos requerimientos energéticos (0.06 kWh m^{-3}). La demanda energética va incrementándose en la medida que el agua requiere un transporte o tratamiento, llegando a alcanzar 3.70 kWh m^{-3} cuando el agua es desalada (Corominas, 2009). Los sistemas de riego también varían en cuanto a su demanda energética. Los sistemas de riego por gravedad prácticamente no requieren energía. Sin embargo, como se ha desarrollado en el apartado anterior, se han incrementado la superficie con sistemas de riego a presión, lo que ha provocado un incremento de la demanda energética. El riego localizado necesita por término medio de 0.18 kWh m^{-3}, mientras que los sistemas de aspersión requieren de 0.24 kWh m^{-3} (Corominas, 2009).

Los requerimientos energéticos del conjunto del sistema están estrechamente relacionados con los costes de suministro del agua y con las emisiones a la atmosfera de gases de efecto invernadero. En la actualidad, el elevado coste energético de la agricultura del regadío es uno de sus principales problemas. En 2008, tuvo lugar liberación del mercado eléctrico español con la desaparición de las tarifas especiales de riego. Este hecho produjo un importante incremento de los costes energéticos en el regadío, llegando a incrementarse en más del 120 % entre 2008-2010 (Rodríguez *et al*., 2011), y experimentando sucesivas subidas hasta la actualidad.

El desarrollo de estudios enfocados a la optimización del uso de la energía en sistema de distribución de agua para riego, no sólo mejorará la eficiencia en el uso de ambos recursos sino que permitirá optimizar dos objetivos fundamentales, como son los económicos y ambientales, permitiendo una gestión más sostenible del regadío.

En este contexto, se pusieron en marcha distintos Planes de Acción para la implementación de la Estrategia de Ahorro y Eficiencia energética (E4) 2004-2012 (IDAE, 2003), con el objetivo de mejorar la intensidad energética de nuestra economía e introducir un cambio en cuanto a materia de medio ambiente se refiere. En primer lugar, se concretó el Plan de Acción para el periodo 2005-2007 estableciendo ciertos objetivos energéticos y medioambientales. Posteriormente, un nuevo Plan de Acción 2008-2012 introdujo nuevos esfuerzos económicos y normativos en relación a la E4, en respuesta a la Estrategia Española de Cambio Climático y Energía Limpia que persigue el cumplimiento español del protocolo de Kioto. Dentro de este último, por parte del Instituto par a Diversificación y Ahorro de la Energía (IDAE) se recoge el Plan de Actuaciones de Mejoras Energéticas en Comunidades de Regantes mediante un sistema de auditorías energéticas (Abadía *et al*. 2008). La realización de auditorías en comunidades de regantes será una actuación fundamental para conocer el uso del agua y la energía que se está llevando a cabo en cada una de ellas, permitiendo identificar los puntos deficientes de la gestión y proponer medidas de mejora.

1.4 Reto de la agricultura de regadío.

La agricultura de regadío debe adaptarse al marco normativo y cumplir con los objetivos marcados en los sectores del agua (DMA) y de la energía (Protocolo de Kioto). Concretamente, en política de aguas el objetivo principal es mejorar el estado económico reduciendo el uso de los recursos hídricos, la contaminación difusa, la demanda energética y las emisiones de CO_2. Por consiguiente, se intensifica la necesidad de desarrollar herramientas enfocadas a la mejora de la eficiencia del uso del agua y energía. Estas herramientas generarán beneficios directos, como es la garantía de suministro de agua y la reducción de la demanda de ambos recursos, junto con beneficios colaterales, como es la mitigación de los impactos derivados del cambio climático. Consecuentemente, estaríamos hablando del nexo agua-energía-cambio climático como un todo (Hightower, 2005).

En la agricultura de regadío, el principal componente de emisiones de CO_2 es la demanda energética, creciente, de los sistemas de riego a presión. Esta energía es requerida por las estaciones de bombeo, para la captación y distribución de agua hacia los cultivos. Actualmente, las necesidades mundiales en materia de recursos energéticos proceden en un 80 % de combustibles fósiles, lo que implica un importante impacto al medio ambiente con las emisiones de gases de efecto invernadero generadas. Por tanto, no sólo es necesario mejorar la eficiencia en el uso de la energía, sino que se debe fomentar la sustitución de recursos no renovables por fuentes de combustible renovables como gas natural, el viento y la energía solar fotovoltaica que, además de necesitar mucha menos agua para su generación, reduce las emisiones de contaminantes y de emisiones de gases de efecto invernadero.

La coordinación de las políticas hídrica, energética, y medioambiental son esenciales para la gestión sostenible de los regadíos. Políticas que deben ser orientadas a perseguir la gestión integral de la agricultura de regadío mediante producciones integradas (BOE, 2002b), que aseguren a largo plazo una agricultura sostenible, introduciendo en ella métodos biológicos y químicos de control, y otras técnicas, como las energías renovables, que compatibilicen las exigencias de la sociedad, la protección del medio ambiente y la productividad agrícola, así como las operaciones realizadas para la manipulación, envasado, transformación y etiquetado de productos vegetales acogidos al sistema. En definitiva, desarrollar una gestión del regadío sostenible, con la mínima huella hídrica, energética y ecológica.

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Objectives and structure of the PhD thesis

2. Objetivos y estructura de la presente tesis doctoral

2.1. Objetivos

El **objetivo general** de la presente tesis doctoral es diseñar, desarrollar, evaluar y optimizar metodologías que mejoren la gestión en el uso del agua y la energía en zonas regables, contribuyendo al uso sostenible de dichos recursos en la agricultura de regadío.

Para la consecución de este objetivo principal se plantean los siguientes **objetivos específicos** a cubrir durante el desarrollo de la investigación.

1. Análisis y caracterización del uso del agua y energía, mediante indicadores de gestión, en comunidades de regantes y propuestas de medidas de mejora.

2. Desarrollo y análisis de un modelo para el uso eficiente de los recursos agua y energía mediante la sectorización de redes de suministro de agua de riego.

3. Creación de un procedimiento de optimización del uso del agua y la energía aplicando criterios ambientales y económicos como objetivos esenciales en la gestión de las redes de riego.

4. Análisis del potencial de las energías renovables como alternativa energética en redes de riego a presión.

2.2 Estructura de la presente tesis doctoral

Esta tesis doctoral es presentada como compendio de publicaciones. La tesis está organizada en siete apartados de los cuales cuatro (apartados 3-6) tienen estructura de artículo científico. Tres artículos han sido publicados y uno aceptado para su publicación en revistas internacionales indexadas, incluidas en los dos primeros cuartiles según Thomson Reuters Journal Citation Reports.

Esta tesis doctoral está escrita en formato bilingüe como requerimiento para la obtención de la Mención Internacional. Se ha considerado adecuado incluir en inglés los apartados correspondientes a los artículos científicos, siguiendo la misma estructura que los trabajos publicados.

El apartado 1 es una introducción general donde se especifica el contexto y se justifica la necesidad de esta tesis doctoral. En este apartado 2 se definen los objetivos planteados en esta investigación.

El apartado 3, correspondiente a la publicación “The role of energy audits in irrigated areas. The case of ‘Fuente Palmera’ irrigation district”[*Carrillo Cobo, M.T., Rodríguez Díaz, J.A., Camacho Poyato, E. Spanish Journal of Agricultural Research. 2010. 8 (S2) S152-S161. IF: 0.646 (Q2)*], correspondiente al objetivo 1. En este estudio se muestra la primera etapa para la mejora de la gestión de los recursos agua y energía en zonas regables. Se desarrolla para ello una metodología de toma de datos, tanto hidráulicos como eléctricos, la cual se aplica en la comunidad de regantes de Fuente Palmera (Andalucía). Además, con los datos obtenidos de la auditoría del uso del agua y la energía se identifican deficiencias a la vez que se proponen medidas de mejora.

En el apartado 4 se aborda el objetivo 2 con la publicación “Low energy consumption seasonal calendar for sectoring operation in pressurized irrigation network” [*Carrillo Cobo, M.T., Rodríguez Díaz, J.A., Montesinos, P., López Luque, R., Camacho Poyato, E. Irrigation Science. 2011. 29, 157-169. IF: 1.635 (Q2)*]. El modelo desarrollado (WEBSO) permite establecer un calendario óptimo de sectorización de una red de distribución de agua de riego a una escala mensual y considerando las prácticas de manejo de los regantes. También es posible evaluar el ahorro energético potencial que se puede alcanzar en zonas regables al establecer la sectorización como medida de mejora en la gestión.

El apartado 5 se corresponde con la publicación “New model for sustainable management of pressurized irrigation networks. Application to Bembézar MD irrigation district (Spain)” [*Carrillo Cobo, M.T., Camacho*

Poyato, E., Montesinos, P., Rodríguez Díaz, J.A. Science of the Total Environment.2014. 473-474, 1-8 IF (2012): 3.258 (Q1)]. Se ha desarrollado un modelo de optimización multiobjetivo que persigue el cumplimiento del objetivo 3. El modelo permite seleccionar el patrón de riego óptimo en una zona regable optimizando simultáneamente objetivos ambientales (mínima huella de carbono) y económicos (máximo beneficio).

En el apartado 6 se desarrolla la publicación *"Exploring the role of solar energy in pressurized irrigation networks"*. [*Carrillo Cobo, M.T., Camacho Poyato, E., Montesinos, P., Rodríguez Díaz, J.A. Spanish Journal of Agricultural Research. Aceptado 2013. IF (2012): 0.659 (Q2)*]. En este estudio se ha optimizado el uso del agua y la energía aplicando la metodología desarrollada en el apartado 4 (WEBSO). Además, se ha diseñado y evaluado la viabilidad técnica y económica de instalar un sistema fotovoltaico para suministrar parte de la energía requerida en una zona regable para el riego (objetivo 4). Así, se analizan los beneficios que ofrece el uso conjunto de medidas de optimización de la demanda energética junto con la implementación de otras fuentes alternativas de suministro de energía.

Este documento de tesis doctoral finaliza con el apartado 7 orientado a recopilar las conclusiones globales del conjunto de la investigación. Para finalizar, se proponen nuevas líneas de investigación que permitan el objetivo de alcanzar una gestión cada vez más sostenible de los recursos agua y energía en las redes de riego a presión.

The role of energy audits in irrigated areas. The case of ‘Fuente Palmera’ irrigation district (Spain)

3. The role of energy audits in irrigated areas. The case of 'Fuente Palmera' irrigation district (Spain)

This chapter has been published entirely in the journal" Spanish Journal of Agricultural Research": Carrillo Cobo, M.T., Rodríguez Díaz, J.A., Camacho Poyato, E. 2010.

Abstract. In recent years, energy consumption for irrigation has grown rapidly. Actually, nowadays energy represents a significant percentage on the total water costs in irrigation districts using energy to pressurize water. With the aim of improving energy efficiency in the Fuente Palmera irrigation district, was applied the protocol for conducting energy audits in irrigation districts developed by Spanish Institute for Diversification and Energy Savings (IDAE). The irrigated area organized in two independent sectors according to a homogeneous elevation criterion is analyzed and simulated. The potential energy savings derived from this measure was evaluated. For this purpose, a model based on the hydraulic simulator EPANET has been carried out. Its energy demand was estimated in 1360 kWh ha^{-1} and its overall energy efficiency in 56 %. The district was globally classified in group C (normal). Results show potential energy savings of up to 12 % were obtained when the network was divided in sectors and farmers organized in two irrigation shifts. Further energy savings could be achieved by improving the hydraulic structures, such as the pumping station or the network layout and dimensions.

Additional keywords: energy efficiency, pressurized irrigation networks, water management, water supply systems.

3.1 Introduction

Energy consumption has continuously grown in the last decades worldwide. Because of increased energy costs, energy scarcity and energy related pollution, in the last years all economic sectors have intensified their efforts to improve energy use efficiency.

Irrigated agriculture is one of the sectors that have experienced a notable increase in energy use during recent years. In Spain, this increase is mainly due to irrigation modernization programs, where open channel distribution systems are being replaced by on-demand pressurized networks. These measures have succeeded in improving irrigation efficiency. However, they have led to a significant increase in energy consumption. Actually, Corominas (2009) reported that while water use per hectare has been reduced by 23 % since 1950, energy demand has been increased by 670 %.

In the last years, research efforts were devoted to the improvement of irrigation efficiency by means of benchmarking techniques and performance indicators (Malano and Burton, 2001; Rodríguez-Díaz *et al.*, 2008). Recent studies have focused on the need to improve water and energy efficiency at the same time (Pulido-Calvo *et al.*, 2003; ITRC, 2005; Moreno *et al.*, 2007, 2009; Vieira and Ramos, 2009; Daccache *et al.*, 2010). Other research works have highlighted that energy savings of up to 20% could be achieved by introducing minor changes in the irrigation district's management practices (Rodríguez-Díaz *et al.*, 2009; Jiménez-Bello *et al.*, 2010; Moreno *et al.*, 2010).

An aggravating factor is that, due to the liberalization of the Spanish Electricity Market, on 1st January 2008 the special tariffs for irrigation disappeared and now irrigation districts have to use the same tariffs as the rest of the industry. During the months of June and July, when the peak of the irrigation demand is concentrated, most of the daily hours are included in periods of expensive tariffs.

In this context, the European Directive 2006/32/EC (OJ, 2006), on energy and energy services efficiency, established the necessity of carrying out actions to achieve energy savings of at least 9 % before 2016. This objective was implemented in Spain through the "Strategy for Energy

Saving and Efficiency in Spain 2004-2012 (E4)". The measures under this strategy were reflected on the Energy Action Plan for 2005-2007 (EAP 4), which set some energy saving measures. Subsequently, with the aim of meeting the Kyoto Protocol, the Action Plan E4 Plus (EAP4+), scope 2008-2012, was launched which aims to reduce emissions by 20% in 2020 (IDAE, 2007).

In the irrigated agriculture sector, two main measures are proposed in these plans. The first measure is the migration from sprinkler to drip irrigation systems, and the second is the improvement of efficiency through energy audits in irrigation districts. In this way, the Spanish Institute for Diversification and Energy Saving (IDAE, 2008) proposed a protocol for conducting energy audits, which evaluates efficiency by means of water and energy performance indicators. This methodology allows detection of inefficiencies and provides information on the required improvement actions (Abadía *et al.*, 2008). The initial set of indicators proposed by IDAE has been extended in recent studies (Abadía *et al.*, 2009) and applied to several irrigation districts in other Spanish regions (Abadía *et al.*, 2007; Córcoles *et al.*, 2008). In other works, alternative protocols for energy audits were proposed, following similar methodologies and outputs (Ederra and Larumbe, 2007).

In this work, water and energy use were evaluated at the Fuente Palmera irrigation district, using the IDAE protocol for energy audits. Alternatives management measures would be adopted for achieve energy savings such as sectoring the network in several sectors according to homogeneous group. This measure was analyzed on the hydraulic model EPANET and the potential energy savings derived from this measure was evaluated.

3.2 Material and Methods

3.2.1. Study area

The Fuente Palmera irrigation district, located in Córdoba (Southern of Spain) has a total irrigated area of 5611 ha (Figure 3.1). The climate in the region is predominantly Mediterranean, with rainfall concentrated mainly in autumn and spring, and dry spells in summer. The average annual rainfall in the area is 550 mm, and the average temperature is 17.9 ºC. In the analyzed irrigation season (2007) annual rainfall was 523 mm and potential evapotranspiration was 1323 mm (Carrillo-Cobo, 2009). Consequently 2007 can be considered representative of the average year (Rodríguez-Díaz, 2003). There is a wide range of crops in the district, with cereals, citrus and olives trees covering more than 60 % of the area (Carrillo-Cobo, 2009).

Figure 3. 1. *Location of the Fuente Palmera irrigation district within the Córdoba province and Spain*

Irrigation water is diverted from the Guadalquivir River and conveyed to an elevated reservoir through a first pumping station. At the reservoir there is a booster pumping station feeding 85 hydrants. The pressurized collective network has a total length of 45 km. It was designed to supply 1.2 L s^{-1} ha^{-1} arranged on demand, with a minimum pressure head of 30 m at every hydrant. The topography is quite steep, and hydrant elevation ranges from 86 to 165 m.

The booster pumping station (altitude of 113.9 m) is equipped with six horizontal centrifugal pumps of 1825 kW, two of 495 kW and one of 540 kW, equipped with variable speed drives, being the total installed power 2.2 $kWha^{-1}$. The pumps are activated sequentially according to manometric regulation. The pumping station has a telemetry system which records hydraulic parameters (pressure head and pumped flow) and electric intensity every minute.

Although most of the district is currently irrigated by drip irrigation systems, Fuente Palmera was originally designed for sprinkler irrigation, with higher pressure requirements.

3.2.2. Hourly irrigation water demand patterns

To classify the irrigation demand in homogeneous groups, the non-hierarchical clustering algorithm K-means (Cuesta, 2001) was used. The objective of this algorithm is to minimize variance within clusters and maximize variance between clusters (Jain, 2000). Its main limitation is that the number of clusters has to be fixed a priori.

The K-means algorithm is based on the minimization of a performance index, which is the sum of the squared distances of all the elements within the cluster to the centroid of the cluster. To measure the distance between elements, the Euclidean distance has been used (Rodríguez-Díaz *et al.*, 2008).

Using the recorded flow at the pumping station, one vector was created for every week including the 24 ratios of the hourly average pumped water to daily average pumped water. Following this procedure, a daily water demand pattern was created for every week. Then, the K-means algorithm was applied to these demand patterns, corresponding to the whole irrigation season, and then they were grouped into homogeneous clusters. The analysis was performed for two, three and four clusters.

3.2.3. Performance curves

The information collected at the pumping station was used to energetically characterize the irrigation district. This analysis was carried out in two main steps. The first step was the generation of the frequency distribution of demanded flow for the irrigation season, at 50 L s^{-1} intervals.

The second step was the analysis of the hydraulic performance of the pumps installed at the pumping station. Reliable data on flows, pressures and power recorded at the pumping station were used to establish the pumping station characteristics curves (flow and pressure head; flow and power; flow and performance). Pumping performance (η) was determined as:

$$\eta = \frac{\gamma \cdot \mathrm{F} \cdot \mathrm{H}}{\mathrm{W}} \qquad [3.1]$$

where γ is the water specific weight (9800 N m^{-3}), F is the demanded flow rate (m^3 s^{-1}), H is the pressure head at the pumping station (m) and W is the power consumption recorded at the pumping station (W).

3.2.4. Energy efficiency indicators

Energy indicators were selected from those suggested by the IDAE (2008) for conducting energy audits in irrigated areas. In this work indicators have been classified in four groups:

- Descriptor indicators, informing about water use and irrigated areas within the irrigation district.

- Power indicators, analyzing power requirements. They also allow comparison between contracted power and recorded power use. These indicators can be used to assess whether the current energy contract meets the district's power demand, and to provide information to optimize the contract.

- Energy indicators, analyzing energy consumed for pumping and energy costs.

- Efficiency indicators. This is the most important group of indicators. They provide an energy assessment and a district classification. These are the indicators included in this group:

- Energy dependency rate (EDR):

$$EDR = \frac{Total\ volume\ pumped}{volume\ of\ water\ entering\ the\ system} \qquad [3.2]$$

- Energy change index (ECI):

$$ECI = \frac{\sum V_i \cdot H_i}{volume\ of\ water\ entering\ the\ system} \qquad [3.3]$$

where V_i and H_i are the volume and pressure head supplied by pumping. Thus, ECI represents the average pressure head.

- Pumping energy efficiency (PEE):

$$PEE_i(\%) = \frac{w_s}{w_a} \cdot 100 \qquad [3.4]$$

where W_s is power given to the water flow and W_a is the electrical power consumed, determined as:

$$W_a = \sqrt{3} \cdot V \cdot I \cdot \cos\varphi \qquad [3.5]$$

where V is the voltage of each pump (V); I is the intensity (A) and cos φ is the pump power-factor. Ws was obtained from the following equation:

$$Ws = \gamma \cdot F \cdot H_m \qquad [3.6]$$

where γ is the water specific weight (9800 N m^{-3}); F is the flow rate (m^3s^{-1}); and H_m is the pressure head supplied by the pumping station (m).

- Energy supply efficiency (ESE):

$$ESE = \frac{|\Delta E|}{ECI} \; If \; \Delta E < 0 \qquad [3.7]$$

This index represents the ratio of the theoretical energy requirements and the energy supply. ΔE is the difference between the initial energy of the water (IE) before being diverted from the water source and the energy required for supplying the water and for operating the irrigation system (ER):

$$ID - ER = \pm\Delta E \qquad [3.8]$$

- Overall energy efficiency (OEE), that takes into account the efficiency of the pumping station and the efficiency in the water supply:

$$OEE = PEE \cdot ESE \qquad [3.9]$$

3.2.5. Energy saving scenarios

In order to evaluate the impact of possible energy saving measures, two scenarios were developed taking into account different management strategies. Then, both scenarios were simulated using the EPANET hydraulic model (Rossman, 2000). The second scenario represent an alternative management strategy, not implying any change or upgrade in the hydraulic infrastructures. Their main characteristics are defined below:

Scenario 1. It represented current management. The network worked on-demand and the pressure head was fixed to 85 m. The hourly demand patterns, calculated using cluster analysis techniques, were used to establish the hourly base demand.

