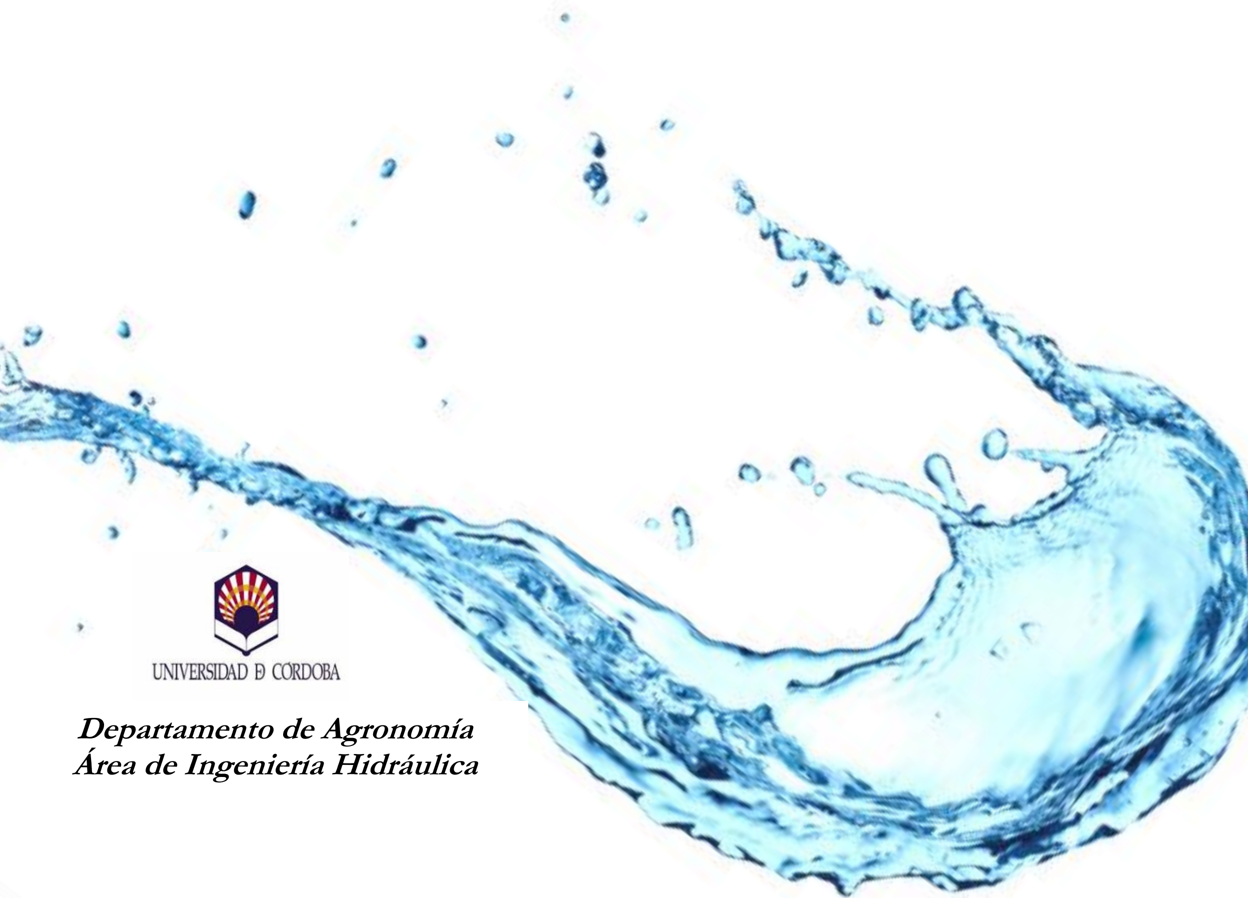
Optimum management of pressurized irrigation networks

Optimización de la gestión de redes de riego a presión

Irene Fernández García



UNIVERSIDAD DE CÓRDOBA

Departamento de Agronomía
Área de Ingeniería Hidráulica

TITULO: *Optimización de la gestión de redes de riego a presión.*

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

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Optimum management of pressurized irrigation networks

Optimización de la gestión de redes de riego a presión

Tesis doctoral presentada por

Irene Fernández García

para la obtención del título de

DOCTOR CON MENCIÓN INTERNACIONAL

POR LA UNIVERSIDAD DE CÓRDOBA

Directores

Dra. Mª Pilar Montesinos Barrios (Profesora Titular de Universidad)

Dr. Juan Antonio Rodríguez Díaz (Ramón y Cajal)

Mención de doctorado internacional

Esta tesis cumple con los requisitos establecidos por la Universidad de Córdoba para la obtención de la mención de doctorado internacional:

- Estancia de 3 meses realizada en Centre for Water Systems, de la Universidad de Exeter (Reino Unido), bajo la supervisión del Dr. Dragan Savic.

- Informe previo de dos doctores externos y con experiencia investigadora acreditada de alguna institución de educación superior o instituto de investigación de fuera de España.

- Un miembro del tribunal pertenece a un centro de investigación extranjero.

- Parte de la tesis está escrita en inglés y castellano.

Tesis como compendio de publicaciones

Esta tesis se presenta como compendio de publicaciones, cumpliendo con los requisitos establecidos por la Universidad de Córdoba para este fin. Tres capítulos de la presente tesis se corresponden con tres artículos científicos publicados en revistas incluidas en el primer cuartil según la última relación del Journal Citation Reports (2013) y dos de ellos se encuentran actualmente en fase de revisión:

1. Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P (2013) *Optimal Operation of Pressurized Irrigation Networks with Several Supply Sources*. Water Resources Management 27: 2855–2869. Índice de impacto: 2.463. 1er cuartil en el área de ingeniería civil, posición 10/ 124

2. Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014) *Methodology for detecting critical points in pressurized irrigation networks with multiple water supply points.* Water Resources Management 28 (4): 1095-1109. Índice de impacto: 2.463. 1er cuartil en el área de ingeniería civil, posición 10/ 124

3. Fernández García I, Moreno MA, Rodríguez Díaz JA (2014) *Optimum pumping station management for irrigation network sectoring: Case of Bembezar MI (Spain).* Agricultural Water Management 144: 150- 158. Índice de impacto: 2.333. 1er cuartil en el área de agronomía, posición 16/ 78

4. Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014) *Energy cost optimization in pressurized irrigation networks*. Irrigation Science (submitted)

5. Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014) *Incorporating the irrigation demand simultaneity in the optimal operation of pressurized networks with several water supply points*. Water Resources management (submitted)

Además de los trabajos anteriores, se incluye como anexo un artículo publicado en una revista del primer cuartil, que analiza los efectos que ha tenido la transformación de las redes de distribución del agua hacia sistemas a presión y justifica la necesidad de desarrollar estrategias encaminadas a mejorar la gestión del agua y la energía:

Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P, Berbel J (2014) *Effects of modernization and medium term perspectives on water and energy use in irrigation districts*. Agricultural Systems 131: 56-63. Índice de impacto: 2.453. 1er cuartil en el área de agricultura, posición 4/ 56

TÍTULO DE LA TESIS: *Optimización de la gestión de redes de riego a presión*

DOCTORANDA: Irene Fernández García

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

Los procesos de modernización que el regadío ha experimentado en los últimos años, en los que las redes a presión han sustituido a las antiguas redes de canales abiertos, han derivado en un aumento en la eficiencia en el uso del agua pero también una mayor dependencia energética. Así, sistemas que anteriormente no requerían de aportes significativos de energía para el suministro del agua, tras la modernización requieren de elevados consumos energéticos para su funcionamiento. Además, tras la liberación del mercado energético, en los últimos años los costes de la energía han experimentado un gran crecimiento. La mayor dependencia energética unida a los costes crecientes, han ocasionado que el coste de la energía vinculada al suministro de agua sea un gran limitante de la productividad agrícola y una gran preocupación del sector del riego que ve mermada la rentabilidad de su actividad motivada por los altos costes asociados al agua.

Diversos autores han trabajado en la optimización de los sistemas de distribución de agua con el objetivo de reducir su demanda energética. Así, existen medidas como la sectorización de las redes, la detección de hidrantes con especiales requerimientos de energía o la regulación adecuada de la estación de bombeo, que han demostrado que reducir significativamente los requerimientos energéticos es posible. No obstante, los trabajos previos se han centrado en redes ramificadas con un solo punto de suministro (las más comunes en el regadío pero no las únicas) y careciendo habitualmente de un carácter integrador en el que todas las medidas de ahorro sean consideradas simultáneamente.

En ambos aspectos, esta Tesis Doctoral supone un importante avance en el estado del conocimiento actual, dado que se desarrollan modelos de gestión de redes de riego válidos tanto para uno como para varios puntos de suministro y se integran todas las medidas desarrolladas para determinar la combinación óptima de medidas de ahorro.

Así, en un primer trabajo se desarrolla un modelo para la gestión de redes a presión con varios puntos de suministro basado en técnicas de optimización multiobjetivo. Para ello ha sido necesario sectorizar la red en grupos de hidrantes de demanda energética homogénea de acuerdo a sus características hidráulicas y topológicas y, posteriormente, establecer estrategias de gestión que permiten minimizar el consumo energético manteniendo los criterios de calidad en el servicio de distribución de agua en términos de caudal y presión.

En el segundo trabajo, se desarrolla una nueva metodología adecuada para la detección de puntos críticos (hidrantes con altos requerimientos de energía). Además, se ofrecen medidas de mejora para el control de dichos puntos y reducir su repercusión en la demanda global de energía en la red.

Ambas medidas se integran junto con la gestión óptima de la estación de bombeo en el tercer trabajo, en donde se analiza la gestión de la estación de bombeo y las posibles mejoras en la misma mediante la instalación de nuevos variadores de frecuencia, cuando el riego se gestiona en turnos de riego (sectorización).