Scenario 2. The irrigated area was organized in two independent sectors according to a homogeneous elevation criterion. The first sector included the hydrants under 127 m height, while in the second, hydrants above that elevation were included (Figure 3.2). In this scenario the network was managed under semi-arranged demand and each sector could irrigate for 12 h per day only. The pressure head was fixed to 65 m and 85 m for scenarios 1 and 2, respectively. In order to ensure that every farm receives the same amount of water as in scenario 1, despite the reduction in the time allowed for irrigation, the base demand was doubled, assuming a uniform distribution pattern during the irrigation period. Therefore farmers had to apply higher flows in a shorter period of time.

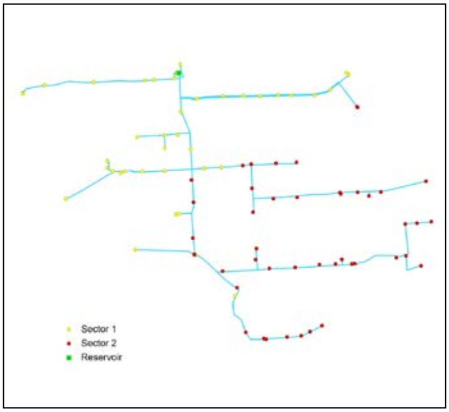

Figure 3. 2. *Irrigation network of the Fuente Palmera Irrigation Districts. The two sectors used in scenario 2 are represented with hydrants of different colours.*

3.3 Results

3.2.1. Hourly demand patterns of the irrigated area

The evolution of the average monthly water demand in 2007 is presented in Fig. 3.3.

The irrigation season started at the beginning of March and ended in the middle of October. The peak demand period occurred from June to August. Although the month with the largest demand was July, the peak daily irrigation demand was on 14th August (1478 L s^{-1}). Between November and February farmers did not irrigate.

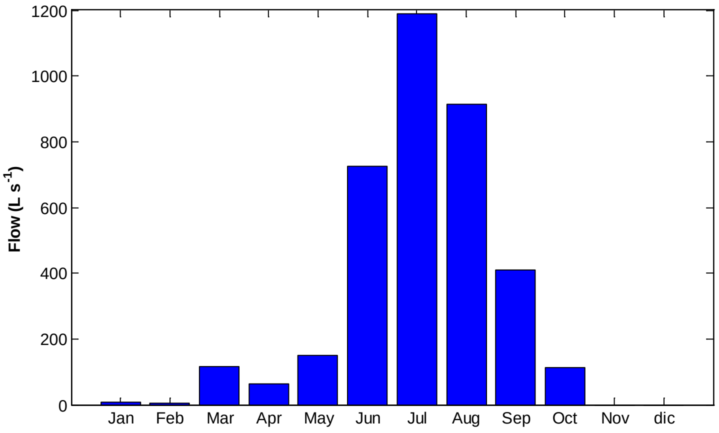

Figure 3. 3. *Average monthly irrigation water demand in 2007.*

The weekly demand patterns were used to perform the cluster analysis. The irrigation season took 43 weeks. After repeating the analysis for two, three and four clusters, the best fit (minimizing the variance within clusters) was obtained for two clusters. One of the clusters included 35 weeks, with small variability among hours (cluster 1 in Fig. 3.4), and the second cluster included the eight remaining weeks, with significant variability between peak and off-peak hours (cluster 2 in Figure 3.4). Cluster 2 included the low water demand weeks.

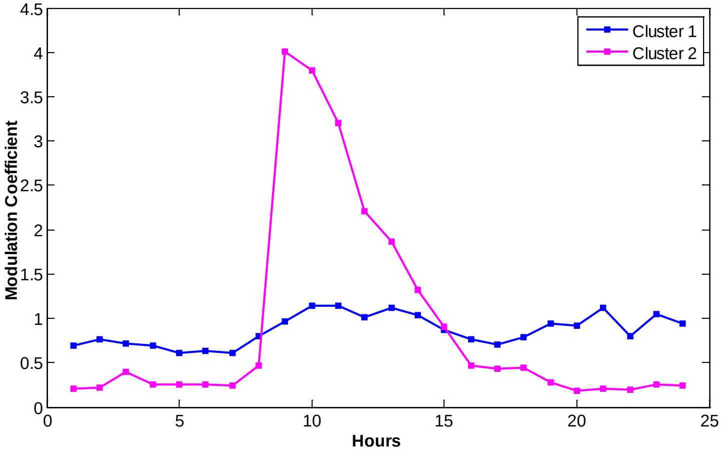

Figure 3. 4. *Hourly demand patterns*

Cluster 1 covered the peak demand period and its standard deviation (0.64) was smaller than in cluster 2 (0.70). Therefore cluster 1 was the most representative irrigation pattern of the irrigation district. In this cluster, water consumption was very homogeneous during the day, with slight increases during the mornings and afternoons (from 18:00), regardless to the energy costs. In cluster 2, consumption was mostly concentrated from 7:00 to 14:00. Thus, most of the water demand occurred when the energy price is maximum.

3.2.2. Energy analysis

Figure 3.5 presents the frequency distribution of pumped discharge. Results confirmed that low flows were the most common. Actually, 40 % of the instant flows were in the range 0 – 0.05 $m^3 s^{-1}$. However, when a discharge of 0.1 $m^3 s^{-1}$ was exceeded, flow frequencies sharply dropped, always remaining below 3 % frequency in each interval.

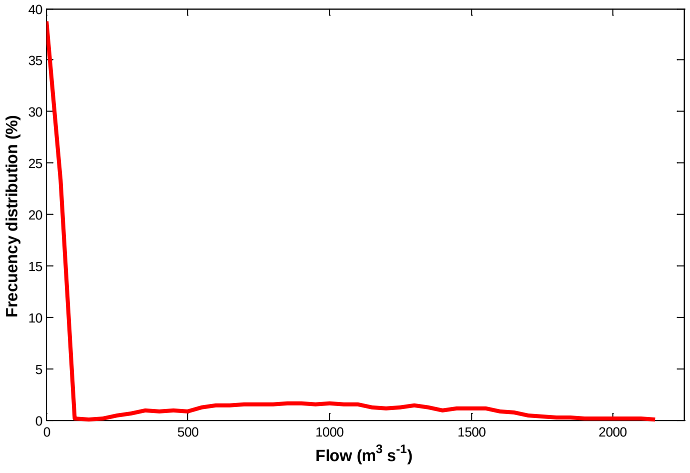

Figure 3. 5. *Frequency distribution of pumped discharges in the Fuente Palmera district.*

The hydraulic behavior of a particular pump is specified in its characteristic curves, which relate discharge, pressure head, hydraulic performance and power. These curves were derived from actual data recorded at the pumping station every 15 minutes and are presented in Fig. 3. 6 (a, b, c).

The comparison of Fig. 3. 6 c (performance of the pumping station) with Figure 3.5 (discharge histograph) shows that for the most common flow rates (0 – 0.1 $m^3 s^{-1}$) the pumping station performance was extremely low (even lower than 25 %). Flows above this range can be classified in two groups: the first group was composed of flows from 0.1 to 1 $m^3 s^{-1}$, where performance may exceed 90 %; the second group included flows in excess of 1 $m^3 s^{-1}$, for which performance was around 70 %.

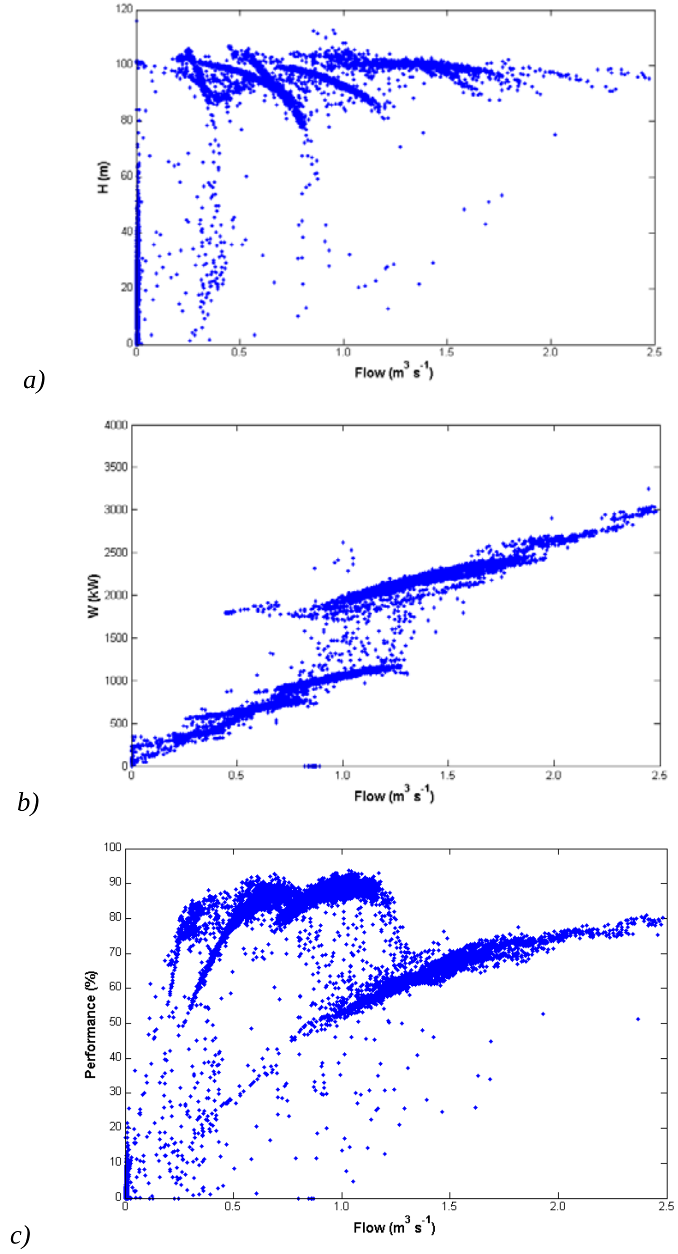

Figure 3. 6. *Characteristic curve of the pumping station: a) head as a function of discharge, b) power as a function of discharge, c) pumping station performance as a function of discharge.*

3.2.3. Performance indicators

1. Descriptors (Table 3.1)

The average applied depth was 1783 m^3 ha^{-1} and the irrigated area during the studied irrigation season was 5228 ha. The applied depth was significantly smaller than the irrigation water requirements, which were estimated as 4760 m^3 ha^{-1}. The deficit irrigation is a common practice in this irrigation district and that less than half of the total water requirements are applied. Comparing the volume of water diverted for irrigation (measured at the pumping station), and the volume of water supplied to users (measured at the hydrants), the conveyance efficiency was estimated as 96 %, which implies adequate maintenance with very low water losses.

2. Power indicators (Table 3.1)

Although the average recorded power was 1989 kW, there was a significant variability among months. The peak power was 5070 kW. Even during the peak demand season the power performance (ratio of the recorded power and contracted) was 68 %. The contracted power could be reduced, achieving relevant savings in energy tariffs. In the off-peak months both recorded and contracted power were significantly lower, being the ratio for the entire season 71 %. The ratio of the peak power consumption and the irrigated area was 0.9 kW ha^{-1}, which is small in comparison with the total installed power (2.2 kW ha^{-1}). Thus the pumping capacity was too big even for the peak demand months.

3. Energy indicators (Table 3.1)

In the Fuente Palmera district 0.73 kWh were required to pump every cubic meter of water, implying energy consumption per unit of irrigated area of 1360 kWh ha^{-1}. The average energy cost was 0.05 € m^{-3}. As a consequence, energy represented about 30 % of the total Management, Maintenance and Operation (MOM) costs.

Table 3. 1. Descriptors, power performance, energy performance and efficiency indicators of the Fuente Palmera irrigation district.

Indicators	Descriptors	Irrigable area (ha)	5612
		Irrigated area (ha)	5228
		Volume of water entering the system (m^3)	9759313
		Volume of irrigation water supplied to users (m^3)	9318984
		Irrigation water per unit irrigable area (m^3 ha^{-1})	1660
		Irrigation water per unit irrigated area (m^3 ha^{-1})	1782
	Power	Maximum monthly contracted power (kW)	7500
		Maximum power recorded (kW)	5070
		Maximum power performance (%)	68
		Maximum power recorded per unit irrigated area (kW ha^{-1})	0.9
		Average monthly contracted power (kW $month^{-1}$)	2800
		Average monthly consumed power (kW $month^{-1}$)	1989
		Average power performance (%)	71
		Power factor (%)	95
	Performance	Annual energy consumption (kWh)	7114186
		Reactive energy consumed (kWarh)	300382
		Energy consumed per unit of irrigated area (kWh ha^{-1})	1361
		Energy consumed per volume of irrigation water that enters the system (kWh m^{-3})	0.73
		Energy cost per irrigable area (€ ha^{-1})	93
		Energy cost per irrigated area (€ ha^{-1})	87
		Energy cost per m^3 which enters the system (€ m^{-3})	0.05
		Energy cost per m^3 delivered to users (€ m^{-3})	0.05
		Energy cost to total water costs ratio (%)	28
	Efficiency	EDR: Energy dependency rate (%)	100
		ECI: Energy charge index (m)	70
		PEE: Pumping energy efficiency (%)	69.5
		ESE: Energy supply efficiency (%)	80.8
		OEE: Overall energy efficiency (%)	56

4. Efficiency indicators (Table 3.1)

Since in the Fuente Palmera district all water is pumped, the EDR was 100 %, being the ECI 70 m. The PEE indicator was around 70 %, which in the classification proposed by IDAE (2008) is considered as excellent efficiency, included in Category A.

The ESE indicator depends on the network's design and management as it represents the ratio between the minimum energy required by the system for supplying water to all the hydrants and the energy consumed in the pumping station. In the particular case of Fuente Palmera this indicator was 80.8 %.

The OEE takes into account PEE and ESE. In Fuente Palmera OEE is 56 %, which is a relatively small value for this indicator. It means that the irrigation district is classified as C (normal efficiency) in the classification proposed by IDAE. Since PEE was classified as excellent, corrective measures should be aimed at improving the ESE indicator.

3.2.4. Energy saving scenarios

The output of the EPANET simulations for the three studied days (6th June, 15th July and 14th August) is summarized in Table 3.2. Pumping performance was slightly higher for scenario 1 (where the network operated on-demand, ranging between 67 % and 77.74 %) than for scenario 2 (where irrigation was organized in two sectors, with an average performance of 71 %). When the average flows presented in Table 3.2 were analyzed in Figure 3.6 c, on 6th June and 15th July, performance was around 80 % (these average flows are on performance curve's maximum). For flows larger than 1 $m^3 s^{-1}$ (as happened on 14th August) performance was less than 70 %.

Although the average power was very similar in the on-demand and sectored scenarios, the peak power was significantly reduced when sectoring was introduced. This is because in scenario 2 the water demand pattern was uniform, avoiding peaks in irrigation demand. This reduction in the peak power led the pumping station to work more time under high performance conditions and therefore implied a reduction in the daily energy costs.

Table 3. 2. *Summary report of energy indicators determined applying Epanet to the different scenarios (*).*

Day	Average demand (L s^{-1})	Average pumping energy efficiency	kWh m^{-3}	Average power (kW)	Peak power (kW)	€ day^{-1}
Scenario 1						
06-Jun	652	75.02	0.31	718	931	1162
15-Jul	943	77.74	0.30	1028	1498	1764
14-Aug	1478	67.07	0.33	1768	2274	1819
Scenario 2						
06-Jun	652	72.41	0.32	1398	1886	1049
15-Jul	943	69.74	0.32	1583	2080	1601
14-Aug	1478	71.07	0.32	1490	1983	1596

*Energy consumption in the first pumping station, from the Guadalquivir river to the reservoir, is not included in this analysis

Actually, in scenario 2, reductions of up to 12 % in energy costs could be achieved. The savings in relation to scenario 1 in both, peak power and energy costs, are summarized in Table 3.3.

Table 3. 3. Peak power and energy cost savings (%) in the scenario 2.

	Peak power savings	Energy cost savings
06-jun	-3.45	9.72
15-jul	11.3	9.27
14-Aug	14.44	12.29

3.4 Discussion

With the aim of improving irrigation efficiency, modernization of obsolete open channel distribution networks has been a common practice in Spain in the last decades. On-demand irrigation represents a step forward in flexibility for water users and an efficient way to reduce the water demand.

On the other hand, it implies a significant increase in energy costs. In the coming years, irrigated agriculture will have to face the challenge of improving efficiency in all the resources involved in agricultural production, not only water. Thus, it is time to reflect on this and assess whether on-demand irrigation represents a clear benefit in terms of global sustainability and on the economic profitability of irrigated agriculture. In this context, energy audits represent an important measure to evaluate energy use in irrigation districts and to detect inefficiencies.

In this work, the energy audits protocol has been applied to Fuente Palmera irrigation district. Analyzing the obtained indicators, the district was globally classified in group C (normal) according to the classification provided by IDAE. The OEE was estimated in 56 %. These findings are consistent with other works in different Spanish regions, where the average OEE for several irrigation districts take value similar as 67 % in irrigation districts in Murcia (Abadía *et al.*, 2007), 41 % in Castilla-La Mancha (Córcoles *et al.*, 2008) or 59 % in irrigation districts of Navarra (Ederra and Larumbe, 2007).

Introducing sectors in network management (organizing farmers in two shifts) was proposed as an energy saving measure. Additionally, this energy saving measure improves ESE (Rodríguez-Díaz *et al.*, 2009). The viability of this measure has to be analyzed in every case, checking that the on-farm irrigation systems can perform adequately when the irritation time is reduced. However, Carrillo-Cobo *et al.* (2011) reported that in the particular case of Fuente Palmera, even in the peak demand months and taking into account that flows are limited to 1.2 L s^{-1} ha^{-1}, farmers would be able to apply their irrigation water with small probabilities of supply failures, mostly when the local practices (deficit irrigation) are considered.

This management strategy was hydraulically simulated on EPANET, resulting in energy savings of approximately 12 %. These energy savings may compensate the increment in energy tariffs. Further energy savings could be achieved by improving the hydraulic structures, such as the pumping station or the network layout and dimensions.

3.5 Acknowledgements

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Low energy consumption seasonal calendar for sectoring operation in pressurized irrigation networks

4. Low energy consumption seasonal calendar for sectoring operation in pressurized irrigation networks

This chapter has been published entirely in the journal" Irrigation Science":
Carrillo Cobo, M.T., Rodríguez Díaz, J.A., Montesinos, P., López Luque, R., Camacho Poyato, E. 2011.

Abstract. Pressurized irrigation networks and organized on-demand are usually constrained by the high amounts of energy required for their operation. In this line, sectoring, where farmers are organized in turns, is one of the most efficient measures to reduce their energy consumption. In this work, a methodology for optimal sectoring is developed. Initially it groups similar hydrants in homogeneous groups according to the distance to the pumping station and their elevation, using cluster analysis techniques and certain dimensionless coordinates. Second, an algorithm based on the EPANET engine is implemented to search for the best monthly sectoring strategy that accomplish supplying the actual irrigation demand under minimum energy consumption conditions. This methodology is applied to two Spanish irrigation districts (Fuente Palmera and El Villar). Results showed that organizing the networks in sectors, annual energy savings of 8 and 5 % were achieved for Fuente Palmera and El Villar when the theoretic irrigation needs were considered. However, these savings rose up to 27 and 9 %, respectively when the local practices, deficit irrigation, were taken into account. Thus, they confirm that water and energy efficiency cannot be optimized independently and need to be considered together.

Keywords: water supply systems, water management, energy and water efficiency

4.1 Introduction

Trying to improve the efficiency in the use of the irrigation water, modernization processes of irrigation schemes have been a common practice in recent years. The hydraulic infrastructures have been improved and the old open channel distribution networks have been replaced by new pressurized networks arranged on-demand (Plusquellec, 2009). This change increases the conveyance efficiency reducing water losses throughout the distribution system. Additionally, with the new systems arranged on-demand, farmers get a much greater degree of flexibility allowing the use of more efficient systems such as trickle or sprinkler and therefore increasing uniformity and irrigation frequency (Rodríguez Díaz *et al.*, 2007a; Lamaddalena *et al.*, 2007; Pérez *et al.*, 2009).

But in return the pressurized networks require large amounts of energy for their operation. For example in Spain, where an ambitious modernization plan of irrigation schemes has been carried out (MAPA, 2001), Corominas (2009) reported than while water use has been reduced from 8250 m^3 ha^{-1} to 6500 m^3 ha^{-1} (-21%) from 1950 to 2007, the energy demand was increased from 206 kWh ha^{-1} to 1560 kWh ha^{-1} (+657%) in this period. Thus several authors have highlighted the necessity of reducing the energy requirements improving the performance of the different irrigation network's elements such as the pumping efficiency, optimum network's design, on-farm irrigation systems or using renewable energy resources (ITRC, 2005; Moreno *et al.* 2007 and 2009; Pulido Calvo *et al.*, 2003; Abadía *et al.*, 2008; Vieira and Ramos, 2009; Daccache *et al.*, 2010).

In this way, the Institute for Diversification and Energy Savings of Spain (IDAE) proposes several measures to optimize energy demand in pressurized networks. These measures include network sectoring according to homogeneous energy demand sectors and organize farmers in irrigation turns, pumping station adaptation to several water demand scenarios, detection of critical points within the network and energy audits (IDAE, 2008).

Rodríguez Díaz *et al.* (2009) developed a methodology for evaluating the energy savings measures proposed by IDAE (2008) and tested them in the irrigation district of Fuente Palmera (FP) (Southern Spain). Thus potential energy savings were calculated for each measure. In that study, sectoring was the most effective measure with average potential savings of around 20 %. This is consistent with other authors' findings (Sánchez *et al.*, 2009; Jiménez Bello *et al.*, 2010) who proposed methodologies based on genetic algorithms but do not take into account the network's topology.

However the work done by Rodríguez Díaz *et al.* (2009) had some limitations: i) the network was simulated using real demand data but for the peak demand period only and the proposed measures were optimum only for that period; ii) a homogeneous cropping pattern was assumed for all fields within the district when in reality each field had different crops; iii) a wide range of open hydrant probabilities were used in the simulations, but without taking into account the most likely value of probability in relation with the allocated flow per hydrant and the water demand scenario; iv) the sectoring criteria was based on the hydrants' elevations what is useful for abrupt areas but not for flat areas where friction losses are more significant than elevations.

This work represents a step further in the methodology developed by Rodríguez Díaz *et al.* (2009) and its previously cited limitations have been addressed. Thus a sectoring method based on the topological characteristics of the network is developed, as well as a methodology for searching low energy consumption monthly calendars for sectoring operation in irrigation networks for different irrigation demand patterns. Both procedures have been applied to Fuente Palmera (FP) and El Villar (EV) irrigation networks of which topology are steep and flat respectively.

4.2 Material and Methods

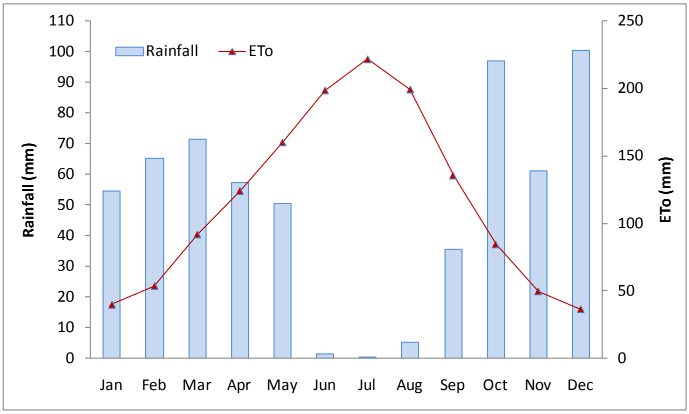
4.2.1. Study area

Two Andalusian (Southern Spain) on-demand pressurized systems, FP and EV, were selected for this work (Figure 4.1). Both networks are placed in the Guadalquivir river basin (Rodríguez Díaz *et al.*, 2007b).

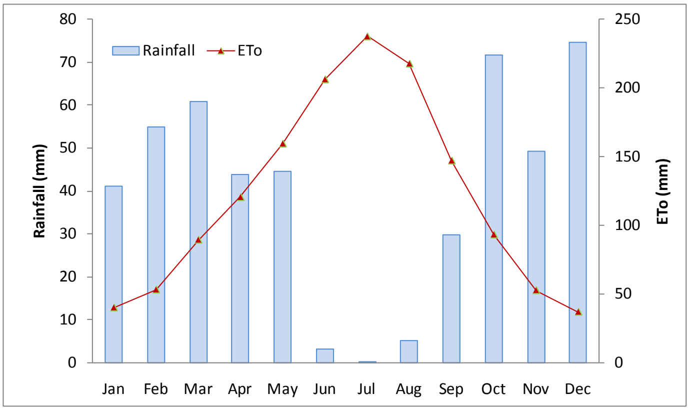
Figure 4. 1. *Location of Fuente Palmera and El Villar irrigation districts*

The climate in the region is predominantly Mediterranean, with rainfall mainly in autumn and spring and dry spells in summer (Rodríguez Díaz *et al.*, 2004). The average monthly rainfall and evapotranspiration, measured in meteorological stations within the irrigation districts, are shown in Figure 4.2.

FP irrigation district (Córdoba province) has an irrigated area of 5611 ha. Most of the district is devoted to extensive field crops, being the most representative citruses, cereals and olive trees (Carrillo, 2009). Water is taken from the Guadalquivir River and stored in a pond from where it is pumped directly to 85 hydrants. The main pipe network length is over 46 km. It was designed to supply on demand. Hydraulic valves installed in every hydrant limit the flow to 1.2 L s^{-1} ha^{-1}. Topography is quite steep and the maximum difference among hydrant elevations is 79 m. The pumping station has 6 pumps of 1825 kW, 2 of 495 kW and one variable speed pump of 540 kW. A service pressure of 30 m for all hydrants in the network is guaranteed. The pumping station has a telemetry system which records the pressure head and pumped flows every minute.



a) FP



b) EV

Figure 4. 2. *Average monthly rainfall and evapotranspiration*

EV irrigation district (Seville province) irrigates 2729 ha. Due to the climatic and soil condition, there is a wide variability of crops in the area. The most representative crops are cereals, cotton and olive trees, which sum 80 % of the irrigation area.

In this irrigation district, water is taken from the Genil River and conveyed to a reservoir from where is pumped through a pumping station with 6 main pumps of 383 kW and 2 auxiliary pumps of 127 kW and 271 kW respectively. Then water is delivered by the irrigation network. It is composed of 31 km of main pipes, which carry water to 47 hydrants, guaranteeing a service pressure of 30 m in all hydrants, as well as in FP irrigation network.

4.2.2. Topological coordinates algorithm for defining sectors in irrigation networks

Energy requirement at a pumping station to supply water to a certain hydrant i, H_p, was calculated using the following equation:

$$H_p = H_{ei} + H_{li} + H_{reqi} \quad [4.1]$$

where H_{ei} represents the hydrant elevation measured from the water source elevation, H_{li} are the friction losses in pipes and H_{reqi} is the pressure head required at hydrant to be able to operate the irrigation system properly (30 m in the study cases).

H_{reqi} was considered a design constraint and was assumed invariable. However the other two terms could vary for every hydrant, H_{ei} depending on hydrant elevation and H_{li} on hydrant water demand and its distance from the pumping station.

To take these variables into account a simplistic methodology was proposed. Thus the following topological dimensionless coordinates were used:

$$z_i^* = \frac{z_{ps}}{z_i} \quad [4.2]$$

$$l_i^* = \frac{l_i}{l_{max}} \quad [4.3]$$

being z_i^*, the dimensionless hydrant elevation, which is directly related to H_{ei}; z_{ps} and z_i are the pumping station and hydrant i elevations respectively. The second dimensionless coordinate, l_i^*, affects H_{li}; l_i and l_{max} are the distances from the pumping station to hydrant i along the distribution network and to the furthest hydrant, respectively. Therefore, with these two coordinates, the network topology could be characterized in relation to the pumping station location. The use of dimensionless coordinates allows comparison among networks of different sizes.

When all the hydrants within the network were identified by these coordinates, they were classified into statistically homogeneous groups using cluster analysis techniques. With this aim, the K-means algorithm was used herein (Holden and Brereton, 2004). By means of this algorithm, groups of homogeneous data were formed with no vertical structure or dependence. The objective of the K-means algorithm is to minimize variance within clusters and maximize variance between clusters (Jain, 2000). This algorithm is based on minimizing a performance index, which is defined as the sum of the distances of all the objects inside the cluster to its centroid. The Euclidean distance has been used to measure the distance between elements (Rodríguez Díaz *et al.*, 2008). When using the K-means algorithm it is necessary to fix the number of clusters to be created a priori. In this paper, the clustering algorithm was applied for 2 and 3 cluster. Each cluster represented a homogeneous irrigation sector. Every level of sectoring implied a proportional reduction in the number of hours available for irrigation. Thus, no more sectoring levels (4 or 5) were considered because they would make impossible the application of the required depths in most of the hydrants.

4.2.3. Sectoring operation algorithm to reduce monthly energy consumption

The algorithm WEBSO (Water and Energy Based Sectoring Operation) that has been developed to reduce monthly energy consumption according to the previous sectoring definition is summarized in Figure 4.3. As energy management is directly related to irrigation water demand, two objectives were considered simultaneously: minimize both energy consumption for the whole network and provide irrigation water to all the hydrants. WEBSO was implemented in visual basic and simulated the network hydraulic behavior for every month under different loading conditions randomly generated.

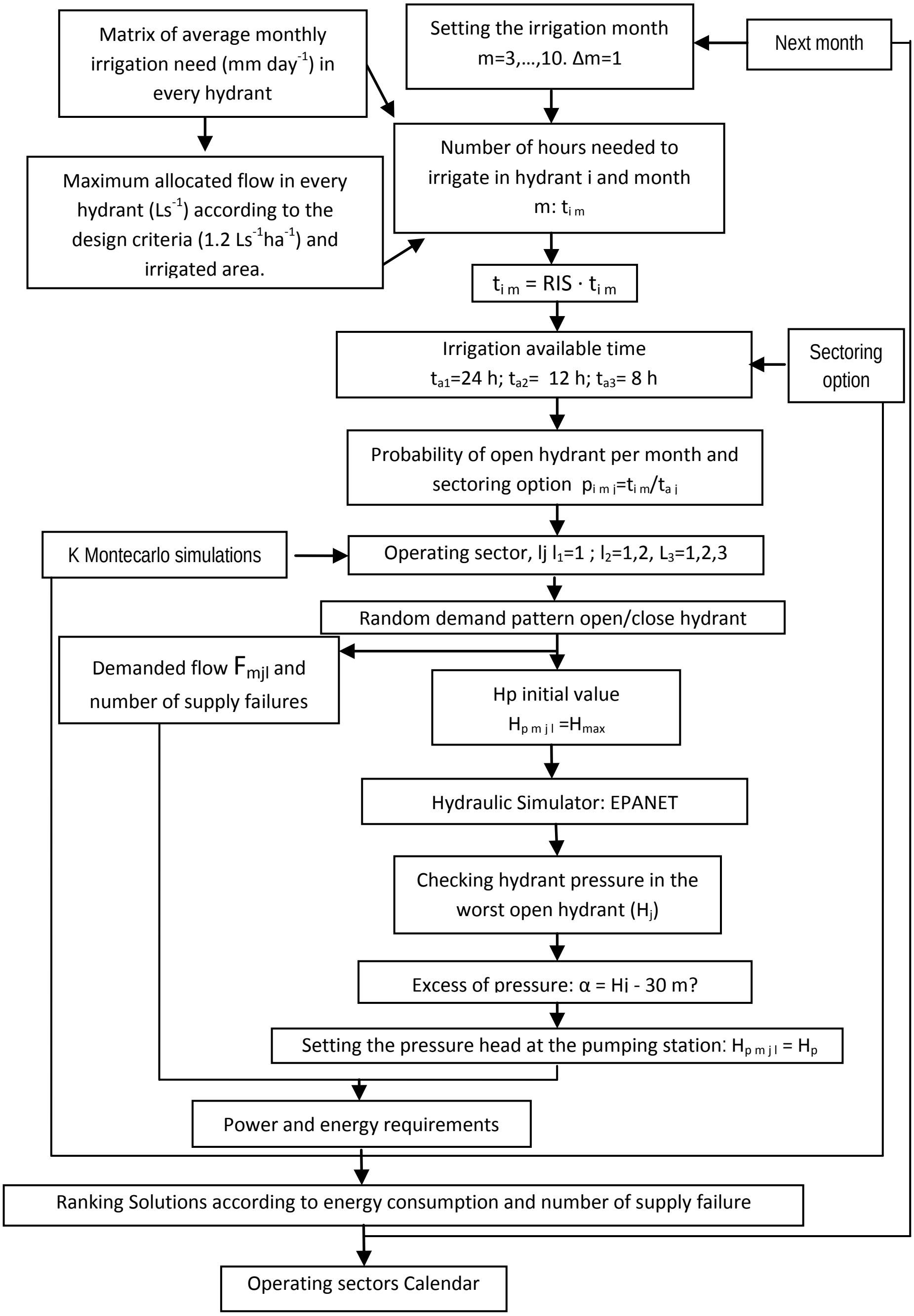


Figure 4. 3. *Schematic representation of the optimization algorithm*

Initially the existing crops associated to each hydrant during the irrigation season were recorded. From these data, the theoretical daily average irrigation needs per month and hydrant (mm) were estimated as described in FAO 56 (Allen *et al.*, 1998), using the computer model CROPWAT (Clarke, 1998). This information can be easily transformed into daily irrigation need, IN_{im} in (L $ha^{-1}day^{-1}$).

Clément (1966) suggested that the probability of open hydrant might be estimated as the quotient between hours needed to irrigate the field associated to each hydrant and the water availability time in hours. Then, the irrigation time required in hours, per hydrant and month, t_{im} was calculated as follows:

$$t_{im} = \frac{1}{3600} \cdot \frac{IN_{im}}{q_{max}} \qquad [4.4]$$

Where q_{max} is the maximum flow allowed per hydrant, equal to 1.2 L s^{-1} ha^{-1} for the analyzed networks. It was considered as a network design criterion.

Local irrigation practices were considered, adjusting theoretical irrigation needs to actual values by means of the irrigation adequacy performance indicator Annual Relative Irrigation Supply (RIS). RIS is the ratio of the total annual volume of water diverted or pumped for irrigation and total theoretical irrigation needs required by the crops (Rodríguez Díaz *et al.*, 2008) and is calculated per irrigation season. RIS values bellow 1 indicate that the crop water requirements were not completely fulfilled and therefore deficit irrigation, on the contrary RIS over 1 indicates excess irrigation. Theoretically the best RIS value is 1 (satisfy irrigation needs), however it can be far from actual values in real irrigation districts. For this reason, different RIS values were considered, as they modify t_{im} as follows:

$$t_{im} = \frac{1}{3600} \cdot \frac{IN_{im} \cdot RIS}{q_{max}} \qquad [4.5]$$

RIS bellow 1 diminishes t_{im} in relation with its value to fulfill theoretical irrigation needs and RIS over 1 increases it.

One unique RIS value for each system (FP and EV) was calculated considering water consumption and crop rotations in the 2008 irrigation season. The theoretical irrigation needs were calculated according to Allen *et al.* (1998).

The water availability time, t_{aj}, depends on the number of operating sectors. Using the previous sector identification, the networks might operate considering the whole network (1 sector) or 2 or 3 sectors, working one after another everyday what means that farmers could only irrigate in turns. Thus t_{aj} was assigned three possible values according to the number of operating sectors, j, per day: 24 hours when the network was operated on demand (1 sector); 12 hours for two operating sectors and finally 8 hours for 3 operating sectors. Thus, farmers could irrigate on-demand but only in certain hours of the day. Then the open hydrant probability according to the number of operating sectors per month (p_{imj}) was calculated according to the following equation:

$$p_{imj} = \frac{t_{im}}{t_{dj}} \qquad [4.6]$$

When t_{im}, was bigger than t_{dj}, it was considered as a supply failure as the hydrant did not have enough time to satisfy irrigation needs according to RIS. These hydrants did not accomplish the implicit water demand satisfaction constraint. An open hydrant probability matrix, OHPM, made up by probabilities per hydrant, month and operating sectors was created then.

Per each m month, j sectoring option, and operating sector, l, k Montecarlo simulations were carried out using OHPM data to generate random demand patterns (distribution of open and close hydrants for a certain iteration), based on the [0,1] uniform distribution. Thus, in each iteration, a random number, R_{imjl}, was generated for every hydrant to define if it was open or close. When p_{imjl} was greater or equal to R_{imjl} the hydrant was assumed open and the base demand, q_i, was calculated by:

$$q_i = q_{max} \cdot S_i \qquad [4.7]$$

where S_i is the irrigation area associated to each hydrant. If not, R_{imjl} was greater than p_{imjl}, the hydrant was assumed closed and its base demand was set to zero. A new random demand pattern of open and close hydrants was generated in every iteration.

Then the network was simulated for each loading condition (RIS and open/close hydrant distribution) using EPANET (Rossman, 2000) as hydraulic simulator. It was integrated within the visual basic program through its dynamic link library (.DLL).

Starting from the maximum theoretical pressure head, H_{max}, that ensures that when all hydrants were open received at least 30 m pressure head, the lowest pressure head, H_{pmjl}, needed at the pumping station to supply water to all open hydrants was calculated. After simulating the network for the maximum theoretical pressure head (H_{max}), the pressure in the most restrictive hydrant (the hydrant which minimum pressure) is determined (H_j). Then, if the pressure is higher than the required 30 m, the excess pressure (α) is determined (H_j minus the required 30 m). After that, this excess of pressure is reduced in pressure head at the pumping station obtained the minimum pressure head that guarantee the required working pressure in all the hydrants (H_{pmjl}). This minimum pressure that ensured that the working hydrants for a certain loading condition got at least the required pressure was taken as the dynamic pressure head defined by Rodriguez Diaz *et al.* (2009).

The pumped flow, F_{mjl} in ($m^3\ s^{-1}$) and the minimum pressure head required at the pumping station, H_{pmjl} were obtained for every demand pattern and operating sector. Then power requirements, $Power_{mjl}$, (in kW) at the pumping station were calculated according to the following equation:

$$Power_{mjl} = \frac{\gamma \cdot F_{mjl} \cdot H_{mjl}}{\eta} \qquad [4.8]$$

Where γ is the water specific weight (9800 N m^{-3}) and η the pumping system efficiency (in this work 0.75 pumping efficiency has been assumed). Consequently, energy consumption in kilowatt-hour per working day and operating sector under each loading condition was estimated as follows:

$$E_{mjl} = \frac{Power_{mjl}}{1000} \cdot t_{aj} \qquad [4.9]$$

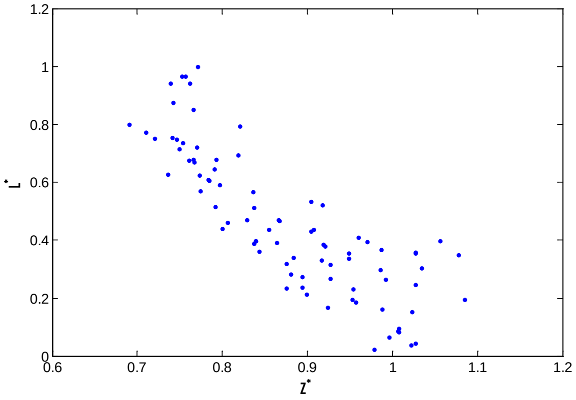
The process was repeated k times for every operating sector and month of the irrigation season (from March to October). The outputs (pumped flow, dynamic pressure head, power and energy) were all recorded. The k values of all outputs per operating sector and month were averaged. Then averaged pumped flow and energy consumption per sector were aggregated to get the whole water and energy consumption for the entire network when two or three sectors were operating.

All generated solutions were ranked according to both energy consumption and the percentage of supply failure, with the aim of helping water managers to evaluate the set of generated alternatives, being flexible or tolerant with failures in pressure or demand, taking into account simultaneously the number of failing hydrants and the irrigation deficit magnitude. The top solution for each sectoring strategy was the lowest energy alternative that ensured demand satisfaction (no supply failure).