La tarifa energética también juega un importante papel en la gestión del riego, dado que se organiza en periodos con diferente coste unitario dependiendo de la hora del día y el mes del año. Así, la concentración del riego en horas con coste energético más bajo puede llevar a importantes ahorros económicos. En el cuarto trabajo se desarrolla un modelo para la gestión óptima del riego considerando estrategias de reducción de los requerimientos energéticos y los períodos tarifarios.

Un problema hasta ahora tampoco abordado ha sido el efecto de la simultaneidad de la demanda de agua cuando existen diversos puntos de suministro. Se trata de un problema complejo dado que los caudales circulantes pueden variar significativamente dependiendo de la configuración de la red (combinación de tomas abiertas y cerradas) en un momento determinado. No obstante, un conocimiento profundo del efecto de la simultaneidad en las variaciones de presión en los hidrantes permite un mejor ajuste de la altura manométrica en cabecera y reducir considerablemente la demanda de energía. Este efecto ha sido ampliamente estudiado en redes ramificadas pero hasta la fecha no se ha abordado en redes con varios puntos de suministro. En el quinto trabajo se desarrolla un modelo adecuado para analizar el efecto de la simultaneidad en redes complejas con varias fuentes de suministro y se analizan sus repercusiones para la implementación de medidas de ahorro energético.

Por todo esto, consideramos que se trata de una Tesis de gran calidad y que aborda un problema real, de gran actualidad y con gran aplicabilidad al sector. La Tesis se presenta como un compendio de cinco artículos científicos, tres de ellos publicados en algunas de las revistas más prestigiosas en éste área, todas en el primer cuartil, y dos trabajos actualmente en revisión:

1. Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P (2013*) Optimal Operation of Pressurized Irrigation Networks with Several Supply Sources*. Water Resources Management 27: 2855–2869.

2. Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014) *Methodology for detecting critical points in pressurized irrigation networks with multiple water supply points*. Water Resources Management 28 (4): 1095-1109.

3. Fernández García I, Moreno MA, Rodríguez Díaz JA (2014) *Optimum pumping station management for irrigation network sectoring: Case of Bembezar MI (Spain)*. Agricultural Water Management 144: 150- 158.

4. Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014) *Energy cost optimization in pressurized irrigation networks*. Irrigation Science (submitted)

5. Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014) *Incorporating the irrigation demand simultaneity in the optimal operation of pressurized networks with several water supply points*. Water Resources management (submitted)

Además, los trabajos se complementan con un análisis de la demanda energética actual en zonas regables típicas de Andalucía, junto con un análisis de las perspectivas de crecimiento a medio plazo. Dicho artículo ha sido publicado en la revista Agricultural Systems, también en el primer cuartil de su área de conocimiento:

Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P, Berbel J (2014) *Effects of modernization and medium term perspectives on water and energy use in irrigation districts*. Agricultural Systems 131: 56-63.

Por todo ello, se autoriza la presentación de la tesis doctoral "Optimización de la gestión de redes de riego a presión".

Córdoba, 7 de Noviembre de 2014

Firma de los directores

Fdo: Prof. Dra. Pilar Montesinos Barrios	Fdo: Prof. Dr. Juan Antonio Rodríguez Díaz

Agradecimientos

Gracias a todas las personas que me han acompañado durante este viaje, por su apoyo profesional y personal:

A mis directores de tesis, Dra. Pilar Montesinos Barrios y Dr. Juan Antonio Rodríguez Díaz. Gracias por confiar en mí desde el primer momento, por vuestra guía durante la realización de esta tesis y por vuestro empuje para conseguirlo.

Al Dr. Emilio Camacho Poyato, por su ayuda en todo momento. Esta tesis también recoge tus aportaciones.

Al Dr. Julio Berbel Vecino, por ofrecerme la oportunidad de trabajar con él y por sus conocimientos en otros ámbitos del sector de la agricultura de regadío.

Al Dr. Miguel Ángel Moreno, por su contribución en la realización de esta tesis.

A la Universidad de Córdoba, por la concesión de una de las ayudas para realizar una estancia en un centro extranjero con el fin de obtener la mención de doctorado internacional.

Al Dr. Dragan Savic, del Centre for Water Systems (Universidad de Exeter), por acogerme en su departamento para la realización de la estancia y por dedicar parte de su valioso tiempo a guiarme en el trabajo llevado a cabo en su centro. Gracias a mis compañeros Dr. Enrico Creaco y Gerard Sanz, por hacer de esa estancia una etapa inolvidable.

Al Dr. Nicola Lamaddalena y al Dr. Enrico Creaco, por su valoración de esta tesis.

A mis compañeros del departamento, Teresa Carrillo y Rafa González, por ayudarme a resolver las dudas sobre programación que han surgido al realizar esta tesis. Y, junto a ellos, a Manuel Martín, Rafa Pérez y Jorge García, por vuestro apoyo personal y por los buenos momentos que hemos pasado juntos. Gracias por el buen ambiente de trabajo. Sin vosotros, la realización de esta tesis no hubiera sido tan llevadera.

Un merecido agradecimiento a mi familia. A mi padre, Juan Ramón, mis hermanas, Conchi y Puri y mi cuñado, Fran, por estar conmigo en todo momento y ayudarme a superar los momentos de fragilidad que han surgido durante el desarrollo de esta tesis. A mi sobrino, Fran, porque contigo también nacieron nuevas ilusiones para esta familia. A Luis, por estar ahí en todo momento y ayudarme a ver siempre el vaso "medio lleno".

Las últimas líneas van para la persona gracias a la cual estoy hoy aquí, a mi madre. Porque sé que estés donde estés te sentirás orgullosa de mí.

Summary

The increasing food demand linked to the population growth requires higher agricultural production. In this context, irrigation agriculture plays a major role by ensuring and enhancing crop productions. However, considering the global scarcity and inequality of water resources, measures to improve water use efficiency are requested. In Spain, due to the tough climate with low and irregular precipitations in large zones of the country, irrigation agriculture has undergone a thorough intensification, by changing the old open channel distribution systems to pressurized networks. This modernization process has entailed higher water use efficiency but the energy consumption has increased dramatically in the last years. Moreover, the competition for energy resources is growing fast, which means high energy prices. Thus, strategies to improve water and energy use in pressurized irrigation networks are strongly demanded.

This thesis holds eight chapters plus one appendix with different methodologies to reduce energy requirements in multi-sources pressurized irrigation networks. Chapter 1 contextualizes the topic stated in this document and the objectives pursued are shown in chapter 2.

Chapter 3 describes a new sectoring methodology to reduce the energy consumption in irrigation networks with multiple supply points. Using the multiobjective algorithm NSGA-II (Non-Sorting Genetic Algorithm), the proposed model determines the optimal number of operating sectors in every month and the associated pressure heads in the pumping station. The evaluation of this methodology in PF (Palos de la Frontera) irrigation network showed potential energy saving between 20 % and 29 %.

Considering the impact of critical points on network performance, hydrants with high energy demand, chapter 4 presents a strategy to optimize the energy consumption in multi-source irrigation networks by critical points control. This methodology has been also evaluated in PF irrigation network, given rise to potential energy saving of 36 % by replacing two pipes and installing four booster pumps.

The considerable increase of electricity tariffs has entailed a sharp impact on water costs for farmers. Hence, the methodology raised in chapter 5 integrates the two optimization models described in sections 3 and 4 with a new module to include the electricity tariff. By this new approach, the annual management strategy of the irrigation network that involves the minimum operational cost is determined.

Chapter 6 incorporates the management of the pumping station in the sectoring strategy stated in chapter 3 and analyzes the inclusion of variable speed drives (VSDs) to ensure that the pumping station works under optimal operation conditions. This model has been tested in BMI (Bembézar Margen Izquierda) irrigation network, providing potential energy savings of up to 26 % by installing two VSDs.

To consider the on-demand operation of the network, chapter 7 integrates an analysis of multiple random demand patterns and their effects on the variability in pressure at hydrants, when the sectoring strategy proposed in chapter 3 (which initially considered the simultaneous operation of all hydrants) is assumed. By this new analysis, additional energy savings from 9 % to 15 % with respect to the consideration of the concurrent operation of all hydrants can be achieved assuming pressure deficits of 21 % and 34 % in the most critical hydrant with an ocurrence frequency of 27 % and 36 % in the peak month.

The general conclusions drew from this thesis and the avenues for future research in the optimization of management of irrigation networks are included in chapter 8.

This thesis highlights the importance of the efficient management of pressurized irrigation networks and proposes several strategies to reduce the energy consumption and operational costs for farmers. The methodologies described in this document can be applied to irrigation networks with one and multiple water sources, improving the existing methodologies that were limited to branched networks.

Measures such as the rehabilitation of irrigation networks combined with the strategies stated in this thesis could also contribute to enhance the energy use efficiency.

Resumen

El aumento de población mundial que se ha producido en las últimas décadas y el que se prevé para los próximos años supone un crecimiento significativo de la demanda de productos agrícolas. En este contexto, el riego juega un papel clave ya que permite garantizar y aumentar las producciones agrícolas en zonas en las que no se dispone de recursos hídricos naturales suficientes para satisfacer las necesidades de agua de los cultivos. En España, con un clima caracterizado por precipitaciones escasas e irregulares en la mayor parte de su territorio, la agricultura de regadío ha sufrido una profunda transformación, evolucionando desde sistemas de riego mediante canales abiertos hacia redes a presión, más eficientes en el transporte y la distribución del agua. Este proceso de modernización de las infraestructuras hidráulicas ha supuesto una mejora de la eficiencia en el uso del agua, pero, por el contrario, el consumo energético se ha incrementado considerablemente. Por otro lado, la competencia por la energía es cada vez mayor lo que se traduce en un aumento del precio de este recurso. Por tanto, es necesario desarrollar estrategias que permitan mejorar la eficiencia en el uso de los recursos agua y energía en las redes de riego.