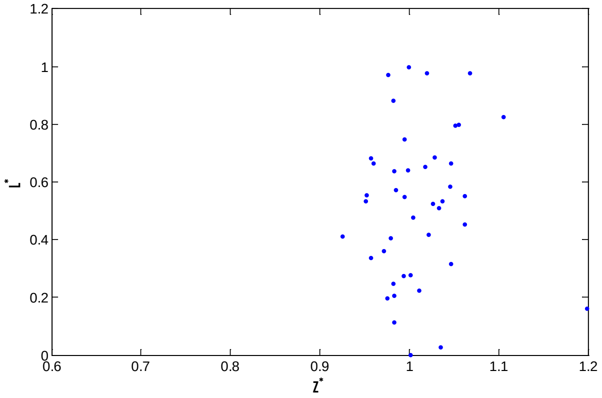
4.3 Results

4.3.1 Optimal network sectoring

Figure 4.4 shows the topological characterization of both irrigation networks by the dimensionless coordinates z^* and l^*, allowing the comparison of network of different total pipe length (46 km in FP and 31 km in EV) and with nearly a double number of hydrants and double irrigated area in FP (85 hydrants and 5611 ha) than in EV (47 hydrants and 2729 ha). Graphs differ considerably due to the two different topologies. FP coordinate z^* varied from 0.7 to 1.1, being z_p = 113.9 m and z_i varying between 86.1 m and 158.2 m. Most hydrants were over the pumping station elevation (z^*<1) and only a few were below. The wide z* interval was a measure of the elevation difference among hydrants, the maximum being 72 m resulting from the rough terrain. This circumstance combined with the regular distribution of l^* values (from 0 to 1) being $l_{i,min}$ = 244 m and $l_{i,max}$ = 11299 m, implied that the pumping head was related to both coordinates. EV network was located in a flatter area (the maximun elevation difference among hydrants was 45.6 m) as the narrower z^* interval showed, varying only between 0.9 and 1.1, being z_p = 184.7 m, $z_{i,min}$ = 154 m and $z_{i,max}$ = 200 m. The l^* varied in the whole range, with $l_{i,min}$ = 9 m and $l_{i,max}$ = 6233 m, this value was 1.8 times smaller than l_{max} in FP due to the central location of its pumping station. Thus, in the case of EV, hydrant distances to the pumping station was the most important driver of energy consumption.



a) FP



b) EV

Figure 4. 4. *Coordinates z* and l* for all the hydrants.*

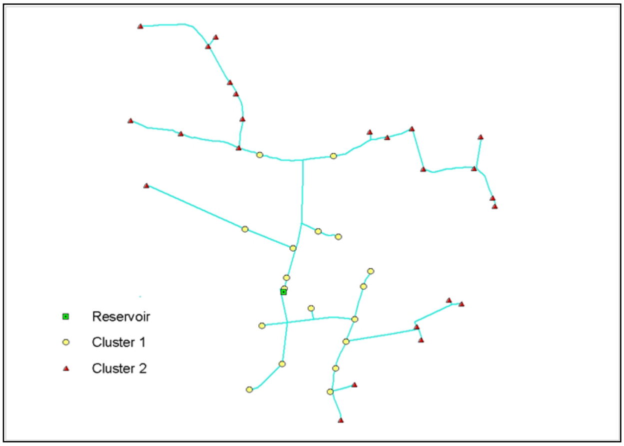
Using cluster analysis techniques, homogeneous groups were created according to the coordinates system defined by l^* and z^*. The clustering method k-means was applied for 2 and 3 clusters in both networks. Every cluster defined an irrigation sector. The proposed sectoring options (two and three sectors) for both networks are shown in Figures 4.5 and 4.6. Figure 4.5a shows two-sectors sectoring option in FP where it can easily detect the combined influence of hydrant elevation and distance to the pumping station. In Figure 4.5b hydrant elevation is more relevant than distance and sectors distribution is less clear.

a) 2 homogeneous irrigation sectors

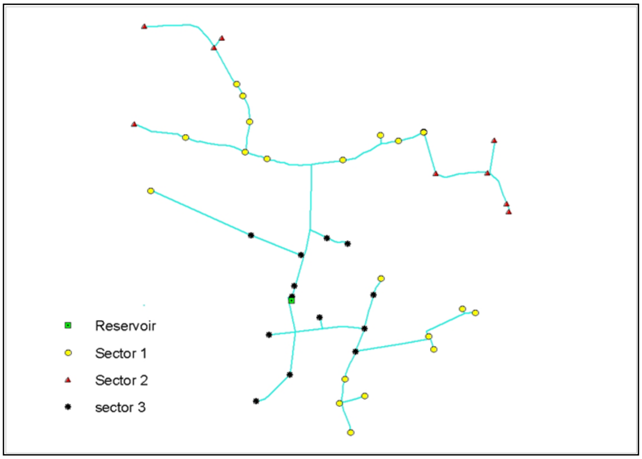
b) 3 homogeneous irrigation sectors

Figure 4. 5. *Proposed network's sectoring for FP*

In relation with sectoring options in EV, in Figures 4.6a and 4.6b sectors definition are directly related to hydrant distance to the pumping station, being distributed in concentric rings around the pumping station.



a) 2 homogeneous irrigation sectors



b) 3 homogeneous irrigation sectors

Figure 4. 6. *Proposed network's sectoring for EV.*

4.3.2 Seasonal calendar for sectoring operation

The algorithm described in Figure 4.3 was applied to both irrigation districts according to the sectors established in the previous section. Thus the networks were simulated for the whole irrigation season (from March to October) and for different operation strategies: one sector only (on-demand), two sectors and three sectors with RIS =1 for both irrigation networks and with RIS = 0.4 in the case of FP and RIS = 0.24 for EV. In this work, k, the number of Montecarlo simulations, was set to 500 carrying out 24000 hydraulic simulations (24000 = 500 (simulations) 8 (months) (1+2+3) (operating sector per sectoring option)), providing enough different possibilities to be evaluated by water managers.

The analysis were initially carried out for RIS = 1. The first output was the open hydrant probability (equation 4.6) which was related to both sectoring operation and the variability of irrigation needs from one month to other.

The open probabilities for all hydrants and sectoring strategy were averaged and are shown in Table 4.1 for RIS =1. Sometimes these values were higher than 1 (highlighted in Table 4.1) what implied that this sectoring option was not fully adequate because averaged hydrant operating time was not enough to supply irrigation demand. This situation occurred in both networks during the highest demand months when three sectors were operating. Moreover in the case of EV, it also happened for two operating sectors during the peak demand month (June) implying that this network did not admit any sectoring during this period. Hence, it reflected the fact that this network offered fewer possibilities for sectoring.

Table 4.1 shows average probabilities of all hydrants estimated from hydrant probability per month and sectoring strategy (standard deviations are showed as well). So, even in case of average values less than 1, it was possible to find some hydrants with probability to be open over 1. This circumstance was defined as supply failure. In this way, Table 4.2 shows average percentage of supply failure hydrants in the 500 iterations carried out per month, sectoring option and each operating sector for both irrigation networks. Thus, in EV, in June for the two sectors option and when sector 1 was operating, all open hydrants were unable to supply irrigation needs during the available time for irrigation.

Table 4. 1. *Average values of $p_{m,i}$ and standard deviations for the theoretical irrigation needs*

Sectoring options	Average $p_{i,m}$ (standard deviation) (RIS=1)															
	FP								EV							
	Month								Month							
	3	4	5	6	7	8	9	10	3	4	5	6	7	8	9	10
1	0.08	0.05	0.11	0.42	0.37	0.27	0.13	0.04	0.09	0.04	0.29	0.59	0.47	0.35	0.22	0.04
	-0	-0.03	-0.06	-0.09	-0.09	-0.1	-0.07	-0.03	-0.04	-0.02	-0.09	-0.04	-0.15	-0.17	-0.1	-0.02
2	0.16	0.11	0.22	0.85	0.75	0.54	0.27	0.09	0.19	0.08	0.59	1.18	0.93	0.7	0.43	0.08
	-0.1	-0.06	-0.12	-0.17	-0.17	-0.2	-0.14	-0.06	-0.07	-0.05	-0.18	-0.08	-0.31	-0.33	-0.21	-0.04
3	0.24	0.16	0.33	1.27	1.12	0.81	0.4	0.13	0.28	0.12	0.88	1.77	1.4	1.05	0.65	0.12
	-0.1	-0.09	-0.17	-0.26	-0.26	-0.3	-0.21	-0.1	-0.11	-0.07	-0.26	-0.12	-0.46	-0.5	-0.31	-0.06

On the contrary in FP during the same period, the maximum supply failure value was 20 % for the sector option and sector two was operating, and during July this value diminished to 9 %. Thus, only a small percentage of hydrants would not have been operating enough time to satisfy their full monthly irrigation needs. Additionally, taking into account that FP's average probability for June and for two operating sectors was 0.85 with standard deviation of 0.17, what means that only few farmers would be slightly below the full satisfaction of irrigation needs and the proposed reduction in time available for irrigation would not necessarily imply a dramatic change for them.

Table 4. 2. *Percentage of open hydrants where $t_{i,m}$ is bigger than t_a (supply failure)*

Sectoring option	Operating sector	FP					EV				
		Month					Month				
		5	6	7	8	9	5	6	7	8	9
1	1	0	0	0	0	0	0	0	0	0	0
2	1	0	14	9	0	0	0	100	56	23	0
	2	0	20	4	0	0	0	94	26	14	0
3	1	0	87	75	30	0	24	100	94	85	9
	2	0	79	57	30	0	42	91	81	66	25
	3	0	58	59	55	0	21	100	100	91	33

A different situation was found in EV for the same month and sectoring option, where the average of open hydrant probability was 1.18, pointing out that the farmers needed an increment of approximately 20 % of the available irrigation time for full demand satisfaction. Therefore in this situation, irrigation districts managers must take the decision of adopting one strategy or another. As will be shown later when local farmers' behavior is taken into account by specific RIS values, different sectoring operation alternatives compared to those from full irrigation needs satisfaction (RIS = 1) are obtained.

Tables 4.3 and 4.4 show the monthly average flow and required pressure head at the pumping station for all the sectoring strategies, including those where supply failures were detected.

Table 4. 3. *Average monthly demanded flow in FP and EV*

Sectoring options	Operating setor	Q (L s^{-1})															
		FP								EV							
		Month								Month							
		3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	545	373	786	2906	2544	1840	911	305	279	141	830	1703	1371	1027	640	155
2	1	329	223	430	1774*	1598*	1155	527	160	216	129	648	1232*	1165*	961*	621	141
	2	761	508	1128	3853*	3471*	2464	1272	466	329	163	1027	1689*	1401*	1048*	648	144
3	1	1070	720	1641	4301*	4148*	3273*	1703	587	397	177	1170*	1420*	1329*	1244*	903*	181
	2	441	302	631	1968*	1873*	1502*	746	228	189	117	498*	638*	555*	468*	310*	95
	3	137	102	125	401*	405*	381*	272	130	243	129	710*	916*	916*	860*	645*	149

*Hydrants where the ratio $t_{i,m}$ and t_a ($p_{i,m}$)is bigger than one were found.

Table 4. 4. *Required pressure head at the pumping station*

Sectoring options	**Oerating setor**	**H (m)**															
		FP								**EV**							
		Month								**Month**							
		3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	77	69.5	73.3	88.7	87.7	84.2	77.6	67	41.3	34.3	53.7	71.9	65.8	59.3	50.7	36.3
2	1	78.1	73.7	77.4	101.4*	99.5*	93.2	82.8	72	36.6	31.9	42.7	51.1*	50.6*	48.4*	44.8	35.4
	2	58.3	55.4	58.7	84.4*	80.1*	70.2	62.6	56	44.9	40.1	69.8	97.8*	92.4*	76.7*	60.3	34.7
3	1	67	65	67.8	91.6*	86.8*	78.5*	69.3	62	39.7	36	47.7*	48.5*	46.1*	44.7*	41.3*	33
	2	81.3	75.8	80.7	105.7*	104.6*	98.8*	86.3	75	48.6	40.4	78.5*	87.0*	86.6*	86.2*	66.2*	35.8
	3	34.4	36.2	41.2	42.2*	42.2*	35.5*	32.8	33	37.6	32.2	44.0*	50.7*	50.7*	50.5*	47.0*	37.5

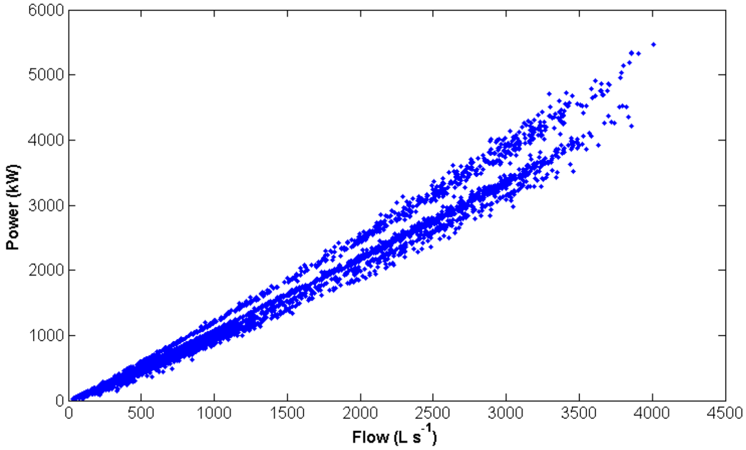
*Hydrants where the ratio $t_{i,m}$ and t_a ($p_{i,m}$)is bigger than one were found.

The differences in required pressure head among operating sectors were significant in both networks. It is important to highlight that a dynamic pressure head model was used to calculate the required pressure to satisfy pressure requirement at the most energy demanding open hydrant at a certain time (Rodríguez Díaz *et al.*, 2009). Especially in the maximum demand months of the year when some pipes were overloaded, a significant increase of the pumping head was required to compensate the increment of friction losses driven by higher circulating flows.

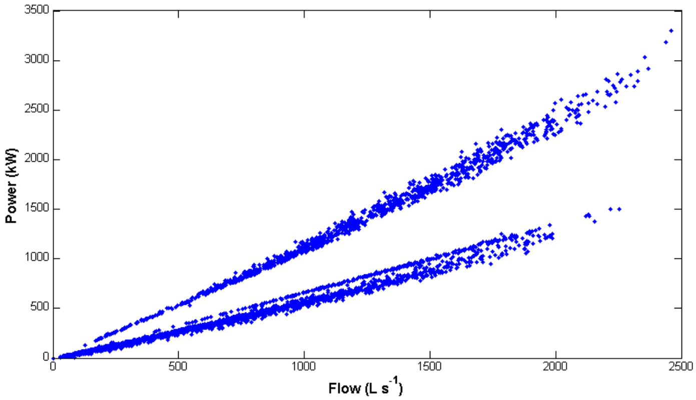
The required power was calculated in each iteration using equation 4.8. Thus, power demand curves were obtained for all the sectoring strategies. The curves corresponding to on-demand management are shown in Figure 4.7. Differences in power, up to 1000 kW for a given flow, are shown in Figure 4.7a for FP network due to random selection of irrigating hydrants in every iteration. Figure 4.7b shows the case of EV where two separate branches are clearly distinguishable in the power demand curve. It indicates that there were some critical points which are hydrants with special energy requirements because of their elevation or distance in relation to the pumping station. (Rodríguez Díaz *et al.*, 2009).

Given that EV was a flat network and elevation differences were not relevant, these critical points were far from the pumping station or located in some specific pipes with small diameters so that when they were overloaded the pressure requirements increased significantly due to higher friction losses. This fact reduced sectoring options in EV. Thus, an analysis of critical points in this network would be desirable in order to take the adequate measures to sort out these local problems.

The changes in power requirements depending on the water demand and location of the open hydrants led to potential energy savings compared to the current management when the network was operated on demand and fixed pressure head. Applying equation 4.9 to all simulations the energy requirements per working day were obtained.



a) FP



b) EV

Figure 4. 7. *Power demand curves for both networks when they are operated on demand (In EV the two separate branches indicate that there were some critical points with different energy requirements than the rest of the network)*

The average values, as well as the percentage of reduction in energy consumption per month (in comparison with on-demand operation (1 sector)) are summarized in Table 4.5 where monthly energy consumptions are compared for all sectoring strategies and the potential savings that would be achieved by adopting them. In FP, potential savings were very stable during the irrigation season for two operating sectors, as pressure head was mainly conditioned by elevation and the pipe diameters were not undersized. In contrast, in EV where friction losses were predominant, the savings were highly dependent on the time-spatial distribution of water demand.

The lowest energy consumption sectoring calendars for both irrigation districts are also shown in Table 4.5 by shaded cells. They are a combination of the best results for three analyzed sectoring strategies. Every month the lowest energy requirement strategy with no supply failures was selected. Accomplishing these restrictions, for FP two sectors were recommended but keeping the network working on-demand in June and July. Adopting this management strategy, potential energy savings of almost 8 % over the annual energy consumption could be achieved (8020 MWh to 7390 MWh). On the other hand, EV had less flexibility for sectoring and it was not allowed in June, July and August. Three sectors were optimum only for October and two for the rest of the irrigation season. Because of these limitations only 5 % of savings over the annual consumption were obtained (3500 MWh to 3330 MWh). Assuming an average energy cost of 0.10 € kWh^{-1}, the adoption of these measures would lead to annual savings of approximately 63000 € in FP and 17500 € in EV.

In FP, there were few supply failure hydrants in June and July, the irrigation district manager might consider two sectors operating in the peak demand period, assuming some supply failures and saving up to 15 % (8020 MWh to 6855 MWh) over the on demand management (130000 € year^{-1}). Thus a good knowledge of the local farmers’ practices was necessary before adopting these measures. For this reason, the analysis was repeated for the RIS values that characterized farmers´ behavior in both irrigation districts. These values were calculated by Blanco (2009) for the studied irrigation season resulting RIS = 0.41 for FP and RIS = 0.24 for EV, showing that deficit irrigation is a common practice in both districts.

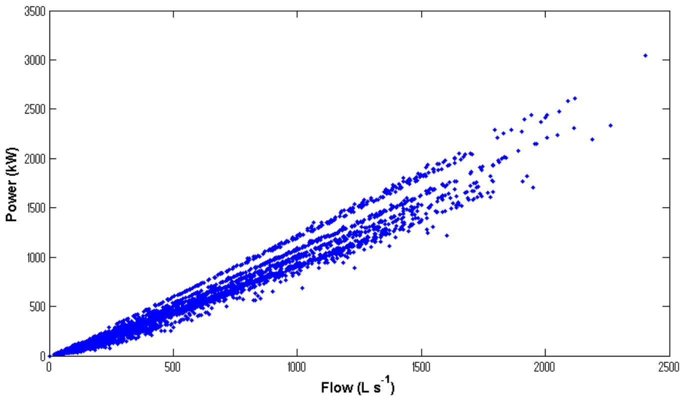
Table 4. 5. *Average energy requirements per working day (kWh day^{-1}), potential energy savings (%) and recommended sectoring calendar for the theoretical and the actual demand*

Sectoring options	FP (RIS=1)								EV (RIS=1)							
	Month								Month							
	3	4	5	6	7	8	9	10	3	4	5	6	7	8	9	10
1	13164	8127	18057	80802	69962	48593	22186	6373	3618	1517	13973	38412	28292	19099	10164	1759
2	10610	6641	14248	68615*	59909*	41164	17943	4996	3050	1402	11328	29069*	23391*	16848*	9444	1661
	-19%	-18%	-21%	-15%	-14%	-15%	-19%	-22%	-16%	-8%	-19%	-24%	-17%	-12%	-7%	-6%
3	11733	7679	17486	64720*	59932*	43764*	20000	6053	3463	1610	14849*	27934*	23418*	17162*	9397*	1458
	-11%	-6%	-3%	-20%	-14%	-10%	-10%	-5%	-4%	(-6%)	(-6%)	-27%	-17%	-10%	-8%	-17%
Sectoring options	FP (RIS=0.41)								EV (RIS=0.24)							
	Month								Month							
	3	4	5	6	7	8	9	10	3	4	5	6	7	8	9	10
1	4759	2765	6705	29638	24732	17213	7663	2814	1266	951	2790	5982	4811	3407	2149	947
2	4105	2644	5515	24594	21050	14454	6432	2526	1174	905	2403	5182	4410	3204	2053	928
	-14%	-4%	-18%	-17%	-15%	-16%	-16%	-10%	-7%	-5%	-14%	-13%	-8%	-6%	-4%	-2%
3	3385	2456	4753	20354	18716	12780	6041	2136	1264	914	2707	6044	4592	3345	2086	932
	-29%	-11%	-29%	-31%	-24%	-26%	-21%	-24%	0%	-4%	-3%	(-1%)	-5%	-2%	-3%	-2%

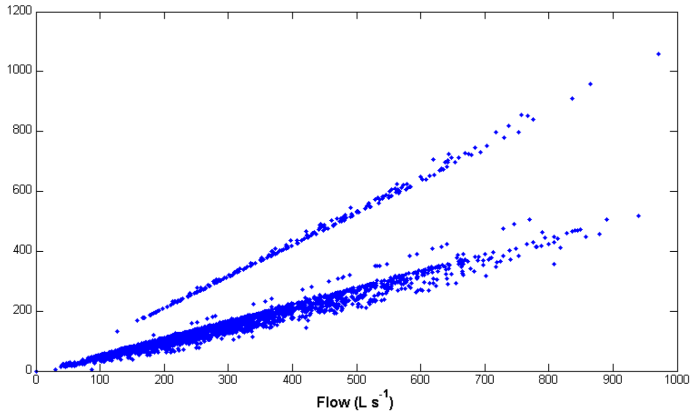
* Systems failures occurred

** Monthly optimums are shaded

As it has been shown above the optimum sectoring strategy has proven to be highly sensitive to water demand. When the water demand was reduced by smaller RIS values, the supply failures disappeared so farmers always had enough time to apply smaller irrigation depth independently of the sectoring strategy. In this case, the optimum sectoring calendars changes from the ones calculated for the full theoretical irrigation requirements, RIS = 1. The new power demand curves are shown in Figure 4.8, differing from those in Figure 4.7, in particular for EV (Figure 4.7b) where the upper branch is significantly reduced due to the smaller flows circulating along the critical pipes.



a) FP



b) EV

Figure 4. 8. *Power demand curves for both networks when they are operated on demand for actual water demand.*

The optimum calendars for both networks under their real water demand are shown in Table 4.5 too. In this situation, the lowest energy requirement and fully demand satisfaction strategy for FP was to be operated in three sectors all the irrigation season and the potential savings in the annual energy consumption were 27 %. In the case of EV, two sectors are recommended for the entire irrigation season (9 % of energy savings).

4.4 Conclusion

Nowadays water and energy efficiency cannot be considered independently. Thus, although sectoring is an efficient measure to reduce the energy consumption in irritation networks, it depends largely on the networks topology and its design as well as water demand in the network. As irrigation water demand tend to be very concentrated in some months of the year, the optimum measures and therefore the optimum sectoring strategy may differ from one month to other depending of the water demanded at every hydrant. A particular analysis, taking into account the local farmers’ irrigation practices, would be necessary for any network before the adoption of sectoring measures.