Esta tesis se estructura en ocho capítulos y un apéndice con distintas metodologías enfocadas a la optimización del uso de la

energía en redes de riego a presión, con independencia del número de puntos de suministro de los que disponga. El capítulo 1 pone en contexto el tema que se discute en la presente tesis y justifica los objetivos perseguidos en este documento, que se presentan en el capítulo 2.

En el capítulo 3 se presenta una nueva metodología para la optimización de redes de riego con varios puntos de suministro, mediante la determinación del calendario mensual óptimo de operación de sectores y las correspondientes alturas manométricas en las distintas estaciones de bombeo. El algoritmo multiobjetivo NSGA-II (Non-Sorting Genetic Algorithm) se ha usado durante el proceso de optimización, mediante el cual se han determinado ahorros energéticos potenciales entre el 20 % y el 29 % en la red de riego de la comunidad de regantes de Palos de la Frontera (PF).

En el capítulo 4 se describe una metodología, válida para redes con múltiples fuentes de suministro de agua, fundamentada en el análisis de puntos críticos, que son hidrantes con una demanda de energía elevada. Mediante el procedimiento desarrollado en este capítulo, se ha estimado un ahorro energético potencial del 36 % en la red de riego de PF, llevando a cabo una serie de mejoras en la red como la sustitución de dos tuberías y la instalación de cuatro rebombeos.

Para considerar el impacto que tiene la tarifa eléctrica sobre los costes de funcionamiento de la red que afronta el agricultor, el capítulo 5 incorpora un módulo relativo a la tarifa eléctrica en los procedimientos de optimización propuestos en los dos capítulos anteriores para obtener estrategias que permitan reducir el consumo de energía en función de la estructura de la tarifa eléctrica, permitiendo así obtener la estrategia anual de funcionamiento de la red que minimiza el coste total de operación.

El capítulo 6 aborda el análisis del funcionamiento óptimo de la estación de bombeo, incorporándolo en la estrategia de sectorización contemplada en el capítulo 3. La incorporación de variadores de velocidad en la estación de bombeo para conseguir que ésta trabaje en condiciones óptimas de funcionamiento también se evalúa en este capítulo. El modelo propuesto se ha analizado en la red de riego de la comunidad de regantes del Bembézar Margen Izquierda (BMI), determinando ahorros energéticos potenciales de hasta el 26 % si se instalan dos variadores de velocidad.

En el capítulo 7 se incluye el análisis del funcionamiento de la red a la demanda en la estrategia de sectorización propuesta en el capítulo 3, que consideraba el funcionamiento de todos los hidrantes a la vez, y los efectos que tiene la simultaneidad de operación de hidrantes sobre la variación de presión en los mismos. Mediante este análisis se han estimado ahorros energéticos adicionales con respecto a la operación simultánea de todos los hidrantes entre el 9 % y el 15 %, con déficits de presión que oscilan entre el 21 % y el 34 %, con frecuencias del 27 % y del 36 % en el hidrante más desfavorable y en el mes crítico.

El capítulo 8 recoge las conclusiones que se extraen de esta tesis y las posibles vías futuras de investigación en esta línea.

En esta tesis se destaca la importancia de mejorar la eficiencia energética en las redes de riego a presión, proponiendo distintas estrategias para reducir el consumo energético y los costes de operación en redes desde uno hasta varios puntos de suministro.

Medidas como la rehabilitación de redes de riego, combinada con las estrategias presentadas en esta tesis, pueden contribuir también a lograr una mayor eficiencia energética.

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γ	Water specific weight
η	Global efficiency of pumps
η_c	Cable efficiency
η_l	Efficiency related to head losses in pump pipes
η_m	Motor efficiency
η_p	Pump efficiency
η_v	Variable speed drive efficiency
CID	Penalty factor depending on irrigation deficit
CMPD	Penalty factor depending on the magnitude of pressure deficit
D_s	Number of days in month *s*
EC	Energy consumption
FPD_{js}	Frequency of pressure deficit at hydrant *j* in month *s*
FPH	Hydrant with pressure failure
H_{iws}	Pressure head of pumping station *i* when sector *w* operates in month *s*
H_{w-j}	Required weighted pressure head when hydrant *j* operates
H_{w-mch}	Required weighted pressure head when the most critical hydrant operates

i	Pumping stations index
IN	Theoretical daily irrigation requirements per month and hydrant
j	Index related to nodes
k	Index related to simulation
l_j^*	Topological dimensionless coordinate related to friction losses in pipes
l_{j-i}	Distance between the hydrant *j* and the pumping station *i*
l_{max-i}	Distance between the furthest hydrant and the pumping station *i*
h_j^*	Hydraulic dimensionless coordinate
N	Number of pumping stations
N_s	Number of irrigation network operation months
N_{ind}	Population size
N_{iter}	Number of iterations
N_{sect}	Number of operating sectors during month *s*
n_v	Number of decision variables
p_{ws}	Open hydrant probability per sector *w* and month *s*
P_j	Pressure at hydrant *j*
$\overline{Pbq_{FPHj}}$	Average pressure of the fourth quartile for hydrant *j*
PD_j	Pressure deficit at critical hydrant
PE_j	Pressure equity at critical hydrant
Pf	Pressure failure percentage

$\overline{Plq_{FPHj}}$	Average pressure of the first quartile for hydrant *j*
P_{ser}	Service pressure
q_j	Base demand in hydrant *j*
q_{max}	Design flow
Q_{iws}	Pumped flow by pumping station *i* when sector *w* operates in month *s*
$Qreq_s$	Theoretical irrigation requirements during month *s*
$Qsupply_s$	Flow supplied by pumping station during month *s*
R_{kws}	Random number per simulation *k*, sector *w* and month *s*
s	Month index
S_j	Irrigation area associated to each hydrant
t_{ds}	Water availability time during month *s*
t_{rs}	Daily irrigation time required during month *s*
t_s	Daily irrigation time during month *s*
w	Index related to sector
z_j^*	Topological dimensionless coordinate related to the hydrant elevation *j*
z_i	Pumping station elevation *i*
z_j	Hydrant elevation *j*

List of abbreviations

BMI	Bembézar MI (irrigation district)
EEA	European Environment Agency
FAO	Food and Agriculture Organizations of United Nations
GA	Genetic Algorithm
GEN	number of Generations
GRB	Guadalquivir River Basin
IDAE	Spanish Institute for Energy Diversification and Savings
IWMI	International Water Management Institute
MAPA	Spanish Ministry of Agriculture, Fisheries and Food
MARM	Spanish Ministry of Environment and Rural and Marine Affair
ME	Spanish Ministry of Economy
MINETUR	Spanish Minsitry of Industry, Energy and Tourism
MOGA	Multi-Objective Genetic Algorithm
NSGA-II	Non-dominated Sorting Genetic Algorithm
PF	Palos de la Frontera (irrigation district)
VSD	Variable Speed Drive
VSP	Variable Speed Pump
WECO	Water, Energy and Cost Optimization

WECP	Water and Energy optimization by Critical Points
WECPM	Water and Energy optimization by Critical Points for Multiple supply sources
WEBSO	Water and Energy Based Sectoring Operation
WEBSOM	Water and Energy Based Sectoring Operation for Multiple Supply Sources
WEBSOMPE	Water and Energy Based Sectoring Operation for Multiple supply sources considering Pumping Efficiency

1. Introduction

1.1. Background

Currently, the world's population stands at around 6 thousand millions and it is expected to grow up to 9 thousand millions by 2050. Thus, a significant increase on food requirements is predicted. The expected growth of demands for cereals and meat are M 1000 t and M 200 t, respectively, by 2050 (FAO 2011).

From this perspective, measures to attend the increasing food demand are required. Some of the possible measures are the expansion of the cropped area, the investment in irrigation including innovations in irrigation systems or the promotion of agricultural trade within and between countries (IWMI 2007).

Irrigated agriculture has played a major role in the increase of crop productions. Thus, the area equipped for irrigation has grown considerably in the last decades. In 1989/1991, the area equipped for irrigation accounted for M 244 ha, increasing up to M 287 ha in 2005/2007. Moreover, an additional increment of M 32 ha is predicted to occur in 2050 to satisfy the growing food demand (Conforti 2011).

Hence, 70 % of the freshwater withdrawals in the world (Conforti 2011) are used by irrigated agriculture. Taking into account the current pressure on water resources and the projected increase of irrigated area, improvements in the irrigation sector to achieve higher water use efficiency are strongly demanded.

1.2. The Spanish irrigation agriculture

In Spain, characterized by Mediterranean climate with scarce and irregular rainfall, irrigation agriculture is essential and accounts for 60 % of the total agricultural production. The irrigated area is around M 3.5 ha, which is one third of the irrigated area in the European Union (López-Gunn *et al.* 2012). Irrigated agriculture uses 58 % of the water resources on average. Although in the driest region this proportion reaches 80 %.

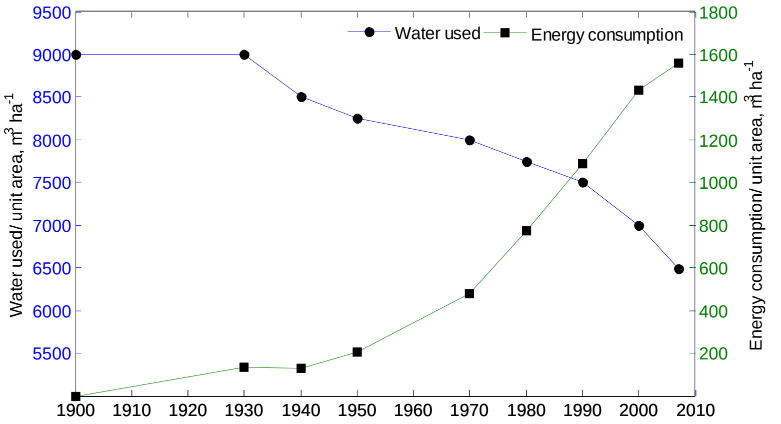
Therefore, an efficient management of the water resources must be considered to couple the water scarcity with the high volume of water used for irrigation. Thus, the Spanish National Irrigation Plan (MAPA 2001) included specific measures for the irrigation sector such as the modernization of hydraulic infrastructures, the incorporation of research programs and innovative techniques in the irrigation systems and the use of alternative water sources. These measures aimed to increase farmers' income by the consolidation of a competitive agri-food sector and consequently retain population in rural areas. This first plan was developed up to 2008 although in 2006, the Spanish Shock Plan for Irrigation was published due to the impact of the severe drought conditions (MARM 2006). The modernization of the hydraulic infrastructures was considered in this plan, upgrading more than 860,000 ha with the aim to achieve water savings of 1162 hm^3.

The modernization of the hydraulic infrastructures to improve water use efficiency has consisted in the migration from old open channel to pressurized systems. Moreover, these new infrastructures have encouraged the adoption of more efficient irrigation systems at field level, such as drip or sprinkler, at the expense of a reduction of surface irrigation. Thus, drip-irrigated area has grown by 44 % from 2002 to 2009 while the irrigated area by surface systems has decreased considerably (MARM 2010).

However, the new pressurized networks require energy for their operation according to the on-farm irrigation systems, the topography and the hydraulic configuration of the network. Thus, the energy consumption per unit area has risen by 657 % between 1950 and 2007 while the water used by unit area decreased by 21 % in the same period (Corominas 2010) (Fig. 1.1).

Different analysis of the modernization projects impacts on the irrigation districts have been carried out. An evaluation about the impact of the transformation of the hydraulic infrastructures in five irrigation districts of Gualdalquivir River Basin (South Spain) has showed a reduction of 23 % in the volume of water applied along with an increase of 52 % in the water costs (Fernández

García *et al.* 2014- see Appendix A). This implies a significant increment of costs for farmers, who also have to cope with the agricultural products price volatility. Thus, their incomes are diminishing and the profitability of irrigated agriculture is being questioned in many cases.



**Source: Author's elaboration based on Corominas (2010)*

Fig 1.1. Evolution of water used and energy consumption in the irrigation sector

Furthermore, the cost increase is not only due to the higher energy requirements in pressurized networks, but also for the rise of electricity tariffs. After the liberalization of the electricity market in 2003 and the elimination of the electricity tariff for the irrigation sector in 2008, the electricity bill has sharply raised.

According to this context of overall energy scarcity and increasing demand, the European Union has proposed a target of energy saving of 9 % for 2016. This purpose is contained in Directive 2006/32/CE on energy end-use efficiency and energy services.

Within the framework of the Energy Saving and Efficiency Strategy in Spain 2004-2012, the Action Plan 2005-2007(IDAE 2005) and the Action Plan 2008- 2012 (IDAE 2007), with specific measures to improve the energy efficiency in the irrigation districts, were developed. Afterwards, the European Union through Directive 2012/27/UE has committed to achieve an energy saving of 20 % in 2020. Under this Directive, the Action Plan 2011-2020 (IDAE 2011) was published in Spain, with measures to accomplish energy savings in every sector. Measures for the irrigated agriculture included in this Plan are the promotion and the dissemination of irrigation techniques leading to higher energy efficiency, the migration to less energy demanding irrigation systems, such as drip or low pressure sprinkler systems, and energy audits.

The Spanish Strategy for Sustainable Irrigation Modernization, Horizon 2015 (MARM 2010) is the first resource efficiency plan that promotes simultaneously both water and energy use efficiency in the irrigated agriculture. Under this strategy, objectives such as the improvement in water and energy use and the incorporation of alternative energy resources to achieve the sustainability of the sector are pursued.

1.3. Energy optimization in irrigation networks

There is a growing need for achieving high energy efficiency in irrigation networks. Thus, several techniques to reduce the energy consumption in pressurized networks have been developed.

Measures like grouping hydrants in sectors according to their energy requirements (Carrillo Cobo *et al.* 2011), detection of critical points (hydrants with high energy needs) (Rodríguez Díaz *et al.* 2012), improvements of pumping station operation (Moreno *et al.* 2007) or energy audits (Abadía *et al.* 2008) have been tested in irrigation networks showing significant potential energy savings. However, these strategies were designed for branched networks with one single supply point and cannot be applied to multi-sources irrigation networks, which are also common in the irrigation agriculture.

Sectoring and critical points control strategies in networks with more than one supply point have not been considered until now and hence, their development will extend the energy efficiency concept to all types of irrigation networks. Also, linking sectoring, with different flow regimes according to the operating sector and measures to optimize the performance of the pumping station, further reductions in the energy consumption will be achieved.

Given the mathematical complexity of the stated strategies, optimization tools are required for their implementation (Baños *et al.* 2011). Although there is wide variety of optimization procedures, heuristic techniques, genetic algorithms can be easily applied to the complex approaches required to minimize both water and energy uses in pressurized irrigation networks. According to the problem approach, genetic algorithms can be formulated with one single objective or with several objectives, called multiobjective genetic algorithms in that case (Savic 2007). As actual optimization problems rarely address one single objective, but several conflicting objectives, multiobjective algorithms have been successfully used in many optimization problems of water distribution systems: network design and rehabilitation (Chandapillai *et al.* 2012), leakage detection (Creaco & Pezzinga 2014) and pumping operation optimization (Moreno *et al.* 2007). Therefore, multiobjective genetic algorithms, as optimization tools in the raised strategies, may provide accurate results in a short time.

In essence, the integration, using multiobjective genetic algorithms as optimization tool, of different network operation strategies valid for networks with one or several supply points such as sectoring, critical points control, optimization of the pumping station and the incorporation of the electricity tariff to minimize the operational costs, will provide a versatile decision support system to technical advisers and farmers, which will entail energy savings in the irrigation supply and hence, higher revenues for farmers.

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2. Objectives and thesis structure

2.1. Objectives

The overall objective of this thesis is to develop strategies to optimize water and energy use in pressurized irrigation networks useful for systems with one single supply point and with several source nodes.

To achieve this aim, the following specific objectives have been formulated:

1. Develop a procedure focused on network sectoring to optimize both water and energy use.

2. Develop a methodology to improve water and energy management by critical points control.

3. Include the electricity tariff in the sectoring and critical points control strategies stated in objectives 1 and 2.

4. Integrate the pumping station operation in the sectoring procedure described in objective 1.

5. Incorporate the irrigation demand simultaneity in the sectoring strategy.

2.2. Thesis structure

This thesis is arranged in eight chapters and one appendix. Following the introduction (**chapter 1**) and the objectives pursued in this thesis (**chapter 2**), the chapters considered are:

Chapter 3 presents a new methodology for sectoring irrigation networks with several source nodes in order to reduce the energy consumption, using the multiobjective genetic algorithm NSGA-II as optimization tool. This chapter has been published under the title "Optimal Operation of Pressurized Irrigation Networks with Several Supply Points" (2013) by Fernández García I, Rodríguez Díaz JA, Camacho Poyato E and Montesinos P in *Water Resources Management*.

The efficient management of multi-sources pressurized irrigation networks by controlling critical points is described in **chapter 4**. Measures to improve the operation of the critical points detected are proposed achieving significant energy savings. This chapter has been published under the title "Methodology for detecting critical points in pressurized irrigation networks with multiple water supply points" (2014) by Fernández García I, Montesinos P, Camacho Poyato E and Rodríguez Díaz JA in *Water Resources Management*.

Chapter 5 incorporates the electricity tariff in previous chapters, thus combining the strategies that lead to the reduction of energy consumption with the decrease of the operational costs. This chapter corresponds to the article "Energy cost optimization in pressurized irrigation networks" (2014) by Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA submitted to *Irrigation Science*.

Chapter 6 integrates the optimal operation of the pumping station in the sectoring strategy described in chapter 3. The installation of variable speed drives is evaluated to determine the best working conditions of the pumping station. This chapter has been published under the title "Optimum pumping station management for irrigation network sectoring: Case of Bembézar MI (Spain)" (2014) by Fernández García I, Moreno MA and Rodríguez Díaz JA in *Agricultural Water Management*.

To consider the on-demand operation of irrigation networks with several supply points, **chapter 7** presents a methodology to include the analysis of the demand simultaneity in the sectoring strategy stated in chapter 3, also evaluating the effects of different configurations of open and closed hydrants on variability in hydrant pressure. This chapter corresponds to the article "Incorporating the irrigation demand simultaneity in the optimal operation of pressurized networks with several water supply points" (2014) by Fernández García I, Montesinos P, Camacho Poyato E and Rodríguez Díaz JA submitted to *Water Resources Management*.

Chapter 8 details the conclusions reached in this thesis and the avenues for future research in this area.

Appendix A corresponds to the article "Effects of modernization and medium term perspectives on water and energy use in irrigation districts" by Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P, Berbel J published in Agricultural Systems in 2014. This article provides an evaluation of the effects of the modernization of hydraulic infrastructures to pressurized irrigation networks in five irrigation districts. The analysis carried out in this article justifies the overall objective of this thesis.