In this study a methodology for sectoring based on dimensionless coordinates and cluster analysis techniques was developed. This methodology for grouping hydrants according to the same pipe length and land elevation characteristics cannot always be the best solution to reduce energy consumption as this definitely reduces the total amount of water flowing in the network but tends to concentrate all the water volume in the same pipe reach creating higher head losses. However it is very useful when the networks are not undersized or farmers typically apply less water than the design flow. In other cases, it should be convenient to include a hydraulic coordinate to avoid the malfunction of the hydraulic elements. Also this methodology can be used in the networks design, providing an optimum sectoring strategy based on the hydrants’ topological characteristics.

The proposed sectors were later evaluated by the algorithm WEBSO based on the EPANET engine. This model links energy saving measures with local irrigation practices. Thus it generates monthly sectoring strategies, ranked according their degree of accomplishment of minimum energy consumption and minimum irrigation deficit objectives.

Both methodologies have been applied to two different networks (FP and EV), obtaining significant savings in energy consumption. Results showed that organizing the networks in sectors, annual energy savings of 8 % and 5 % were achieved for FP and EV when the theoretical irrigation needs were considered. However these savings rose up to 27 % and 9 % respectively when the local farmers' practices, deficit irrigation, were taken into account. These practices have shown a significant influence on the optimum outcome, so a good knowledge of the irrigation districts is necessary before adopting these measures.

Finally these sectoring calendars can be easily implemented in remote-controlled pipe networks, where electrovalves are available in each hydrant, like the networks existing in most of the modernized irrigation districts.

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New model for sustainable management of pressurized irrigation networks. Application to Bembézar Irrigation district (Spain)

5. New model for sustainable management of pressurized irrigation networks. Application to Bembézar MD irrigation district (Spain).

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Abstract. Pressurized irrigation networks require large amounts of energy for their operation which are linked to significant greenhouse gas (GHG) emissions. In recent years, several management strategies have been developed to reduce energy consumption in the agricultural sector. One strategy is the reduction of the water supplied for irrigation but implies a reduction in crop yields and farmer`s profits. In this work, a new methodology is developed for sustainable management of irrigation networks considering environmental and economic criteria. The multiobjective Non-dominated Sorting Genetic Algorithm (NSGA II) has been selected to obtain the optimum irrigation pattern that would reduce GHG emissions and increase profits. This methodology has been applied to Bembézar Margen Derecha (BMD) irrigation district (Spain). Irrigation patterns that reduce GHG emissions or increase actual profits are obtained. The best irritation pattern reduces the current GHG emissions in 8.56 % with increases the actual profits in 14.56 %. Thus, these results confirm that simultaneous improvements in environmental and economic factors are possible.

Keywords: sustainability, water management, energy efficiency, carbon footprint, Evolutionary algorithms, irrigation.

5.1 Introduction

In recent years, many irrigated areas have been subjected to modernization processes with the aim of increasing the water use efficiency, through more efficient irrigation systems such as drip and trickle (Playan and Mateos, 2006). Consequently, pressurized water conveyance systems have replaced the open channels. However, this change has increased their energy consumption because pressurized systems require large amounts of energy for pumping water and energy is becoming the biggest item in the total water costs for irrigation (Corominas, 2009; Jackson *et al.*, 2010). Additionally, the large amounts of energy required for their operation are linked to the carbon footprint. The carbon footprint is the total amount of GHG produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide (CO_2). Therefore, the energy required in the pumping station generates significant GHG emissions which also contribute to accelerate the climate change process.

In the irrigation sector, water supply, energy consumption and GHG emissions are closely linked. Thus, a reduction in the pumped water, and therefore smaller carbon footprint, may lead to reductions in yields and to smaller farmers´ incomes. Consequently, the optimal operation of irrigation networks, under a sustainable point of view, should only be achieved considering simultaneously environmental and economic criteria.

To reduce the energy dependency, several management strategies have been developed to reduce energy consumption in pressurized irrigation networks. A number of studies have focused on the optimization of the network layout and better selection of the pumping systems (Lamaddalena and Sagardoy, 2000; Pulido-Calvo *et al.*, 2003; Moreno *et al.*, 2007 and 2009; Daccache *et al.*, 2010). Other works have developed management strategies where significant potential energy savings can be achieved (Rodríguez Díaz *et al*. 2009; Moreno *et al.* 2010). Related to this, sectoring operation, where farmers are organized in irrigation turns according to their energy demand, and critical points control, hydrants or water delivery points with high energy requirements, have proven to be efficient measures with up to 30% of energy savings (Jimenez Bello *et al.*, 2010; Carrillo Cobo *et al.*, 2011; Navarro Navajas *et al.*, 2012; Rodríguez Díaz *et al.*, 2012). Most of the studies described above focused on the reduction of the energy demand but maintaining the current water supply levels. However, they do not optimize the water use, considering the actual crop pattern and productivity related to water applied and market prices.

In recent years, environmental criteria have been included in the design of new urban water supply systems, at the same level than operation and investment costs (Dandy *et al*., 2006; Wu *et al.*, 2010a and 2010b; Sahely and Kennedy, 2007; Ramos *et al*., 2011). These tools are usually based on multi-objective genetic algorithms (Savic, 2002; Farmani *et al*., 2005), involving more than one objective function to be optimized simultaneously with the best combination of the values for the decision variables.

However, methodologies to reduce the environmental impact and maximize the farmer's profits in pressurized irrigation systems have not been developed yet. Nowadays, markets require that agricultural products are obtained in a sustainable manner, so an efficient use of the resources would give the final product an added value.

In this paper we develop a new model for the sustainable management of pressurized irrigation networks. The model evaluates an environmental objective (GHG control) and an economic objective (farmer's profit) using a multi-objective optimization algorithm to determine the optimal irrigation pattern. It has been applied to a Spanish irrigation district (BMD) to increase the sustainability of the agricultural production in the region.

5.2 Material and Methods

5.2.1. Study area

The BMD irrigation district is located in Andalusia (Southern Spain) (Figure 5.1). The climate in the region is predominantly Mediterranean, with rainfall concentrated mainly in autumn and spring, and dry spells in summer. The average annual rainfall in the area is 540 mm and the average temperature is 17.9 ºC.

BMD was built in 1967. Initially the conveyance system was an open channel network that covered over 11900 ha. Recently (2007), the hydraulic infrastructures have been modernized and the old network was replaced by a pressurized system arranged on-demand, so water is continuously available to farmers.

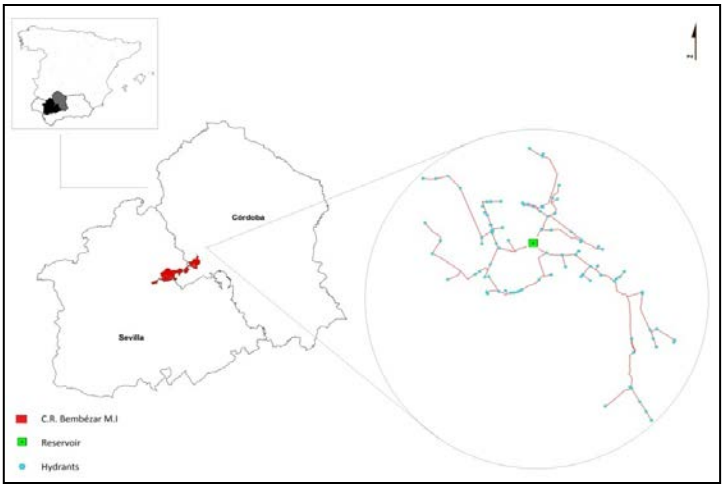


Figure 5. 1. *Location of the BMD irrigation district***.**

The new water conveyance system still uses the old main channel (40 km) which supplies water to 11 pumping stations placed along the channel. Every pumping station supplies to an independent pressurized network. The network is designed to supply 1.2 L s^{-1} ha^{-1} at a minimum operation pressure at hydrant of 300 kPa. Drip irrigation is the most common system (almost 100 %). The network and the pumping stations are monitored by a telemetry system which provides flows and pressure data in real-time.

The conveyance system is organized in eleven sectors. Each sector is supplied by an independent network. Sector V, which covers over 1098 ha, was selected for this study. Its crops and irrigated areas are representative of the whole BMD: Citrus trees (50.3 %), maize (31.8 %), cotton (5.3 %), wheat (8 %), fruit trees (2.4 %) and sunflower (2.2 %). Sector V's water rights, maximum amount of water allocated by the water authority to the irrigated area, are 7.53 Mm^3.

5.2.2. Problem approach

The main goal of this work was to determine the monthly volume of water to apply to every crop within the irrigation district. A multiobjective approach was used to optimize the irrigation pattern with two conflicting objective functions: one aimed at minimizing the environmental impact (GHG emission function, F(1)) and the other related to profit maximization (economic function, F(2)).

The first objective (F1) is minimizing the GHG emission of the water supply:

$$\textbf{Minimize F (1) = (GHG)norm + CP} \qquad [5.1]$$

Where (GHG)norm is the normalized emission in tons of equivalent carbon dioxide generated in the pumping station and CP the penalty cost due to excess of applied water. Both terms are normalized to allow their addition.

GHG emissions were obtained by the following equation:

$$GHG = E_T \cdot EF \qquad [5.2]$$

Where E_T is the annual energy consumed in the pumping station (kWh) and EF the emissions conversion factor used to quantify the GHG emission from the electricity consumption in the pumping station: 0.166 kg CO_2 kWh^{-1} (WWF, 2010).

E_T was estimated as follows:

$$E_T = \frac{\sum_{m=1}^{N_m} \gamma \cdot V_m \cdot H}{\eta \cdot 3.6 \cdot 10^6} \qquad [5.3]$$

Where m is the month index, N_m the number of months of the irrigation season, γ the water specific weight (9810 N m^{-3}), V_m (m^3) the volume of water pumped each month, H the pressure head at the pumping station (m) and η the pumping system efficiency (in this work a pumping efficiency of 0.75 was assumed).

V_m was the monthly allocation of water to each crop and was given by:

$$V_m = \sum_{c=1}^{N_c} \left(\frac{IN_{cm}}{1000} \cdot d_m \cdot A_c \right) \cdot RIS_c \qquad [5.4]$$

Where c is the crop index, N_c the number of crops in the study area, IN_{cm} (L ha^{-1} day^{-1}) the daily irrigation need per month m and crop c, d_m the days of each month, A_C (ha) the area devoted to crop c and RIS_C is the crop Annual Relative Irrigation Supply.

The theoretical daily average irrigation needs per crop and month, IN_{cm} (mm), were estimated for every hydrant as described in FAO 56 (Allen *et al.,* 1998), using the computer model CROPWAT (Clarke 1998). This monthly needs can be easily transformed into daily irrigation need per hydrant, month and crop, IN_{cm} (L ha^{-1} day^{-1}).

RIS is the ratio of the volume of water actually pumped in related to the theoretical irrigation needs (Rodríguez Díaz *et al.*, 2008). Not all water pumped into the pumping station reaches the root zone of the plants. Part of the water is lost in the conveyance system and part in the on-farm irrigation system. The irrigation efficiency can be sub-divided into conveyance efficiency (e_c) which represents the efficiency of water transport in the network and application efficiency (e_a) which represents the water application in the field. Irrigation efficiency is estimated to be 0.9 which results from the multiplication of e_c and e_a (0.8). Then, RIS values around 1.2 indicate that the irrigation needs were fully satisfied, RIS values below 1 mean deficit irrigation and RIS over 1.2 show excess of irrigation.

The pressure head at the pumping station (H) was obtained for the most unfavorable situation when all hydrants are open and minimum service pressure (30 m) is guaranteed in the most energy demanding hydrant. EPANET's engine (Rossman, 2000) was used for that purpose.

The aim of the second objective function (F2) is the maximization of farmer´s profits:

$$\textbf{Maximize F (2) = [(APV + SUB) – (}C_F + C_v\textbf{)] norm} \qquad [5.5]$$

Where APV is the agricultural production value, SUB the total subsidies in the irrigated area, which are obtained as the sum of the unit subsidies per crop and irrigated area, C_F the fixed costs and C_v the variable costs. Profits were normalized in order to compare both objective functions (F1 and F2).

Farmer's profits were calculated considering a balance of incomes and production costs, which are both closely linked to the applied volume of water per crop in the irrigated area. On the one hand, incomes were calculated as the sum of the agricultural production value (APV) and subsidies (SUB). SUB (€) was estimated for every crop within the irrigation district through direct interviews with farmers.

APV (€) was calculated within the irrigation district by mean of the following equation:

$$APV = \sum_{c=1}^{N_c} Y_a \cdot Pr_c \qquad [5.6]$$

where Y_a (kg) is the yield under actual conditions and Pr_c (€ kg^{-1}) the average market price of each crop in this study area during the irrigation season, 2010.

Crop yields in relation to water stress were estimated with the following production curve included in the FAO 33 report (Doorenbos and Kassam, 1979):

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y \left(1 - \frac{ET_a}{ET_m}\right) \qquad [5.7]$$

where k_y is the yield response factor, ET_a the ratio actual evapotranspiration (mm day^{-1}), ET_m the evapotranspiration in no water stress conditions (mm day^{-1}) and Y_m (kg) potential yield when there are not limitations of water. The ET_a in this study was obtained by:

$$ET_a = (IN_{cm} \cdot RIS_c \cdot e_a \cdot e_c) + P_e \qquad [5.8]$$

where P_e the effective rainfall (mm day^{-1}).

On the other hand, the production costs have two components: fixed C_F (€) and variable costs C_V (€). Maintenance, operation and management (MOM) costs and cropping costs (planting, pesticides, fertilizers, pruning and harvesting costs) are considered fix rates per unit of irrigated area. C_F is different for each crop and they were provided by the irrigation manager and local farmers. The variable costs include energy consumption in the pumping station which is linked to the volume of water supplied in different RIS patterns. Thus farmers pay for energy according to a volumetric water pricing system (€ m^{-3}).

$$C_V = E_T \cdot Pr_E \qquad [5.9]$$

where Pr_E is the average unit energy price (0.079 € kWh^{-1}) during the 2010 irrigation season.

Energy consumption is directly linked to GHG emissions and reductions in energy consumption imply reductions in the supplied water. However, less water applied leads to smaller yields and have negative impacts on the agricultural production and farmer's profits. Then, both objectives are conflicting and the aim is to find the irrigation pattern that gives an optimum balance between them.

5.2.3. Optimization method. NSGA-II

The multiobjective algorithm NSGA II (Deb *et al*., 2002) was used and implemented in MATLAB (Pratap, 2010) to obtain the optimal irrigation pattern that gives an optimum balance between objective functions (equations 5.1 and 5.5). The optimization process using the original NSGA-II (Figure 5.2) was adapted to this problem. The initial stages, initial population and objective functions, were slightly modified. The rest of stages, crossover, mutation and selection were not changed from the original algorithm. In the first step, the initial population of N chromosomes (RIS patterns) was randomly generated. Every chromosome represents one irrigation pattern for the irrigation district. In this study, the volume of water applied to each crop is measured in terms of RIS, so the number of variable (C) in the chromosome is a certain number of RIS value, one for every crop in the irrigation district. Each crop in the irrigation district had a RIS value within a range from 0.2 (large deficit irrigation) to 1.2 (full satisfaction of irrigation needs considering conveyance and application efficiency), using real-coding (Elferchihi *et al*. 2009).

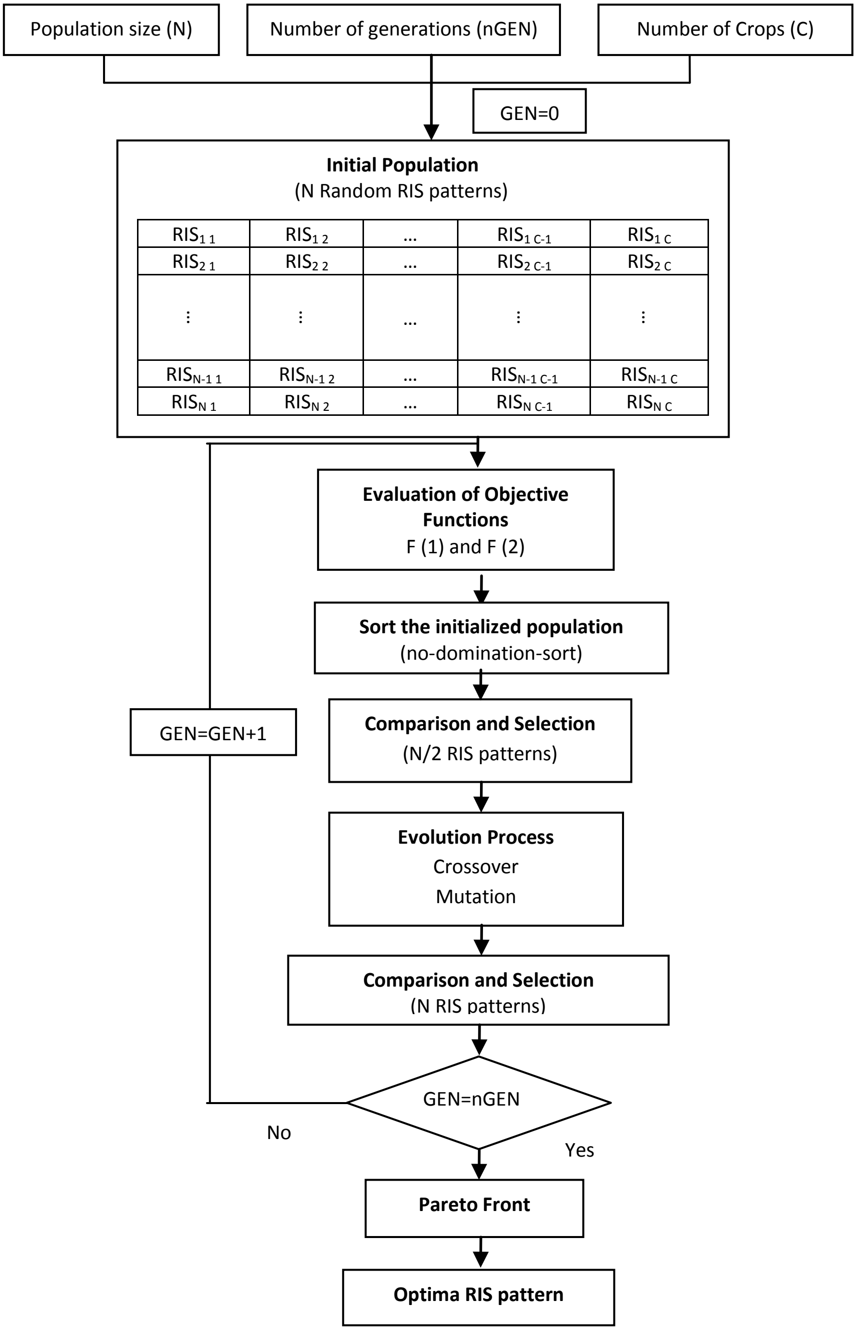


Figure 5. 2. *Optimization process using NSGA-II.*

Then, the objective functions, F(1) and F(2), were calculated for each chromosome. Both terms in F(1) were normalized before adding them up. In the case of GHG emissions the cumulative distribution function for a continuous uniform distribution on the interval [0, 1] was used. However, CP is not a continuous function and its value was assumed 0 when the applied water was equal or less than the water rights and 1 when applied water was more than the water rights. Thus, the minimum value of F1 was 0 and the maximum value 2. If the water consumption exceeds the water rights, the irrigation district would need to buy extra water from other users. However, the purchase of water in the studied area is complex and expensive, therefore this possibility is dismissed. To compare the objectives, F(2) was normalized according to a continuous uniform distribution on the interval [0, 2], like F(1).

In the remaining stages, RIS patterns were modified (crossover and mutation) and the top N were selected based on their objective function values. The process was repeated several generations (GEN). Finally, the set of N optimal chromosomes in the last generation is known as the Pareto Front.

5.3 Results

5.3.1 Evolution of the objective functions in the optimization process

The model based on NSGA-II described in Figure 5.2. was applied to BMD (Sector V) and both objectives, F1 and F2, were optimized. The random initial population was 40 chromosomes (RIS patterns) which were composed of six genes, one for every crop’s RIS value. The initial population was evolved for 1000 generations and the probabilities for crossover and mutation were 90 % and 10 % respectively.

The Pareto front (5.3) was obtained in the optimization process (generation 1000). This graph clearly shows that both objectives (F1 and F2) are conflicting because improvements in one of them imply worsening the other. In only two chromosomes the F1 value is higher than 1, meaning that these chromosomes are penalized due to the excess of applied water and the CP factor is 1. In each generation two or three chromosomes with CP equal to 1 were selected. However, given that the possibilities for purchasing extra water are very limited, this option was penalized.