3. Optimal Operation of Pressurized Irrigation Networks with Several Supply Sources

This chapter has been published entirely in the journal "Water Resources Management", Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P (2013)

Abstract. The evolution of water distribution systems to pressurized networks has improved water use efficiency, but also significantly increased energy consumption. However, sustainable irrigated agriculture must be characterized by the reasonable and efficient use of both water and energy. Irrigation sectoring where farmers are organized in turns is one of the most effective measures to reduce energy use in irrigation water distribution networks. Previous methodologies developed for branched irrigation networks with one single source node have resulted in considerable energy savings. However, these methodologies were not suitable for networks with several water supply points. In this work, we develop an optimization methodology (WEBSOM) aimed at minimizing energy consumption and based on operational sectoring for networks with several source nodes. Using the NSGA-II multiobjective genetic algorithm, the optimal sectoring operation calendar that minimizes both energy consumption and pressure deficit is obtained. This methodology is tested in the irrigation district of Palos de la Frontera (Huelva,

Spain) with three pumping stations, showing that potential annual energy savings of between 20 % and 29 % can be achieved, thus ensuring full pressure requirements in nearly all hydrants, along with the total satisfaction of irrigation requirements.

Keywords. Energy efficiency, genetic algorithms, water distribution systems, Spain

3.1. Introduction

In arid and semi-arid countries, the availability of water resources for irrigation is very low and measures to improve water use efficiency are strongly demanded. Technical improvement measures usually involve replacing open channel systems with pressurized water distribution networks. Consequently, in countries like Spain, drip irrigation is now the most common irrigation method. However, these systems require large amounts of energy for their operation, which may lead to additional costs for farmers unable to afford this expense if their production is devoted to low-value crops (Rodríguez Díaz *et al.* 2011).

To reduce the impact of increasing energy costs, several methodologies to diminish the energy requirements of pressurized systems have been proposed (Abadía *et al.* 2008; Daccache *et al.* 2010; Lamaddalena and Khila 2012). For example, the Spanish Institute for Diversification and Energy Savings (IDAE) recommends energy saving measures, including energy audits, network sectoring by grouping hydrants in irrigation turns with similar energy demand, and critical points detection (hydrants with high energy requirements) (Rocamora *et al.* 2008). For several authors irrigation network sectoring is one of the most promising energy saving measures (Moreno *et al.* 2010; Carrillo Cobo *et al.* 2011). Previous works have shown that network sectoring can achieve potential energy savings of between 20 % and 30 % (Rodríguez Díaz *et al.* 2009; Navarro Navajas *et al.* 2012). In contrast, Rodríguez Díaz *et al.* (2012) proposed critical points detection as an energy saving measure since it permits on-demand irrigation where water is available for farmers 24 h a day.

As irrigation water demand tends to be concentrated in certain months of the year, Carrillo Cobo *et al.* (2011) found that the optimum sectoring strategy may differ from 1 month to another according to the water demand. To solve this problem, they developed the WEBSO algorithm (Water and Energy Based Sectoring Operation) to establish the optimum sectoring strategy depending on the network's topology and monthly irrigation demand.

All the methodologies described above were designed to operate branched networks with a single source node. Therefore, they must be modified to operate irrigation networks with several sources (pumping stations or tanks), which are common in some irrigation districts. In this case, the problem is far more complex because the pressure heads in the different pumping stations vary simultaneously depending on the energy demand generated by the set of open hydrants.

The above optimization problem is constrained and multi-modal, making it very difficult to find a solution using traditional optimization techniques. For this reason, heuristic approaches are adequate when solving this sort of problems (Baños *et al.* 2010). Among the evolutionary heuristic techniques, genetic algorithms (GA) (Goldberg 1989) have been successfully applied to many optimization problems related to both the design (Montesinos *et al.* 1999; Reca and Martínez 2006; Chandapillai *et al.* 2012) and the operation of water distribution systems (Elferchichi *et al.* 2009; Jiménez Bello *et al.* 2010). Over the last decade, many optimization engineering problems (Baños *et al.* 2010) have been formulated as multi-objective optimization problems with several conflicting aims whose interaction generates a set of compromised solutions, what is known as the Pareto front. When several objectives are considered in the operation of water networks, the decision-making process is significantly improved as a wide range of alternatives is usually identified and a more realistic model of the problem is achieved if many objectives are considered.

In this paper, we establish the optimal sectoring operation calendar for irrigation networks with several source nodes using a customized version of the Non-dominated Sorting Genetic Algorithm (NSGA-II) (Deb *et al.* 2002). The possible operating sectors are previously defined using the methodology proposed by Carrillo Cobo *et al.* (2011) and adapted to networks with multiple source nodes. Finally, the new methodology is applied to a real irrigation network in southern Spain to evaluate potential energy savings.

3.2. Methodology

3.2.1. Study area

The Palos de la Frontera irrigation district (PF) is located in the Guadiana river basin. The climate is Atlantic with an average temperature of around 18 °C and annual precipitation from 500 to 700 mm.

The irrigation district covers 3,343 ha of irrigated area. Strawberry is the main crop, and accounts for nearly 75 % of the cropped area. Other crops in the district are citrus, fruit trees and vegetables. Irrigation water is derived from the Chanza and Piedras dams and conveyed to two reservoirs which supply water to three pumping stations. The water is distributed from the pumping stations to 227 hydrants through a network of 513 pipes measuring a total of 79 km in length. Each hydrant is designed to supply 1.2 $ls^{-1}ha^{-1}$ on demand, ensuring a service pressure of 30 m. The pressure head in the pumping stations varies from 45 to 85 m. Pressure heads and pumped flows are recorded by a telemetry system (Pérez Urrestarazu *et al.* 2009). The layout of the PF water distribution system is shown in Fig. 3.1.

3.2.2. Problem formulation

The main goal of this work was to obtain the optimal monthly operation of irrigation water distribution systems with several source nodes (pumping stations) during the irrigation season when the network is operated by sectors. The problem was formulated as a multi-objective optimization problem with two objective functions that included several operational constraints.

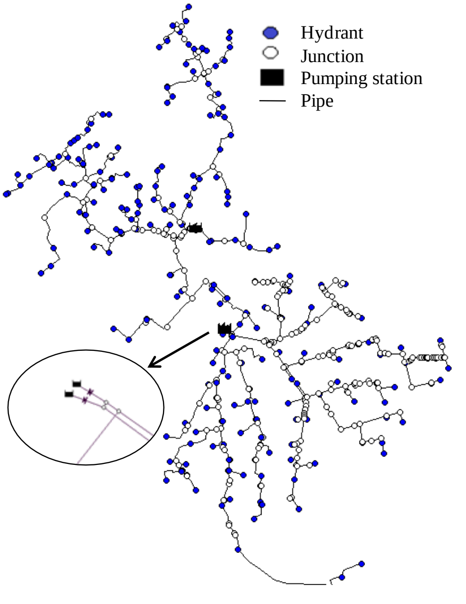

Fig. 3.1. Schematic representation of the PF water distribution network

The monthly operation of the system was evaluated on the basis of a standard day per month as is shown in both objective equations. The methodology was integrated in the WEBSOM algorithm (Water and Energy Based Sectoring Operation for Multiple Supply Sources).

The first objective (*F1*) was to simultaneously minimize seasonal energy consumption and irrigation deficits:

$$F1 = EC_{norm} + CID_{norm} \quad [3.1]$$

Where EC_{norm} is the normalized total energy consumption, and CID_{norm} is the normalized maximum irrigation deficit. Both terms are normalized to allow their summation.

The value of *EC* in (kWh/irrigation season) was calculated as follows:

$$EC = \frac{1}{1000} \cdot \frac{1}{\eta} \cdot \gamma \sum_{s=1}^{Ns} t_s \cdot D_s \sum_{w=1}^{Nsect} \sum_{i=1}^{N} Q_{iws} \cdot H_{iws} \quad [3.2]$$

Where *i* is the pumping stations index, *w* the sector index, *s* the month index, *N* the number of pumping stations, N_{sect} the number of possible sectors, N_s the number of months of the irrigation season, η the global efficiency of pumps (assuming a pumping efficiency of 0.8), γ water specific weight (9800 Nm^{-3}), t_s the daily irrigation time (h) during month *s*, D_s the number of days in month *s*, Q_{iws} the pumped flow by station *i* when sector *w* operates during month *s* (m^3s^{-1}), and H_{iws} the pressure head of pumping station *i* when sector *w* operates during month *s* (m).

The value of the irrigation deficit term *CID* was calculated as the maximum monthly irrigation deficit during the irrigation season:

$$CID = \max\,[Qreq_s - Qsupply_s] \quad [3.3]$$

Where Q_{reqs} is the sum of theoretical flow requirements to irrigate all crops (m^3s^{-1}) and $Q_{supplys}$ is the sum of the supplied flow by all pumping stations (m^3s^{-1}), both for month *s*.

The aim of the second objective function (*F2*) was to minimize the pressure deficits in all hydrants:

$$F2 = \max\left[Pf + CMPD_{norm}\right] \qquad [3.4]$$

Where *Pf* is the pressure failure percentage determined as the ratio between the number of hydrants that did not reach the service pressure and the number of operating hydrants, and $CMPD_{norm}$ is the normalized term that evaluates the monthly magnitude of pressure deficit (service pressure – actual pressure at each hydrant). Both terms were calculated for all months of the irrigation season and the value of *F2* is the maximum monthly value obtained by summing these terms.

The objective equations (3.1) and (3.4) were constrained by the physical laws of mass and energy conservation.

The first stage of the solution process was to define the sectors. Once the possible sectors were defined, the multi-objective optimization problem was solved using the NSGA-II multi-objective algorithm (Deb *et al.* 2002), which was implemented in MATLAB™ (Pratap 2010). A general overview of the whole process is shown in Fig. 3.2. The main stages of the solution process are described next.

3.2.3. Sector identification

The possible irrigation sectors were identified using the dimensionless topological coordinates method (Carrillo Cobo *et al.* 2011). The method was modified in order to be applied to multi-source pipe networks. The two dimensionless coordinates were related to the distance between each hydrant and the pumping stations and their elevations, l^* and z^*, respectively. Thus, the generalized dimensionless coordinates were:

$$z_j^* = \frac{\sum_{i=1}^{N} \frac{z_j - z_i}{|z_j - z_i|_{max}}}{N} \quad [3.5]$$

$$l_j^* = \frac{\sum_{i=1}^{N} \frac{l_{j-i}}{l_{max-i}}}{N} \quad [3.6]$$

Where z_j^* is the dimensionless topological coordinate related to the hydrant elevation j, z_j is the hydrant elevation j, z_i is the pumping station elevation i, and $|z_j\text{-}z_i|_{max}$ is the maximum difference between each hydrant and the pumping station elevation i (absolute value) . l_j^* is the dimensionless topological coordinate which is related to the distance between the source and demand nodes and hence to friction losses in pipes; $l_{j\text{-}i}$ is the distance between the hydrant j and the pumping station i, and $l_{max\text{-}i}$ is the distance between the furthest hydrant and pumping station i. Term $l_{j\text{-}i}$ was calculated using Dijkstra's graph search algorithm (Dijkstra 1959).

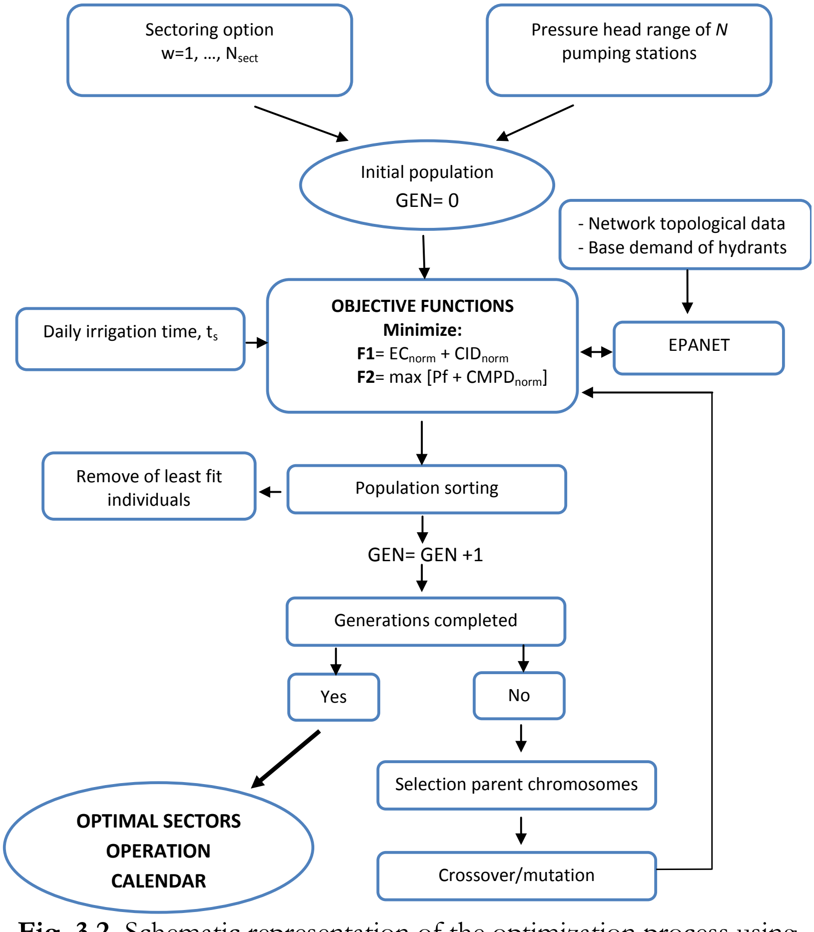

Fig. 3.2. Schematic representation of the optimization process using the WEBSOM algorithm

Once the dimensionless topological coordinates of each hydrant were known, the K-means algorithm (MacQueen 1967) was used to group the hydrants together into homogeneous sets according to their topological coordinates (Rodríguez Díaz *et al.* 2008). All the network's hydrants were classified into 2, 3, 4 and 5 sectors using this methodology.

3.2.4. Multi-objective Solution Algorithm

The NSGA-II multi-objective genetic algorithm (Deb *et al.* 2002) was customized to obtain the optimal sector operation calendar that minimizes both energy consumption and service pressure failures in irrigation networks with several supply sources. A flow chart of the algorithm is shown in Fig. 3.2. The modified stages of the original NSGA-II are described below.

– Initial population

The initial population was formed by randomly generated individuals (chromosomes) that provided information on both the total head of the irrigation network pumping stations and the number of operating sectors per month during the irrigation season. Therefore, the number of variables, *nv*, is $Nsect \times N \times Ns$. The variables within the chromosomes were grouped by months in sets of ($Nsect \times N$) variables. For each month, the variables were grouped by sector and each sector had a variable associated to each pumping station (*N*). It is important to note that the total head of the pumping stations varied depending on the operating sector per each sectoring option. An example of a solution chromosome is shown in Fig. 3.3a. The values of the variables were 0 or a random number selected from between the possible minimum and maximum values for each decision variable using real-coding (Elferchichi *et al.* 2009).

– Evaluation of objective functions

The objective function values (Eqs. 3.1 and 3.4) were calculated for each chromosome. The term t_s in Eq. 3.2 denotes daily irrigation time during month *s*. This term is related to both the daily irrigation time required to match the crop water requirements per month (t_{rs}) and the number of hours that the sector is operating (t_{ds}), and depends on the sectoring option being considered (e.g. if 4 sectors were operating, then t_{ds} was 24/4=6 h). Hence, the greater the number of operating sectors, the lower the water availability time. Therefore, t_s was equal to t_{ds} when the daily irrigation time required (t_{rs}) exceeded the water availability time (t_{ds}). In that case, irrigation requirements were not fully satisfied. In contrast, when t_{rs} was lower than t_{ds}, t_s was equal to t_{rs} and the irrigation requirements were guaranteed in these months.

The variable t_{rs} (h) was obtained by the following expression (Carrillo Cobo *et al.* 2011) where q_{max} is the design flow ($m^3s^{-1}ha^{-1}$) and *IN* (m^3ha^{-1}) is the crop water requirements estimated as described in Allen *et al.* (1998):

$$t_{rs} = \frac{1}{3600} \cdot \frac{IN}{q_{max}} \qquad [3.7]$$

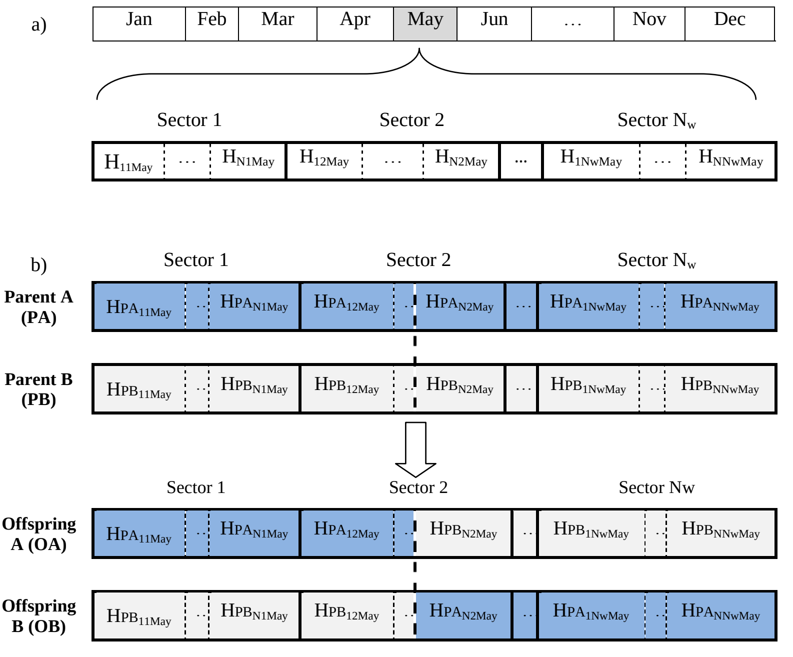

Fig. 3.3 a Schematic representation of a complete chromosome and the set of operation variables of a representative month; **b** Detail of multiple-point crossover in a representative month.

Given that the terms of the objective function F1 had different units, each term was normalized using the continuous uniform distribution U (0,1). Thus, the minimum value of F1 was 0 and the maximum value was 2. In relation to the objective function F2, only the second term had to be normalized by the distribution U (0,1) and then each term varied between 0 and 1. The F2 values therefore ranged from 0 to 2, like function F1.

In order to calculate the objective functions, the irrigation network was simulated using EPANET (Rossman 2000) to obtain the flows supplied by the pumping stations and the pressures at the hydrants throughout the irrigation season. The hydraulic simulator required topological data of the network, the set of monthly operation variables (sectors and pressure heads) stored in each chromosome to be evaluated, and the hydrant base demand. The base demand was determined by multiplying q_{max} by the irrigation area associated to each hydrant (*Sj*), assuming that all hydrants within each operating sector were open.

– Multiple-point crossover

In this paper, we used a multiple-point crossover procedure involving the random selection of pairs of parent chromosomes that exchanged information between several crossing points. A single crossing-point within the operation variables of each month of the irrigation network was randomly selected (Fig. 3.3b).

3.3. Results and discussion

3.3.1. Irrigation Network Sectoring Options

The dimensionless coordinates, z^* and l^*, for the 227 hydrants of the PF irrigation district are shown in Fig. 3.4a. Coordinate l^* was regularly distributed, and ranged from 0.13 to 0.87. The minimum distance between the hydrants and pumping station 1 was 119 m, while the maximum distance was 10,510 m. The distance for pumping station 2 ranged from 126 m to 8,804 m, and from 121 m to 8,809 for pumping station 3. The values of coordinate z^* ranged from -0.96 to 0.88. The negative values of z^* were associated to hydrants with a lower elevation than the pumping station elevations. The elevation of pumping stations 1, 2 and 3 was 25 m, 28 m and 29 m, respectively, while the elevations of the hydrants ranged from 5 m to 48 m. Thus, over 75 % of the hydrants were below the elevations of the pumping stations as shown in Fig. 3.4a and associated to negative values of z^*. The values of z^* close to 0 (both positives and negatives) corresponded to hydrant elevations similar to the pumping station elevations. Likewise, hydrants with values of z^* close to -1.0 were situated below the pumping stations, while hydrants with values of z^* close to 1.0 were located above them.