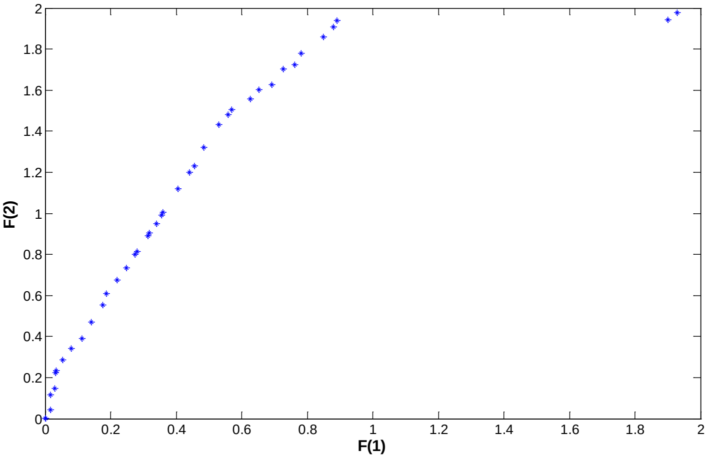
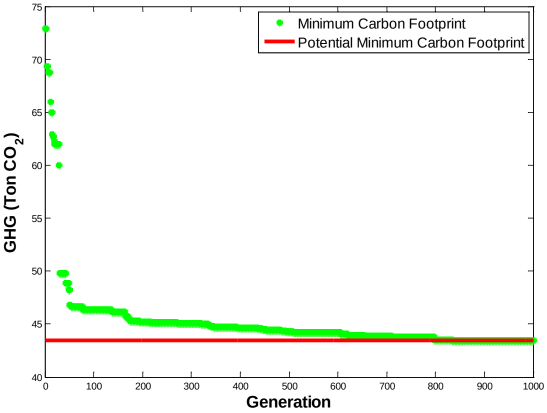
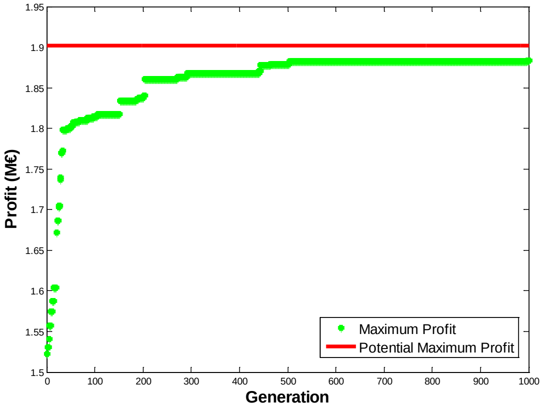


Figure 5. 3. *Pareto Front for generation 1000.*

GHG and profits were obtained from F1 and F2 for every chromosome. Also, the extreme theoretical values of both variables (profits and GHG) were obtained: the potential maximum profit (1.9 M€) was computed when the irrigation needs were satisfied (RIS = 1.2) and the potential minimum GHG (43.45 ton CO_2) when deficit irrigation (RIS = 0.2) was applied to all crops. 5.4 shows the evolution of the minimum values of CO_2 and maximum profits during 1000 generations. Both curves are significantly different. On the one hand, the carbon footprint (Figure 5.4.a) has a strong initial reduction and stabilizes after 800 generations. Finally, after 1000 generations, the GHG emissions are reduced with 43.45 ton CO_2 (potential minimum GHG). However, this solution is not the best for farmers, because it implies deficit irrigation and therefore the obtained profits are very limited (0.17 M€). On the other hand, profits are significantly increased in the first 50 generations and slightly improved in 175, 204, 464 and 504 when they were stabilized (Figure 5.4.b). The most profitable RIS pattern is 1.88 M€, but its associated carbon footprint is increased to 245.19 ton CO_2.



a)



b)

Figure 5. 4. *Objective evaluation during 1000 generations. a) Minimize GHG emissions, b) Maximize Profits*

Table 5.1 compares the extreme values obtained in generations 1 and 1000. The maximum GHG emissions reduction was of 40.37 % (but this solution leads to a reduction in the total profits of 61.15 %). The greatest increase in profit was of 23.71 % (increasing also the GHG emissions in 16.43 %). However, both objectives are conflicting and there is a wide range of solutions with different intermediate values, either more environmentally friendly from a GHG point of view or more profitable for farmers.

Table 5. 1.*Comparison of extreme the values in generations 1 and 1000.*

RIS PATTERNS	GEN 1		GEN 1000		ΔGHG (%)	ΔP (%)
	GHG (ton CO_2)	P (€)	GHG (ton CO_2)	P (€)		
Min GHG	72.86	0.44	43.45	0.17	-40.37	-61.15
Max P	210.58	1.52	245.19	1.88	16.43	23.71

5.3.2 Optimal RIS Patterns

Based on data provided by the irrigation district, the current RIS pattern was estimated for the six main crops: 0.92 (citrus trees), 0.68 (maize), 0.95 (cotton), 0 (wheat), 0.47 (fruit trees) and 0.32 (sunflower). Thus, the annual profit generated in this area was estimated to be 1.29 M€ and the carbon footprint was 182.65 ton CO_2.

Profits (P) and emissions (GHG) of the 40 RIS patterns obtained in the last generation are plotted in Figure 5.5.

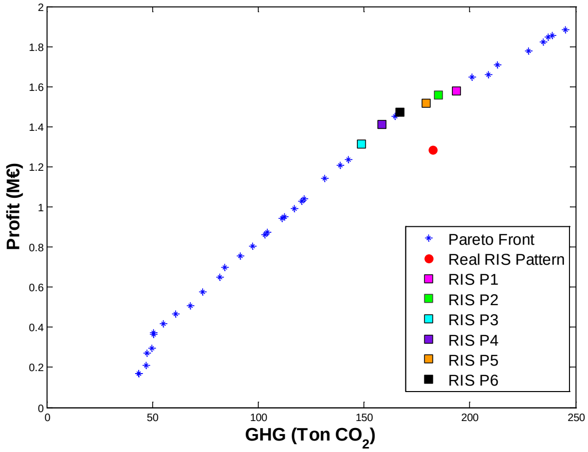


Figure 5. 5. *Profits vs GHG for 40 RIS patterns in the generation 1000, 6 selected RIS patterns and Real RIS pattern in BMD (Sector V).*

Also, the real RIS pattern of the irrigated area is added to the graph, clearly showing that the current management is quite far from those optimum patterns obtained from the Pareto front. In order to facilitate the interpretation of the results, 6 RIS patterns were selected from the 40 optimum patterns in the last generation (1000) and they are also shown in the Figure 5.5. The selection criteria are described below.

The ratio of profits and GHG emissions was calculated for all the solutions in generation 1000 (Figure 5.6).The median value of profits and GHG emissions ratio was obtained in the pattern called RIS P1, which ratio was 8152.95 € ton CO_2^{-1}, while the ratio for the real pattern was only 7045.82 € ton CO_2^{-1}.

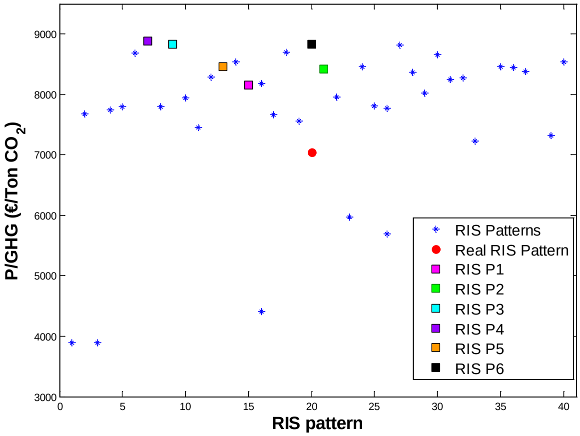


Figure 5. 6. *Ratio of profits and carbon footprint for 40 RIS patterns (6 selected RIS patterns) and real situation in BMD (Sector V).*

Table 5.2 shows the selected RIS patterns and includes their potential improvements compared to the current management (Real RIS).Thus, the RIS P1 pattern increases the actual profits in 22.72 % but also increases the GHG emissions in 6.06 %.

Also, two more RIS patterns were selected from those obtained in the last generation as potential improvements in the real RIS pattern but keeping constant one of the variables: RIS P2 with similar GHG emissions than the real RIS pattern, but increased profits in 21.10 %, and RIS P3, where profits are very similar to the real RIS pattern (2.01 %) but GHG emissions were significantly reduced with 18.63 %. Also, three more RIS patterns (RIS P4, RIS P5 and RIS P6) were selected because they represent significant improvements in both objectives simultaneously. In these three patterns, RIS P4, RIS P5 and RIS P6, GHG were reduced with 13.18 %, 1.71% and 8.56 % respectively while profits were increased in 9.55 %, 17.98 % and 14.56 % (Table 5.2).

Table 5. 2. *Analysis of profits and GHG emissions in the selected RIS patterns compared to the Real RIS pattern.*

	Citrus tree RIS	**Maize RIS**	**Cotton RIS**	**Wheat RIS**	**Fruit tree RIS**	**Sunflower RIS**	**GHG (ton CO_2)**	**P (M€)**	**ΔGHG (%)**	**ΔP (%)**
Real RIS pattern	0.92	0.88	0.95	0	0.47	0.32	182.65	1.29	-	-
RIS P1	1.14	0.63	0.45	0.43	1.19	0.46	193.72	1.58	6.06	22.72
RIS P2	1.2	0.42	0.58	0.27	1.2	0.37	185.06	1.56	1.56	21.1
RIS P3	1.06	0.2	0.27	0.2	1.2	0.23	148.63	1.31	-18.63	2.01
RIS P4	1.15	0.2	0.25	0.2	1.2	0.23	158.58	1.41	-13.18	9.55
RIS P5	1.2	0.36	0.4	0.3	1.12	0.66	179.52	1.52	-1.71	17.98
RIS P6	1.18	0.28	0.2	0.2	1.2	0.2	167.01	1.47	-8.56	14.56

In addition, Table 5.2 shows that all the RIS patterns satisfied the irrigation needs of citrus and fruit trees while wheat received severe water deficits. Maize and cotton received also severe water deficits in all patterns, even in RIS P1 and RIS P2 their RIS value is slightly higher than 40 %. These two patterns improve profits but have higher GHG emissions and then both RIS patterns are not recommended as irrigation patterns in this irrigation district. RIS P3, RIS P4, RIS P5 and RIS P6 have similar figures in terms of water use but RIS P5 gave more importance to sunflower with RIS value over 50 %. These four patterns improve the economic and environmental objectives together. However, RIS P3 and RIS P5 clearly improved one of the objectives only. RIS P3 reduces the carbon footprint while RIS P5 increases profits (17.98 %) with slightly reduces the GHG emissions (1.71 %). The suggested irrigation pattern for BMD (Sector V) will be among those with clear improvements in both objectives: in RIS P4 and RIS P6 GHG emissions were reduced with 13.18 % and 8.56 % respectively while profits were increased in 9.55 % and 14.56 %.

The volume of water applied to every crop for all the selected RIS patterns is summarized in Table 5.3. The total water deficits (difference between the theoretical irrigation needs and the water applied to crops) ranged between 10.84 % (RIS P1) and 31.59% (RIS P3). In RIS P1 and RIS P2 more water is applied than the real pattern while in RIS P3, RIS P4, RIS P5 and RIS P6 less water is applied. Among the best two patterns (RIS P4 and RIS P6), RIS P6 is considered the best option because, although the ratio P/GHG is slightly higher in RIS P4 (8890.62 72 € ton^{-1} CO_2) than in RIS P6 (8827.72 € ton^{-1} CO_2), the water deficit is smaller in RIS P6 (37.87 % versus 38.55 %).

In the recommended irrigation pattern (RIS P6) the water requirements of citrus and fruit trees were fully satisfied but other crops received much less water than the theoretical requirements. This is due to their low market prices in the irrigation season 2010 which reduced their profitability. Thus, oscillations in the market prices from one year to another may have an important impact in the model’s outputs. However, all the selected patterns coincided in applying the full water requirements to citrus and fruit trees because they offer the best balance between applied water and profitability.

Table 5. 3. *Applied water and water deficits in all the selected RIS patterns and the real RIS in BMD (Sector V).*

	Citrus tree	Maize	Cotton	heat	Fruit tree	Sunflower	Total deficit water (%)
Area (ha)	553.2	349.6	58.09	87.82	26.08	23.95	-
Theoretical IN (mm)	649.5	651.4	633.3	365.6	849.28	501.4	-
Real RIS pattern (mm)	597.5	573.2	601.6	0	399.16	160.5	15.93
RIS P1 (mm)	740.4	410.4	285	157.2	1010.6	230.7	10.84
RIS P2 (mm)	779.4	273.6	367.3	98.7	1019.1	185.5	14.82
RIS P3 (mm)	688.5	130.3	171	73.11	1019.1	115.3	31.59
RIS P4 (mm)	746.9	130.3	158.3	73.11	1019.1	115.3	27.01
RIS P5 (mm)	779.4	234.5	253.3	109.7	951.19	331	17.37
RIS P6 (mm)	766.4	182.4	126.7	73.11	1019.1	100.3	23.13

5.3.3 Crop production costs versus profitability

The crop production costs were estimated for every single crop (they are summarized in Table 5.4). The average MOM costs (which include fixed costs associated with the water supply such as water authority, administration and amortization costs) were estimated to be 293 € ha^{-1} whereas the cropping costs varied for every crop. While wheat and sunflower had the lowest cropping costs, they were higher for citrus trees, maize, cotton and fruit trees. In these crops, machinery and harvesting represented between 40 % and 70 % of the fixed costs, followed by pesticides and fertilizers (20-33 %). Variable costs include the energy consumption in the water supply that is linked to the volume of pumped water.

Table 5. 4. *Fixed costs of the six main crops in BMD.*

			Citrus tree	Maize	Cotton	Wheat	Fruit tree	Sunflower
Fixed Costs (€/ha)	MOM Costs		293					
	Planting	Crop Costs	-	185.66	115.85	56.03	-	39.42
	Pesticides and Fertilizers		400.8	631.92	656.11	161.2	532.7	78.04
	Pruning		180	-	-	-	180	-
	Machinery and harvesting		1408	839.93	1044.5	187.3	836.49	183.99
Total (€/ha)			1989	1657.5	1816.5	404.5	1549.2	301.45

The profitability of the six selected patterns and the real RIS pattern are aggregated at Sector V (BMD) level and summarized in Table 5.5. Fixed costs in the current cropping pattern in BMD (Sector V) were estimated to be 2.19 M€ while the total costs in the six selected patterns were higher than in the real pattern (2.28 M€). The total costs varied between 2.26 M€ (RIS P3) and 2.28 M€ (RIS P1) which was the most productive pattern with incomes of 3.86 M€.

Table 5. 5. *Evaluation of the potential profits in the selected RIS patterns and the real RIS in BMD (Sector V).*

				Real RIS pattern	RIS P1	RIS P2	RIS P3	RIS P4	RIS P5	RIS P6
COSTS (M€)	**Fixed**	**MOM Costs**		0.32						
		Cropping Costs	**Planting**	0.08						
			Pesticides and Fertilizers	0.51						
			Pruning	0.1						
			Machinery and harvesting	1.18						
	Variable	**Energy Cost**		0.089	0.092	0.088	0.071	0.075	0.085	0.079
INCOME (M€)		**APV**		3.14	3.44	3.41	3.15	3.25	3.37	3.32
		CS		0.42						
Profit (M€)				1.29	1.58	1.56	1.31	1.41	1.52	1.47

RIS P1 and RIS P2 have higher variable costs than the real RIS pattern (0.087 M€) due to the increased volume of supplied water. RIS P3, P4, P5 and P6 patterns applied a smaller amount of water and had less energy cost than the real RIS pattern.

Subsidies are linked to the crop type and the irrigated area. Cotton was the most subsidized (1545 € ha^{-1}) while fruit trees received less than 200 € ha^{-1}. However, APV depends on the volume of water applied and varies with every RIS pattern. All RIS patterns had higher APV than the real RIS pattern (3.14 M€). All the selected patterns improve the actual profitability.

5.4 Conclusion

In this study, a methodology to optimize the water use, carbon footprint and economic profits in pressurized irrigation systems has been developed. The carbon footprint of the pumping station depends only on the energy required in the water supply. When less water is applied, the energy consumption and the carbon footprint are reduced. However, crop yields vary depending on the applied depths. Therefore, the optimum balance between economical (maximum profits) and environmental (minimum GHG emissions) objectives is extremely complex.

The methodology has been applied to the BMD irrigation District (Sector V), showing a potential reduction in the carbon footprint of up to 76.21 % (but with a reduction in profits of 86.84 %) or an increment in profits of 46.33 % (increasing the carbon footprint in 34.24 %). However, there are intermediate solutions which offer improvements both in economic and environmental aspects. The selected irrigation pattern for the area (RIS P6) increased the profits in 14.56 % and reduced the carbon footprint in 8.56 %. Thus, economic and environmental objectives could be achieved simultaneously adopting alternative management measures that could reduce the energy demand and maximize profits. RIS 6 is an irrigation pattern which fully satisfies the theoretical irrigation needs of fruit and citrus trees while applies deficit irrigation to other crops. These outputs suggest that new models where cropping patterns and water allocation are optimized may improve the current results.

In this work, only the environmental impact of the energy consumption in the pumping station has been considered. However, there are other aspects such as carbon fixation by crops, conservation agriculture, fertilizers or machinery that may contribute to reduce GHG emissions and improve the sustainability of the irrigation sector too. Further studies are needed to evaluate the environmental impact of these activities.

This model has been simplified considering simultaneous demand. However, this is the worst situation in terms of pressure requirements. The adoption of a dynamic pressure head model, that adjusts the pressure in the pumping station to the current location of the water demand, which is linked to the simultaneity of open hydrants, would reduce the energy consumption. Thus, the current management represents the most extreme situation while other options would improve the results, reducing the pressure head and therefore energy demand and carbon footprint, and increase the final farmer´s profits.

This methodology could be applied in other irrigation districts, regardless of irrigated area and crops, to determine the annual optimal irrigation pattern.

5.5 Acknowledgements

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Exploring the role of energy in pressurized irrigation networks

6. Exploring the role of solar energy in pressurized irrigation networks.

This chapter has been published entirely in the journal "Spanish Journal of Agricultural Research": Carrillo Cobo, M.T., Camacho Poyato, E., Montesinos, P., Rodríguez Díaz, J.A. Aceptado para su publicación.

Abstract. The high energy requirements and the rising costs highlight the need to reduce the energy dependence of the irrigation sector. In addition, the renewable energy sources are starting to be considered as an alternative to reduce energy costs with smaller environmental impacts. In this work, a new methodology, that combines sectoring as energy saving measure and solar energy, is developed. Thus, it reduces the energy requirements and the dependence on conventional energy resources. This methodology is applied to the irrigation district of Bembézar Margen Izquierda (BMI). The results show that organizing the network in two irrigation sectors, annual potential energy savings of 30.8 % are achieved. Then, a 2.15 MW photovoltaic (PV) would supply energy to the sector with higher energy consumption. However, conventional energy would be required (with an annual cost of 33.6 € ha^{-1}) when solar energy is not available or it is not enough to supply the demanded flows. Both measures together would reduce the energy costs in 71.7 % and the greenhouse gas (GHG) emissions in 70.5 %. The total investment would be 2.8 M€ but with a payback period of 8 years.

Additional keywords: water management, renewable energy, solar PV, carbon footprint

6.1 Introduction

In the interest of sustainable development and the minimization of climate change impacts, national and international policies are prioritizing the improvement in the use of the natural resources. Water is an essential and limiting resource for private use, industry and agriculture that requires large amounts of energy for its distribution (e.g. pumping) as well as to reach the quality requirements of the different users (e.g. desalination, purification, etc.). This fact highlights the need to improve efficiency in the water-energy nexus, essential for the economic, social and environmental development of any sector. In recent years, irrigation agriculture has increased energy demands and, the high energy tariffs, which follow an upward trend, have created an untenable situation for the sector (Corominas, 2009, Jackson *et al.*, 2010). In the Southeast of Spain, Soto - García *et al.* (2013) determined that the energy consumption in the irrigation district and on-farm irrigation systems accounted between 18 % and 29 % of the total annual energy consumed in the water supply. However, the water supply at basin level (from the water source to the pumping station within the irrigation district) represents the highest energy consumption which ranges, according to water sources, between 0.06 kWh m^{-3} (surface water) to 0.98 kWh m^{-3} (external water transfers).

Several studies have been developed to reduce the energy consumption of the irrigated areas and to improve the efficiency of water and energy. Thus, energy efficiency criteria have been incorporated into the design of networks layout and pumping stations (Lamaddalena & Sagardoy, 2000; Pulido-Calvo *et al.*, 2003; Moreno *et al.*, 2007, 2009; Daccache *et al.*, 2010). Other studies have developed strategies for improving management, reducing the energy requirements of the irrigation networks and therefore reducing energy costs. Measures such as the organization of irrigation turns, critical points control or improvements in the efficiency of the pumping station, can reduce the energy requirements without major investment (Rodríguez Díaz *et al.*, 2009; Moreno *et al.*, 2009, 2010; Jiménez-Bello *et al.*, 2010; Navarro-Navajas *et al.*, 2012; Rodríguez-Díaz *et al.*, 2012; Fernández-García *et al.*, 2013).

Simultaneously, in recent years there is an increasing awareness among scientists about the emission of greenhouse gas (GHG) that contribute to the global warming effect. Thus, many studies have incorporated new environmental criteria, aimed at reducing CO_2 emissions, to the network's management practices. In urban water distribution systems, these measures have been developed with the aim of reducing costs, minimizing emissions in the pumping station (Dandy *et al*., 2006; Wu *et al*., 2010a, 2010b; Sahely & Kennedy, 2007; Ramos *et al*., 2011).

In Spain, electricity is produced mainly from fossil fuels and minerals (66 %) (REE, 2011). These are non-renewable resources which use produce significant environmental impacts. By contrast, the use of renewable energy resources reduces the negative effects on the environment and enables sustainable development in different productive sectors.