Sectors were defined by grouping the hydrants according to the values of the dimensionless coordinates calculated previously. The k-means algorithm was applied to 2, 3, 4 and 5 sectors since the PF irrigation network consists of a large number of hydrants, although the sectoring option is also related to the capability of the hydrant to supply a maximum flow rate. In contrast, Carrillo Cobo *et al.* (2011) proposed 2 and 3 sectors for networks that supply water to a variable number of hydrants (between 45 and 85). Fig. 3.4 shows the sectoring option with 2 sectors (a), 3 sectors (b), 4 sectors (c) and 5 sectors (d), respectively, for the PF irrigation district. As shown in Fig. 3.4a, elevation is more important than distance. Sector 1 comprised 141 hydrants ($z^*<0$), while sector 2 comprised 86 hydrants ($z^*>0$). For the 3 sectors option, coordinate z^* is still the most important for sector identification (Fig. 3.4b). The influence of z^* diminished when the sectoring level increased (Fig. 3.4c and 3.4d).

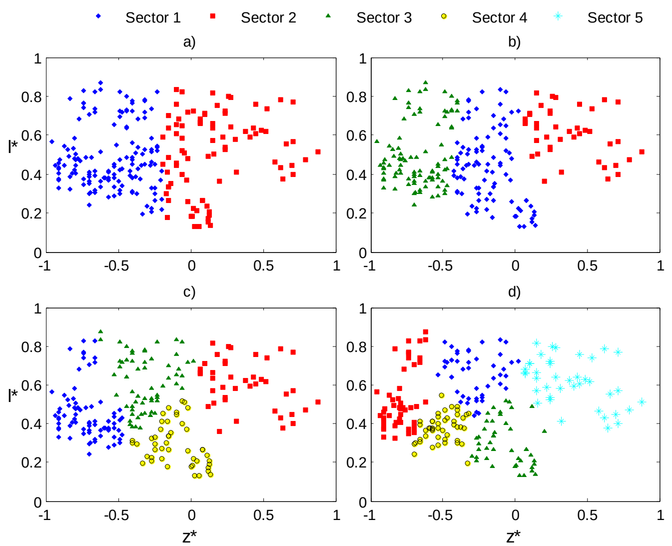

Fig. 3.4. Topological dimensionless coordinates for all hydrants and sectoring options proposed for the PF irrigation district: **a** 2 sectors; **b** 3 sectors; **c** 4 sectors; **d** 5 sectors

Differences were found when comparing the current sectoring of PF irrigation district with 3 operating sectors and the option with 3 operating sectors obtained by the k-means algorithm. This is because the current sectors in PF were defined by grouping hydrants located in the same pipe, while the resulting sectoring by the k-means algorithm was based on the topological characteristics of the hydrants.

3.3.2. Optimal Sector Operation Calendar

The optimization process was applied to the PF irrigation network considering the total satisfaction of theoretical irrigation requirements (6,230 m^3ha^{-1}) (Fernández García 2011). Regarding the number of decision variables, individuals were composed of 180 variables [5 (maximum number of operating sectors)×3 (number of pumping stations)×12 (number of operating months)]. The values of the total head of the pumping stations ranged from 0 (when the pumping stations were not operating) and a random number between 45 m and 85 m (operational range of the pumping stations). The monthly operation of the network is controlled by 12 sets of 15 variables (180 variables/12 months), which are grouped internally into sets of three variables that identify each possible operating sector. The first set of three variables identified the operation of sector 1, the second of sector 2, and so on. Additionally, the first variable within each set of three variables was associated to the total head of pumping station 1, the second to the total head of pumping station 2 and the third variable to the total head of pumping station 3.

As regards the optimization process based on NSGA-II, the population size and the number of generations parameters were set at 50 individuals and 100 generations, respectively. The crossover probability was 0.9 and the mutation probability 0.1. The algorithm evolution during 100 generations (minimum values per generation) is shown in Fig. 3.5. The most significant reduction in the value of objective function F1 occurred in the first 34 generations. The decrease was more gradual in the following generations (Fig. 3.5a). Solutions with an irrigation deficit were eliminated since the second generation and the solutions that satisfied the full pressure requirements in nearly all the hydrants were achieved from generation 26 onwards (Fig. 3.5b).

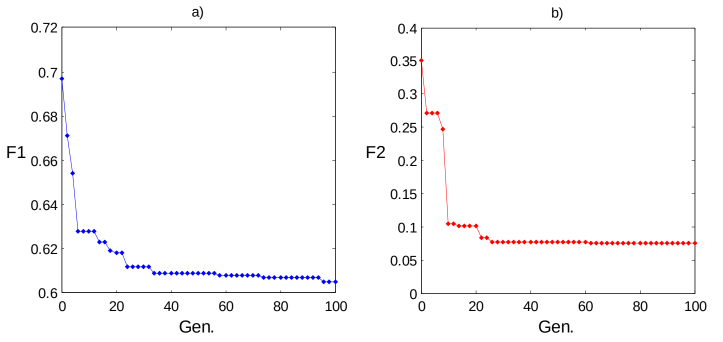

Fig. 3.5. Algorithm evolution: **a** F1; **b** F2

Table 3.1 shows the value range for the terms in objective functions F1 and F2 (energy consumption, irrigation deficit, the number of hydrants that do not reach the service pressure and the pressure in the most restrictive hydrant) for generations 0, 25, 50, 75 and 100. The minimum energy consumption evolved from 2,856 MWh in the initial population to 2,795 MWh in the last generation, hence the reduction was 61 MWh (2 %). However, the minimum energy consumption in the initial population was associated to an irrigation deficit in May (a critical irrigation period for strawberries) equal to 1.7 $hm^3 month^{-1}$ (49 % of crop irrigation requirements). As the *CID* term was 0 from the second generation onwards, irrigation deficit does not appear to be a very restricting constraint since the network was designed to supply the theoretical irrigation needs. As concerns energy consumption, the maximum value in the initial population was 11 % lower in the last generation. However, the current energy consumption in PF (4,115 MWh) was always higher than the consumption of the most energy demanding individuals in the different generations

(25 % higher than the maximum energy consumption solution in generation 100). This difference may increase if the service pressure conditions are relaxed (drip irrigation systems can operate properly with a pressure head below 30 m in the intake hydrant). After generation 25, it is possible to find solutions with a hydrant that operates with a pressure service only 2 m below 30 m (Table 3.1).

Table 3.1. Minimum and maximum energy consumption (EC) in MWh, irrigation deficit (ID) in hm3month-1, number of hydrants with pressure below 30 m (nj) and pressure (P) in the most restrictive hydrant (m) in several generations of the optimization process

Gen	**EC**	**ID**	**n_j**	**P**	**EC**	**ID**	**n_j**	**P**
0	2856	1.7 (49 %)	55	8	3653	0	19	21
25	2827	0	35	9	3401	0	1	28
50	2813	0	37	9	3300	0	1	28
75	2803	0	35	9	3278	0	1	28
100	2795	0	35	9	3278	0	1	28

Table 3.2 shows the 15 best solutions for generation 100. The lowest energy consuming individual did not achieve the service pressure in 7 hydrants (3 % of total hydrants) and the pressure in the most restrictive hydrant was at least 26 m. These solutions may be considered quasi-optimal as these pressure deficits would permit the proper operation of the on-farm irrigation system. In addition, the total fulfillment of irrigation requirements and the simultaneous operation of all the hydrants considered in this work do not occur concurrently. Water availability is frequently lower than the theoretical irrigation requirements. When this is

the case, flow rates and head losses are smaller and the operating hydrants would achieve the service pressure.

Table 3.2. Energy consumption (*EC*) in MWh, number of hydrants with pressure below 30 m (n_j) and pressure (P) in the most restrictive hydrant (m) of the best solutions obtained in the optimization process

Individual	EC	n_j	P
1	2920	7	26
2	2922	7	26
3	2923	7	26
4	3004	5	27
5	3005	5	27
6	3005	5	27
7	3032	4	27
8	3033	4	27
9	3035	4	27
10	3041	1	25
11	3049	1	25
12	3245	2	28
13	3248	2	28
14	3248	2	28
15	3276	1	28

The energy consumption ranged from 2,920 MWh to 3,276 MWh; a considerably lower consumption than the current operation of PF when total irrigation needs are supplied. These values are 10 % and 23 % higher, respectively, than those measured by Rodríguez Díaz *et al.* (2011) in the same irrigation district when only 45 % of the theoretical irrigation requirements were considered. In our work, however, the energy consumption per unit of irrigation water supplied was 0.20 kWh m^{-3}. This contrasts with the real value of 0.25 kWh m^{-3} obtained by

Rodríguez Díaz *et al.* (2011). This value shows that an optimal network operation fosters the sustainable use of agricultural water by minimizing water and energy demands.

Fig. 3.6 shows the Pareto front obtained in the optimization process (generation 100). The objective function F1 was represented only by the term *EC* because the solutions with irrigation deficit were removed from the second generation onwards. Furthermore, the two terms in the objective function F2 are shown separately with their real units. Fig. 3.6a shows the energy consumption versus the number of hydrants that did not achieve the service pressure (the first term of F2), while Fig. 3.6b shows the energy consumption versus the pressure in the most restrictive hydrant (the second term of F2). This figure shows that when energy consumption decreased, the number of hydrants that did not obtain the service pressure increased, and the pressure in the most restrictive hydrant was lower. Table 3.3 shows the optimal sector operation calendar and the total head of the pumping stations according to the operating sector for individual 1 (Table 3.2) during the irrigation season.