The incorporation of renewable energy in water distribution systems is starting to be considered as a new alternative, especially in urban supply systems. For example, turbines for harnessing excess energy when there are large differences of elevation are starting to be installed in water supply systems (Ramos *et al*., 2007). Other alternative is the installation of hybrid systems that establish the optimal combination of several energy sources such as solar, wind and hydro (Moura & Almeida, 2009; Viera & Ramos, 2008, 2009; Ramos *et al*., 2011, Baños *et al*., 2011). These measures allow reducing energy costs and contributing to the sustainable management of water distribution systems.

In the agricultural sector is increasingly common the implementation of renewable energy resources (Vick & Almas, 2011), such as the use of solar energy in the control of greenhouses (Abdel-Ghany & Al-Helal, 2011; Ahmed, 2011) or especially in pumping systems for irrigation (Jafar M.A. 2000; Ramaza-Senol, 2012). However, these energy resources are only being applied in small farms with low power requirements (not exceeding 10 kW).

In this context, the aim of this work is to analyze the potential benefits, economic and environmental, of the joint application of energy saving measures and renewable energy in one irrigation district with high power requirements.

6.2 Material and Methods

6.2.1. Study area

The Bembézar Margen Izquierda (BMI) irrigation district is located in the Guadalquivir river basin (Córdoba, Southern Spain) (Figure 6.1).

Figure 6. 1. *Location of the BMI irrigation district*

The climate in the region is predominantly Mediterranean, with rainfall concentrated mainly in autumn and spring, and dry spells in summer. The average annual rainfall in the area is 540 mm and the average temperature is 17.9 ºC. Climate data was collected from a nearest weather station (Hornachuelos) using data from the Agroclimatic Information Network of Andalusia. The solar radiation profile for BMI irrigation district (obtained using a pyranometer R01-Skye) is shown in Figure 6.2.

The daily average irradiation on the photovoltaic (PV) array is 5.63 kWh $m^{-2}day^{-1}$. The daily average during from May to August is the 8.34 kWh $m^{-2}day^{-1}$with a peak value of 8.94 kWh $m^{-2}day^{-1}$. The irrigation system operates between March and October (daily average irradiation of 6.94 kWh $m^{-2}day^{-1}$). In perennial and summer crops, which are common in BMI, solar radiation and evapotranspiration have similar time distribution curves, so the peak of solar energy supply coincides with the maximum irrigation requirements.

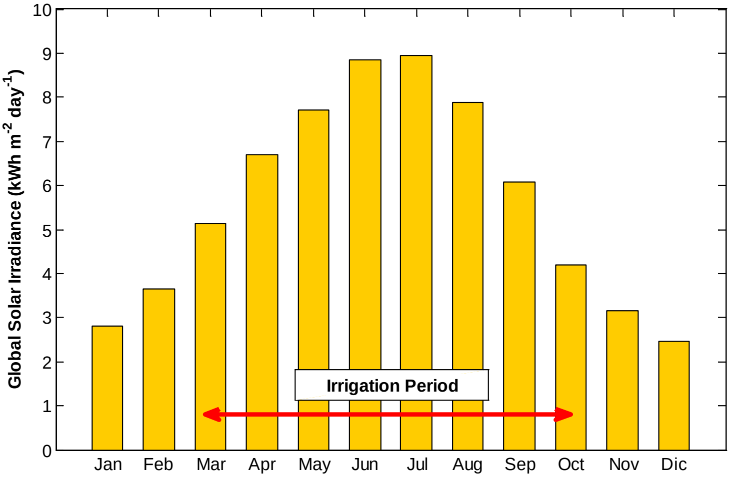

Figure 6. 2. *Global solar irradiance at selected BMI irrigation district.*

BMI has an irrigated area of 3999 ha with a great diversity of crops, being the most representative citruses, maize, olive trees and wheat. The irrigation water is diverted from the Bembézar dam to the pumping station. The pressurized network supplies water to 28 hydrants with a total length of 31.6 km. It was designed to supply 1.2 L s^{-1} ha^{-1} on-demand.

The pumping station has 4 main pumps of 800 kW and 3 auxiliary pumps of 315 kW, ensuring a service pressure of 30 m at hydrant level. The network and the pumping stations are monitored by a remote telemetry system which provides pumped flows and pressure data in real-time.

6.2.2. Energy saving scenarios

Four management scenarios were proposed for the analysis of the energy consumption, CO_2 emissions and the energy costs in BMI. The first scenario represented the current operation of the studied irrigation district. The other three presented different management strategies defined to reduce the annual energy dependence and to analyze the potential role of solar energy as alternative energy resources:

-Scenario 1. It represented the current management of the pressurized network. The network was organized on-demand so all the hydrants were enabled to irrigated 24 h per day. The current pressure head, at the pumping station, is fixed to 52 m to ensure a minimum pressure head of 30 m at hydrant level.

-Scenario 2. The irrigated area was organized into two independent sectors according to two topological dimensionless coordinates (Carrillo-Cobo et al., 2011). The network was managed under semi-arranged demand where farmers were organized in two irrigation turns of 12 hours per day. The required pressure head at the pumping station was different for each sector.

-Scenario 3. A PV system was designed to produce the annual energy required by the sector with the lowest energy requirements in Scenario 2. Thus, this scenario combines sectoring (energy saving strategy) and the use of renewable energy resources.

-Scenario 4. This scenario is similar to Scenario 3 but the PV system was designed to supply energy to the sector with the highest energy requirements in Scenario 2.

6.2.3. Sectoring operation to reduce energy requirements

Nowadays, most of the pressurized irrigation networks are organized on-demand. To reduce their energy demand, sectoring strategies can be applied. The WEBSO (Water and Energy Based Sectoring Operation) algorithm (Carrillo-Cobo *et al.*, 2011) was developed to reduce the monthly energy consumption of on-demand pressurized irrigation networks using a sectoring strategy based on the organization of farmers in irrigation turns according to their energy demand.

The network was organized in homogeneous groups according to the following topological dimensionless coordinates. Then cluster analysis techniques (K-means algorithm) (Mc Queen, 1967) were used to group hydrants into statistically homogeneous clusters.

$$z_i^* = \frac{z_{ps}}{z_i} \qquad [6.1]$$

$$l_i^* = \frac{l_i}{l_{max}} \quad [6.2]$$

Being z_i*, the dimensionless hydrant elevation, z_{ps} is the pumping station elevation and z_i hydrant elevation. The dimensionless coordinate l_i* is the relation between the distances from the pumping station to hydrant i along the distribution network (l_i) and the furthest hydrant (l_{max}).

According to the previous sectoring strategy, the WEBSO algorithm was applied to compute the energy requirements (Figure 6.3). Initially, the theoretical daily average irrigation needs per month and hydrant (mm) were estimated as described in FAO 56 (Allen *et al.*, 1998) using the CROPWAT computer model (Clarke, 1998). Then they were transformed into daily irrigation needs, IN_{im} (L ha^{-1} day^{-1}). From this information, the irrigation time in hours per hydrant and month, tim, was calculated as follows:

$$t_{im} = \frac{1}{3600} \cdot \frac{IN_{im}}{q_{max}} \quad [6.3]$$

Where q_{max} is the network's design flow (1.2 L $s^{-1}ha^{-1}$).

The WEBSO algorithm considered the local irrigation practices adjusting theoretical irrigation needs to the actual water use by the performance indicator Annual Relative Irrigation Supply (RIS). RIS is the ratio of the total annual volume of water diverted or pumped for irrigation and total theoretical irrigation needs required by the crops (Rodríguez Díaz *et al.* 2008) and was calculated per irrigation season. In the study, with high conveyance and application efficiency, the RIS was estimated in 1, after an on-field evaluation using real data from the pumping station

Then, the algorithm assigned an open hydrant probability per month according Clément (1966):

$$p_{imj} = \frac{t_{im}}{t_{dj}} \quad [6.4]$$

Where t_{dj} is the time available to irrigate according to the management strategy: 24 h when the network operates on demand (scenario 1) and 12 h for the operating sectors (scenarios 2, 3 and 4).

Then, an open hydrant probability matrix, OHPM, with the probabilities per hydrant, month and operating sectors was created. Per each month (m), management scenario (j) and operating sector (l), random patterns of open/close hydrant were analyzed with *k* Montecarlo iterations.

In each iteration, a random number based on the [0,1] uniform distribution, R_{imjl}, was generated for every hydrant to define if it was open or close. When p_{imjl} was greater or equal to R_{imjl}, the hydrant was assumed to be open and the base demand, q_i, was calculated by:

$$q_i = q_{max} \cdot S_i \qquad [6.5]$$

Where S_i is the irrigation area associated to each hydrant. In the opposite situation, the hydrant was assumed to be closed and its base demand was set to zero.

The hydraulic simulator EPANET (Rossman, 2000) was used to evaluate each network loading condition (open/close hydrant distribution). The hydraulic simulator can be run from the WEBSO code (in visual basic) by its dynamic link library.

The lowest pressure head, H_{pmjl}, needed at the pumping station to supply water to all open hydrant ensuring that the most pressure demanding hydrant receives a minimum pressure of 30 m, was calculated. Initially, the network was simulated for a maximum theoretical pressure head, H_{max}, and the pressure in the most restrictive hydrant (the hydrant with the lowest pressure) was determined (H_j). If this pressure is higher than the required 30 m, the excess pressure (α) is determined (H_j minus the required 30 m). After that, the pressure head at the pumping station was reduced in α m, obtaining H_{pmjl}. The WEBSO algorithm considered this minimum pressure, H_{pmjl}, as the dynamic pressure head defined by Rodríguez Díaz *et al.* (2009).

The original WEBSO algorithm has been modified fixing the pressure head in each sector (H_{jl}). This value is the maximum value of the all minimum pressure head, H_{pmjl}, obtained in each *k* simulation and month simulated for each operating sector, was considered the fixed pressure head for that sector.

Then, the power requirements, Power_{mjl} (kW) and the energy demand (kWh day^{-1}) at the pumping station were calculated according to the following equations:

$$\text{Power}_{mjl} = \frac{\gamma \cdot F_{mjl} \cdot H_{jl}}{\eta} \tag{6.6}$$

$$E_{mjl} = \frac{\text{Power}_{mjl}}{1000} \cdot t_{aj} \tag{6.7}$$

where γ is the water specific weight (9800 N m^{-3}) an η the pumping system efficiency (in this work 0.75).

The process was repeated *k* times for every operating sector and month of the irrigation season (from March to October). The outputs (pumped flow, fixed pressure head for the sector, power and energy) were all recorded. The *k* values of power and energy were averaged to obtain the averaged energy consumption per sector and month. Finally, the annual energy requirements for the four scenarios were obtained.

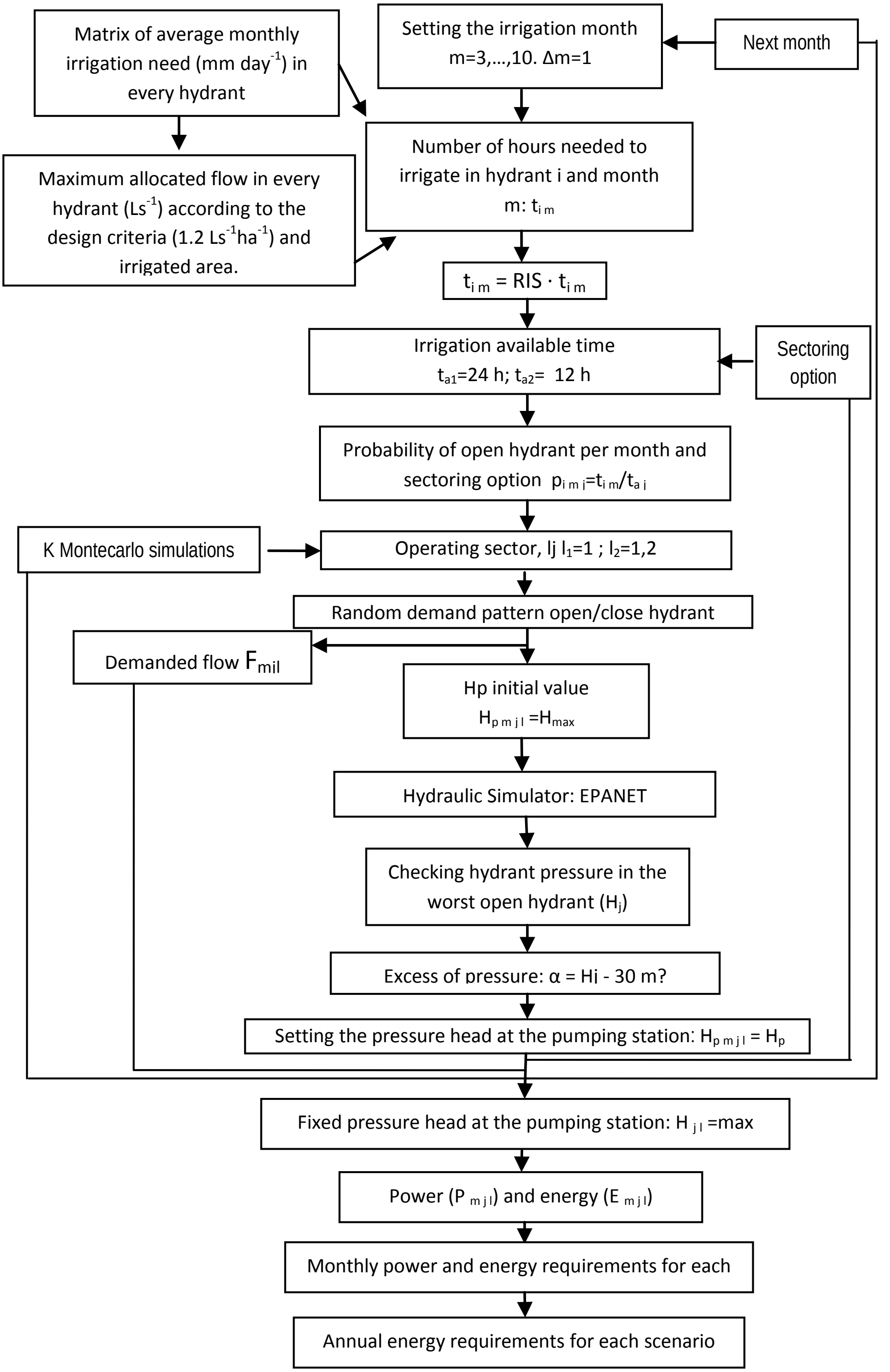

Figure 6. 3. *Schematic representation of modified WEBSO algorithm.*

6.2.4. Solar PV array setups (solar irrigation systems)

Due to the climatic conditions the Solar PV energy technology was selected for this study. The PV power source should be connected to the pump motor (AC) of the pumping station with a DC/AC converter which includes a maximum power point tracker (MPPT) for the proper operation of pumps. These systems usually do not include any battery backup.

As commented above, the irrigation season occurs in months with high solar radiation. However, the smaller production in cloudy days and morning/evening or different seasons may be considered as drawbacks of the system. Therefore, an Intelligent Power System (IPS) should be incorporated. IPS ensures the energy supply to the pumping station even when the solar radiation is insufficient since it allows the connection to the electrical grid. To compute the electric power of the PV system, the following equation was used (UNE, 1998):

$$P = \frac{E}{\frac{G}{G^{*}} \cdot \eta_{pv}} \tag{6.8}$$

Where P is the electric power of the PV array (kW), E is the daily energy demanded by the pumping station in the peak demand month, G the global irradiation on the PV array plane (kWh m^{-2}) for the peak energy demand day, G^{*} the reference irradiation (1 kW m^{-2}) and η_{pv} the PV array efficiency under the operation conditions (80 %). The PV system was dimensioned based on the power requirements obtained from the WEBSO algorithm.

6.2.5. Economic evaluation

In the economic analysis, both the annualized costs of the PV infrastructure and operation costs were considered. The infrastructure cost of the PV system includes the module, structure, electricity works, converter, civil works, control system and processing costs. The operation costs include the electricity consumption in the pumping system and the maintenance of the PV system. The annual energy cost of the corresponding year, for each scenario, was computed by multiplying the daily energy consumption (kWh) by the electricity tariff (€ kWh^{-1}) according to the operation time of the whole network or the sectors. Then, two energy price periods were considered: nocturnal (from 24 h to 8 h) and diurnal (from 9 h to 23 h).

The Internal Rate of Return (IRR) was used as an indicator of the project profitability. IRR is defined as the interest rate at which present value of the cash flows of a project are zero. Higher IRR than the market interest rate means a profitable investment. A discounted cash flow analysis will be performed in order to determine Net Present Value (NPV) of the proposed solar PV array installations. NPV provides an indication of the overall net benefit or loss of the irrigation district when the installation of a solar PV array is considered. Negative NPV indicates that the proposed solar PV systems are not financially viable. The payback period was also used in the economical evaluations. All these rates were calculated for scenarios 3 and 4. A lifetime of 25 years for the PV system and interest rate of 3 % was considered.

6.2.6. Environmental aspects

The carbon footprint is the total amount of GHG produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide (CO_2). The energy consumed in the pumping station generates significant GHG emissions (kg CO_2) which also contribute to accelerate the climate change process. The GHG emissions in the pumping station were calculated by the following equation:

$$\mathrm{GHG} = \mathrm{E_T} \cdot \mathrm{EF} \qquad [6.9]$$

where ET is the annual energy consumption in the pumping station (kWh) and EF the emissions conversion factor: 0.166 kg CO_2 kWh^{-1} (WWF, 2010).

6.3 Results

6.3.1. Evaluation of potential energy savings (Scenario 1 vs. Scenarios 2, 3 and 4)

Homogeneous groups of hydrants were created according to the coordinates system defined by l^* and z^*. Two clusters have been defined using the K-means method in BMI: sector 1 (S1) has 7 hydrants and sector 2 (S2) has 21 hydrants. BMI coordinate z^* varied from 0.9 to 1.16, being z_{ps} =

93 m and z_i varying between 58 m and 103 m. Only two hydrants were over the pumping station elevation (z^*<1). S1 grouped hydrants with z_i in the range of 84 m and 103 m, while S2 elevations are from 58 m to 79 m. BMI coordinate l^* varied from 0 (309 m) to 1 (13,981 m).In consequence, the network was operated in two irrigation turns with 12 hours available for irrigation in each of them.

The WEBSO algorithm was applied to the BMI irrigation district according to the sectors previously established. The network was simulated for the whole irrigation season (March to October) for on-demand irrigation (scenario 1) and two sectors (scenario 2, 3 and 4).

The *k* number of monthly Montecarlo simulations (8 months) were 2000 for scenario 1 and 4000 for scenarios 2, 3 and 4 (2000 for each sector). Thus, the total number of simulations was 48000.

Flow-Pressure head curves were obtained from WEBSO. Figure 6.4 shows the Flow-Pressure head curve for scenario 1. In this case, the maximum required pressure head in the pumping station was approximately 48 m (this optimum pressure is 4 m below the current management in the network).

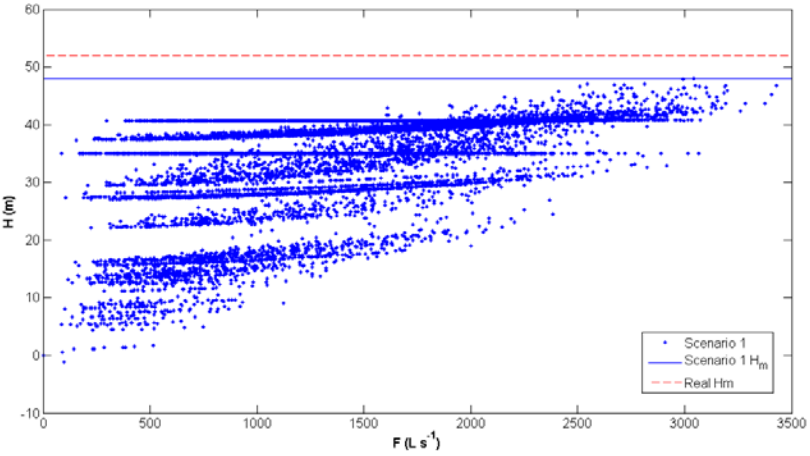

Figure 6. 4. *Flow-Pressure head curve for in Scenario1, the optimum pressure head in Scenario 1 (Scenario 1 H_m) and the current pressure head in BMI (real H_m).*

Similar curves were obtained for the two sectors of scenario 2, 3 and 4 (Figure 6.5). When the network was operated in sectors the pressure head requirements were significantly reduced. In that case, the maximum pressure head in S1 was 41 m while S2 only needed 34 m. These optimum pressures (48 m, 41 m and 34 m) were used in the energy demand analysis. These reductions in pressure head may lead to lower power and energy requirements and hence to lower GHG emissions.

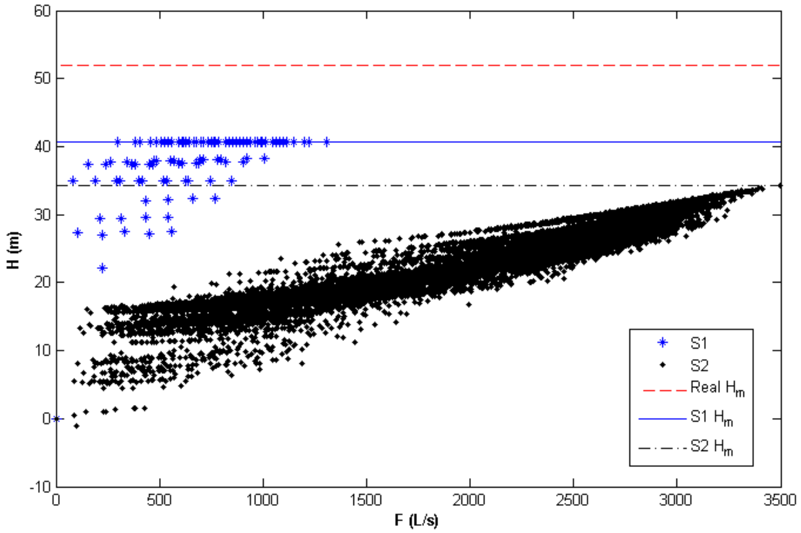

Figure 6. 5. *Flow- Pressure head curves for two sectors (S1 and S2), the optimum pressure head in each sector (S1 H_m and S2 H_m) and the current pressure head in BMI (real H_m).*

The daily energy requirements in every month for on-demand operation (scenario 1) and sectoring operation (scenarios 2, 3 and 4) are shown in Table 6.1. The average energy savings when the network is operated in sectors were 30.8 %, this value is practically constant for all months.

The total annual energy requirements in scenario 1 were 4319 MWh year^{-1} and in scenarios 2, 3 and 4 were 2985 MWh year^{-1}. When sectoring, S1 demanded 31 % (918 MWh year^{-1}) of the annual energy requirements while S2 demanded 67 % (2067 MWh year^{-1}).

Table 6. 1. *Average daily energy requirements (kWh day^{-1}) and potential energy savings (%) for on-demand (Scenario 1) and sectoring (Scenarios 2, 3 and 4)*

		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Scenario 1		1511	13458	24778	31789	30868	25152	12139	1478
Scenario 2,3 and 4	S1	340	2894	5324	6751	6556	5245	2586	311
	S2	708	6515	11966	15202	14798	11900	5751	726
	S1+S2	1047 (30.7%)	9409 (30.1%)	17291 (30.2%)	21950 (30.9%)	21354 (30.8%)	17145 (31.8%)	8337 (31.3%)	1037 (29.8%)

6.3.2. Optimum PV system (Scenario 3 *vs*. Scenario 4)

In the previous analysis, the total energy requirements were reduced when the network was operated in two irrigation turns (two sectors). Now, the energy supply options with a PV system are explored.

Scenario 3 evaluates the feasibility of installing a PV system to supply the annual energy requirements in S1 (918 MWh year^{-1}). Thus, S1 would irrigate for 12 hours during the day supplied by solar energy and S2 would irrigate for 12 hours at night, consuming conventional energy resources but with cheaper electrical energy rates. Contrarily, scenario 4 was sized to supply water with solar energy in S2 (2067 MWh year^{-1}) and S1 would irrigate at night.

The daily energy requirements in the more restrictive month (June) were considered for sizing the PV array. Scenario 3 was sized to provide the daily energy demanded by the S1 (6751.4 kWh day^{-1}) and scenario 4 for the daily energy demanded by S2 (15201.9 kWh day^{-1}). The global irradiation in June is of 8.8 kWh m^{-2} day^{-1}. In consequence, the PV generator power in the scenario 3 was sized to supply 1MW and 2.15 MW for scenario 4.

The energy generated by the PV system during an average day in June (peak demand) and March (off-peak demand) in the scenarios 3 and 4 is illustrated in Figure 6.6. In months with high energy demand, during sunrises and sunsets the PV array do not produce enough energy to meet the energy requirements as highlighted by the yellow shaded area in Figure 6.5.

Thus, during these hours, external energy from the electricity supplier must be purchased.

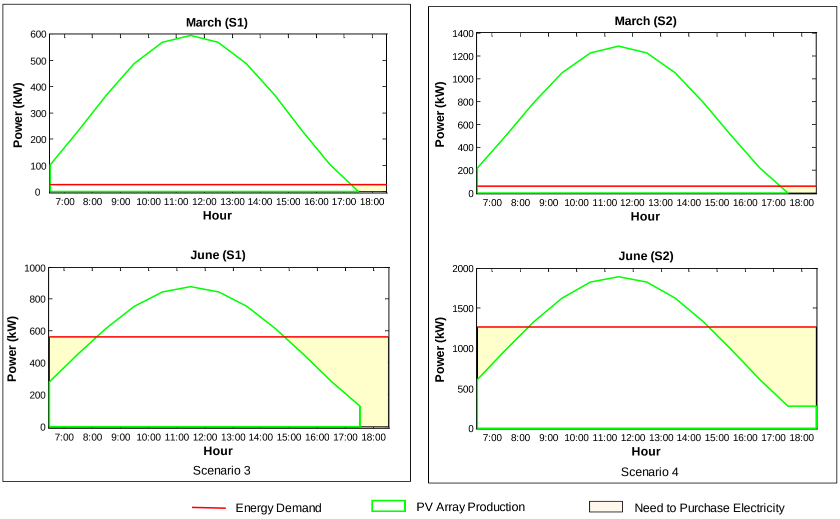

Figure 6. 6. *Average hourly PV array energy production, pumping energy requirements (S1 and S2) and external energy requirements for 1MW (Scenario 3) and2.15 MW (Scenario 4) solar PV systems*

Table 6.2 shows the balance between the annual energy demand, the PV production and purchased from the electricity supplier. The energy produced by the 1 MW PV system in scenario 3 is used to irrigate S1. However, during a few hours, additional energy was needed but only 16 % of the annual energy requirements. Therefore, the total energy that needs to be purchased from the energy supplier in scenario 3 is 2215 MWh, 74 % of the total energy demand.

The 2.15 MW PV system in scenario 4 produces 83 % of the annual energy demanded by S2. The total purchased energy in this scenario 4 is 1272 MWh (42.6 % of the total annual energy demand).

Table 6. 2. *Annual energy balance*

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Energy demand (MWh year^{-1})				
Total	4319	2985	2985	2985
S1	-	918	918	918
S2	-	2067	2067	2067
PV array Production (MWh)				
Total	-	-	1648	3543
Purchased energy (MWh) (%)				
Total	4319 (100%)	2985 (100%)	2215 (74.2%)	1272 (42.6%)
S1	-	918 (100%)	148 (16%)	918 (100%)
S2	-	2067 (100%)	2067 (100%)	354 (17%)

6.3.3. Economic viability

In BMI, the operation costs mainly result from the electricity consumption in the pumping station. The impacts of the implementation of energy saving measures were quantified.

Table 6.3 shows the energy costs for the 4 scenarios. In scenarios 1 and 2, 100 % of the energy requirements had to be purchased. Assuming a unit nocturnal energy price of 0.09€ kWh^{-1} (from 24 h to 8 h) and an average diurnal energy price of 0.12€ kWh^{-1}(from 9 h to 23 h), scenario 2 reduced the annual energy bill in 330668 €, 30.4 % less than in scenario 1 (475085 €). This savings can be achieved without any new investment.

Total energy costs in scenario 3 and scenario 4 were 224440 € and 134258 €, 52.8 % and 71.7 % respectively smaller than scenario 1. However, scenarios 3 and 4, due to the installation of the PV system require important investments of 1.3 M€ and 2.8 M€. The life cycle cost was used to evaluate the financial viability of the system. The unit cost of installed power (W) was 1.3 € W^{-1}. The maintenance and insurance costs were estimated in 25 € W^{-1}.

Table 6. 3. *Energy cost analysis*

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Energy cost (€)				
Total	475085.1	330667.9	224440.4	134257.9
S1		82617.3	17731.6	91797.0
S2		248050.6	206708.8	42461.0
Energy cost per area (€ ha^{-1})	118.8	82.7	56.1	33.6
Economic saving (%)	0	30.4	52.8	71.7
Solar PV power(MW)	-	-	1	2.15
Investment (M€)	-	-	1.30	2.80
Financial viability				
NPV (8%) (€)			288425	1276000
IRR (%)	-	-	9.1	12.2
Payback (years)			10	8

The results (Table 6.3) show that scenario 4 is the best option. The NPV of scenario 4 was 1276000 € while in scenario 3 was 288425 €. Both had IRR greater than the interest rate (8 %) but the payback value for scenario 4 is 8 years while in scenario 3 it is 10. Then, in scenario 4, the PV system investment is amortized in the 9thyear and from this year to the PV system lifetime (25 years) the economic savings in electricity bills will contribute to increase farmer´s profits.

6.3.4. Environmental impacts

The annual carbon footprint of each scenario was quantified by the energy provided by the energy supplier. When irrigation turns are adopted, the energy consumption and CO_2 equivalent emissions are reduced. The carbon footprint in scenario 1 is 716.9 CO_2 tons while in scenario 2 it is only 495.5 CO_2 tons; it implies a reduction of 30.9 %, similar to the energy reduction achieved after sectoring.

The combination of energy saving measures and the PV system for providing renewable energy offers significant reductions in CO_2 equivalent emissions. Scenario 3 has a carbon footprint of 367.7 tons CO_2 and scenario 4 has 211.1 tons CO_2. Scenario 4 is the best option from both the economic and environmental point of view, reducing the GHG emissions a 70.5 % the scenario 1.

6.4 Discussions

In Spain, the irrigated areas with pressurized irrigation networks are usually organized on-demand and usually require lots of energy for their operation. As energy consumption in the pumping stations and GHG emissions are directly linked, the water supply generates significant GHG emissions. Thus, all the measures that reduce the energy demand would contribute to the reduction of the greenhouse effect. From a farmer's perspective, the continued increases in electric tariffs encourage the necessity of adopting energy saving measures that would reduce the total energy costs.

Consequently, in this paper, two strategies for a more sustainable management of pressurized irrigation networks (sectoring and renewable resources) were combined considering economic and environmental criteria. The first strategy to reduce the dependence on fossil resources (sectoring) is based on the organization of the network in irrigation turns. Although sectoring reduces the flexibility, it may lead to energy savings of 30.8 % in BMI. These findings are consistent with those found by Rodríguez Díaz *et al.* (2009) and Carrillo Cobo *et al*. (2011) in other irrigation districts but in the same region.

Renewable energy resources have several advantages such as the reduction in dependence on fossil fuel resources and the reduction in GHG emissions to the atmosphere. Previous works have evaluated the technical and economic viability of PV systems in irrigation supply but only for small pumping stations (less than 10 kW). In this work, a PV system for pumping water was designed to supply energy to a high power requirement pumping station. Results showed that, although in cloudy days and morning/evening periods it should be supplemented with energy from conventional resources, it is possible to reduce both energy demand and its cost.

Scenario 4 (PV system of 2.15 MW) was the best of the four studied scenarios. The PV system produces the 83 % of the annual energy demanded by S2 and the total purchasing needs from the energy supplier were 1271811 kWh (42,6 % of the annual energy demand). Thus, it reduced the GHG emissions in 70.5 % compared to scenario 1. The total investment was 2.8 M€ but with a payback of 8 years.

Therefore, renewable energy resources, along with energy saving strategies, can contribute to the sustainability of the irrigation sector in both economical and environmental terms.

However, in this approach the PV system is oversized with 42 % of annual excess of energy production. Net metering would solve this problem. Net metering allows the design the PV system considering the annual energy demand and reducing the total installed PV power. Thus, the excesses of electrical energy generated by the PV system are fed back into the energy supplier's grid which is considered like a virtual battery and the annual energy balance (excess of energy supplied by the PV system and energy purchased to the supplier) is performed. Then, net metering system would reduce the power requirements for the PV system and therefore reduces the investment costs.

6.5 Acknowledgements

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Conclusions/Conclusiones

7. Conclusions

7.1. General conclusions

A summary of the most relevant findings of the research carried out for this PhD thesis are presented bellow.

1. The characterization of the water and energy use is essential to improve the irrigation districts management.
2. The energy audits, as well as an energy assessment of an irrigation district, permits to identify weaknesses in the management and to plan improvement measures.
3. Sectoring hydraulic networks in irrigation turns is an effective measure to improve the energy supply efficiency, reducing the energy requirements.
4. Models to optimize sectoring based on dimensionless coordinates and cluster analysis techniques allows, in some cases, improving energy supply efficiency and potential energy savings with 30 % (BMI), and therefore achieving energy saving and carbon footprint reductions.
5. Each improvement measure must be specific to each irrigation area, adapted to the topography, hydraulic characteristics, types of crops and local irrigation practices.
6. The multiobjective algorithms permit to optimize the water and energy use in irrigation management, incorporating environmental and economic criteria.
7. Irrigation pattern can be optimized achieving a balance between economic and environmental objectives. Optimal irrigation pattern can increase profit by more than 14 % while the carbon footprint is

reduced, as well as the energy demand in the pumping station, by a 8.56 % (BMD).

8. Photovoltaic systems, as a source of additional renewable energy, are technically viable solutions and improve economic (costs reduction) and environmental aspects (reducing carbon footprint) of irrigation districts.
9. Photovoltaic systems as well as reducing the conventional electricity consumption, allow detaching the operating costs from the increasing of energy unit prize.
10. Sustainable management of irrigation networks is possible with the adoption of specific improvement measures for each study area and with the incorporation of new technologies, such as renewable energy systems. These measures optimize the water and energy use, reducing costs and mitigating environmental impacts.

7.2. Future research arising from this PhD thesis.

This PhD thesis shows that the irrigation district management is potentially improvable. The modernization of irrigation area should not end with the implementation of a technical project, but continue monitoring and integrate management (water-energy-environment nexus) of the irrigation area is required.

Based on the results obtained the following aspects are proposed to continue with the improving of the sustainable management of irrigation networks:

-It is important to extend these studies to the maximum possible irrigable areas. New measures for reducing the energy dependence may be obtained from the analysis of zones with different features and problems.

-Development of new methodologies for energy and water audits adapting them to bigger number of heterogeneous irrigation networks.

-Elaboration of models to optimize both irrigation and cropping surface patterns pursuing a balance between economic and environmental criteria.

-Development and evaluation of new measures to improve the water supply and the adequacy of the pumping station operation.

-Analysis of other potential renewable energy sources, technical and economically viable, which perform as additional energy source in the irrigated areas.

7. Conclusiones

7.1. Conclusiones generales

A continuación se presentan las conclusiones más relevantes de la investigación desarrollada durante la presente tesis doctoral.

1. La caracterización del uso del agua y la energía es esencial para la mejora de la gestión de comunidades de regantes.
2. Las auditorías energéticas, además de calificar energéticamente a una comunidad de regantes, permiten identificar las debilidades en la gestión y planificar medidas de mejora.
3. La sectorización de una red hidráulica en turnos de riego es una medida efectiva para disminuir los requerimientos energéticos del suministro de agua.
4. Organizar el riego en turnos mediante la sectorización de la red permite, en algunos casos de estudio, mejorar la eficiencia energética de suministro con ahorros potenciales de energía mayores al 30% (comunidad de regantes BMI), con el derivado ahorro energético y reducción de la huella de carbono.
5. Cada medida de mejora debe ser específica para cada zona regable, adaptándola a las condiciones topográficas, características hidráulicas, tipos de cultivos y a las prácticas de manejo del riego de los usuarios.
6. Los algoritmos multiobjetivo permiten optimizar el uso del agua y la energía en la gestión del riego, incorporando criterios ambientales y económicos.
7. Es posible optimizar el patrón de riego alcanzando un equilibrio entre objetivos económicos y ambientales. El patrón de riego

óptimo puede incrementar el beneficio en más del 14 % a la vez que se reduce la huella de carbono, y por tanto la demanda energética en la estación de bombeo, en un 8.56 % (comunidad de regantes BMD).

8. Los sistemas fotovoltaicos, como fuente de energía renovable complementaria, son soluciones viables técnicamente que mejoran aspectos económicos (reducción de costes) y ambientales de una zona regable (reduciendo la huella de carbono).
9. La instalación de sistemas fotovoltaicos además de reducir el consumo de energía eléctrica convencional, permiten desvincular los costes de explotación de las subidas del precio de la energía.
10. La gestión sostenible de las redes de riego es posible, con la adopción de medidas de mejora en la gestión específicas para cada zona de estudio y mediante la introducción de nuevas tecnologías, como los sistemas de energías renovables, reduciendo costes y mitigando el impacto ambiental.

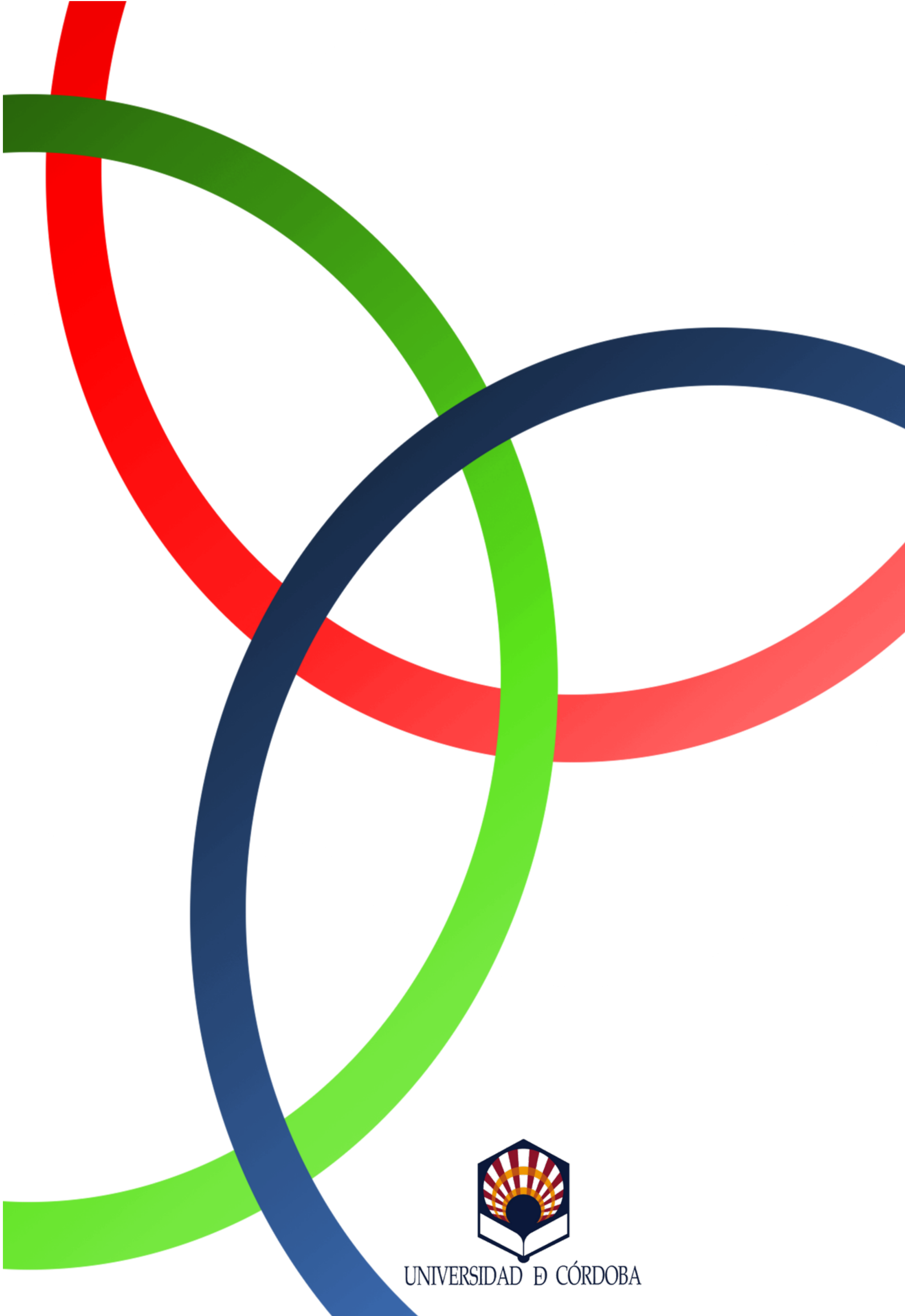
7.2. Líneas futuras de investigación derivadas de esta tesis doctoral.

Este trabajo pone de manifiesto que la gestión del agua en las comunidades de regantes es potencialmente mejorable. El proceso de modernización de una zona regable no debe concluir con la ejecución de un proyecto técnico, sino que es necesario un seguimiento continuado y una gestión integral (nexo agua-energía-medio ambiente) de la zona regable.

Basándose en los resultados obtenidos se proponen los siguientes aspectos para continuar con la mejora de la gestión sostenible de las redes de riego:

- Es importante extender estos estudios al mayor número posible de zonas regables. Nuevas medidas para la reducción de la dependencia energética podrán obtenerse del análisis de zonas con distintas características y problemáticas.

- Desarrollo de nuevas metodologías de auditorías energéticas e hídricas, adaptándolas a un mayor número de zonas regables heterogéneas entre sí.
- Elaboración de modelos que optimicen tanto los patrones de riego como los patrones superficie de cultivos de una zona regable, persiguiendo el equilibrio entre los criterios económicos y ambientales.
- Desarrollo y evaluación de nuevas medidas de mejora, tanto para la red de suministro como para la adecuación del funcionamiento de la estación de bombeo.
- Análisis del potencial de otras fuentes de energías renovables, viables técnica y económicamente, que actúen como fuentes de energía complementarias en las zonas regables.



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