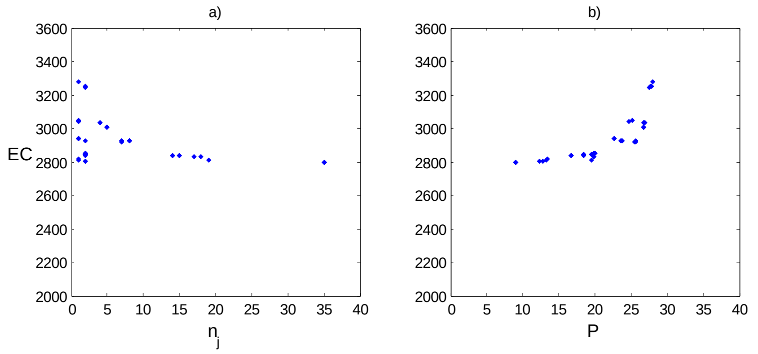

Fig. 3.6. Pareto front of generation 100: **a** Energy consumption (EC) (MWh) vs. hydrants with pressure <30 m (nj); **b** Energy consumption vs. pressure (P) in the most restrictive hydrant (m)

April and May were the months with highest water demand. For this reason, 3 and 2 sectors were operating, respectively, in these months. For the rest of the irrigation season, 2 sectors were operating in January, February and August; 3 sectors in March, July and December; 4 sectors in September and November; and 5 sectors in June and October (the least water demanding periods). For each operating sector during the season, different combinations of working pumping stations were obtained (3 stations, 2 stations or only one). The total head ranged from 45.5 to 81.0 m for the three pumping stations.

Analyzing possible irrigation scenarios is not a difficult task because WEBSOM can run with different service pressures and irrigation demands (model parameters). For instance, the model was run considering a scenario where the minimum required pressure at hydrant was 25 m instead of 30 m and the irrigation demand was 80 % of the full irrigation requirements, obtaining an energy savings of 43 %. There is an almost infinite number of possible irrigation strategies, all of them with lower energy consumption. The upper limit of energy consumption that satisfies the upper limit of water demand has been established within the scenario studied.

3.4. Conclusions

The evolution of water distribution systems to pressurized networks has improved water use efficiency, but has also significantly increased energy consumption. To overcome this problem, we have presented a methodological approach to simultaneously improve energy and water use efficiency in irrigation networks with several supply points. The proposed methodology, known as WEBSOM, provides the optimal monthly operation of irrigation networks with several source nodes during the irrigation season when the network is operated by sectors. We have evaluated different sectoring strategies for sets of hydrants grouped together according to the values of their dimensionless topological coordinates within a multi-objective optimization problem. The optimization problem was defined with two objective functions that included several operational constraints. The problem was solved using a customized version of the multi-objective genetic algorithm, specifically NSGA-II.

Table 3.3. Optimal sectors operation calendar and total head (m) of the pumping stations according to the operating sector for individual 1

		MONTH											
		1	2	3	4	5	6	7	8	9	10	11	12
Operating sector	**Sectoring option**	**2**	**2**	**3**	**3**	**2**	**5**	**3**	**2**	**4**	**5**	**4**	**3**
	H1	0.0	59.6	52.4	52.7	0.0	0.0	78.2	0.0	0.0	0.0	0.0	54.1
1	H2	79.3	78.1	47.8	54.0	59.8	49.2	0.0	0.0	63.9	59.3	52.9	53.3
	H3	61.8	0.0	0.0	54.2	58.7	0.0	81.0	53.6	56.1	0.0	0.0	55.6
	H1	0.0	50.6	0.0	53.7	0.0	77.5	0.0	58.2	0.0	0.0	0.0	58.9
2	H2	0.0	0.0	58.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	H3	66.2	0.0	0.0	0.0	60.2	45.5	57.4	0.0	67.4	46.7	56.4	48.5
	H1			0.0	0.0		47.8	0.0		49.9	0.0	55.1	46.8
3	H2			59.5	0.0		0.0	0.0		0.0	0.0	0.0	0.0
	H3			0.0	75.0		47.2	53.1		50.1	61.4	0.0	0.0
	H1						0.0			0.0	49.9	50.7	
4	H2						0.0			53.0	0.0	0.0	
	H3						57.4			0.0	0.0	0.0	
	H1						53.8				50.4		
5	H2						0.0				0.0		
	H3						0.0				0.0		

The methodology proposed has been applied to a real irrigation network. The optimization process provides sectoring programs during the season that allow energy savings of between 20 % and 29 % when they are compared to the current operation of the network studied. These sectoring strategies satisfy the total irrigation requirements and allow pressure deficits ranging from 7 % (only one hydrant) up to 13 % (3 % of hydrants).

WEBSOM is a powerful water management tool for irrigation water managers as it can be run with different service pressures and irrigation demands according to users' requirements.

Acknowledgments. This research is part of the AMERE project (AGL2011-30328-C02-02), funded by the Spanish Ministry of Economy and Competitiveness.

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4. Methodology for Detecting Critical Points in Pressurized Irrigation Networks with Multiple Water Supply Points

This chapter has been published entirely in the journal "Water Resources Management", Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014)

Abstract. The modernization processes of hydraulic infrastructures from old open channels to pressurized networks have increased water use efficiency along with a dramatic increase of energy consumptions. The significant energy requirements associated with the increment of the energy tariffs for irrigation involve higher production costs for farmers. Therefore, strategies to reduce energy consumption in irrigation districts are strongly demanded. Methodologies based on sectoring and critical points control have been applied to branched networks with a single water supply point, obtaining significant energy savings. In this work, a new critical point control methodology for networks with multiple sources has been developed: the WEPCM algorithm, which uses the NSGA-II multi-objective evolutionary algorithm to find the lowest energy consumption operation rule of a set of pumping stations connected to an irrigation network that satisfies the pressure requirements, when the critical points are successively disabled. WECPM has been applied to a real irrigation district in Southern Spain. The obtained results were compared with those achieved by the WEBSOM algorithm, developed for sectoring multiple source networks. The control of critical points by the replacement of two pipes and the installation of four booster pumps provided annual energy savings of 36 % compared to the current network operation. Moreover, the control of critical points was more effective than sectoring, obtaining an additional annual energy saving of 10 %.

Keywords. Efficiency, energy savings, water supply systems, Spain

4.1. Introduction

In order to reduce the water consumption in agriculture, many irrigation districts have switched from old open channels distribution systems to pressurized networks. By this modernization process higher both the conveyance efficiency and the water use efficiency at field scale are achieved. In Spain, this transformation has meant a dramatic rise of the energy consumption, which has increased from 206 kWh ha^{-1} in 1950 to 1,560 kWh ha^{-1} in 2007, while the water use efficiency has risen by 21 % over the same period (Corominas 2010). Similar trends were observed in other countries such as Australia where the modernization of water distribution systems has resulted in higher energy requirements, with estimated increased up to 163 % (Jackson *et al.* 2010). Nevertheless, the transformation of hydraulic infrastructures has not led farmers to obtain higher profits. On the one hand, a fourfold rise in amortization and maintenance costs was reported by Rodríguez Díaz *et al.* (2012b). On the other hand, the rise of the energy tariffs for irrigation about 120 % since 2008 in Spain (Rodríguez Díaz *et al.* 2011) has also influenced the production costs. Thus, the net electricity consumption per unit of water in the Spanish irrigation systems has grown by 10 % from 2002 to 2008 (Hardy *et al.* 2012). The same trends were observed in other countries such as South Africa with increases in electricity tariffs of 31 % only from 2009 to 2010 (Brazilian *et al.* 2011).

In order to face the high costs, farmers have replaced traditional irrigated crops, with lower water requirements, by higher value crops but more water demanding (Playán and Mateos 2006; Lecina *et al.* 2010). Related to this, Rodríguez Díaz *et al.* (2012a) estimated an increase on theoretical crop evapotranspiration (ETc) around 20 % after the transformation of an irrigation district, in Southern Spain, from surface irrigation system to pressurized irrigation system. Methodologies to improve the energy efficiency in pressurized irrigation networks have been developed (Abadia *et al.* 2008; Moreno *et al.* 2009; Lamaddalena and Khila 2012).

Likewise, the Spanish Institute for Diversification and Energy Savings (IDAE) has proposed energy saving measures suitable for irrigation districts with pressurized networks. Some of these measures consisted in network sectoring by grouping hydrants with similar energy demand and in the control of critical points, which are hydrants with higher energy requirements due to their elevation or their distance to the water source (Rocamora *et al.* 2008).

Carrillo Cobo *et al.* (2011) developed the WEBSO algorithm (Water and Energy Based Sectoring Operation) which provided monthly sectoring strategies based on the hydrants' topological characteristics. Potential energy savings of around 9 % to 27 % in two irrigation districts were achieved by WEBSO. Jiménez Bello *et al.* (2010) proposed a methodology to group intakes into sectors using genetic algorithms and achieving energy savings of 36 % in the studied area. Sectoring changed the operation of the network and implied the reorganization of farmers in turns according to their energy demand.

There are fewer examples of useful methodologies to detect and control critical points. Khadra and Lamaddalena (2010) developed a decision support system to identify unsatisfied hydrants although energy saving actions in these hydrants were not considered. Related to this, Rodríguez Díaz *et al.* (2012b) proposed an algorithm named WECP (Water and Energy optimization by Critical Points control) which detected the critical points of a network according to their hydraulic behaviour and proposed improvements to enhance their performance. Also, Rodríguez Díaz *et al.* (2012b) compared the obtained results of

WEBSO and WECP in two Spanish irrigation districts. The algorithm WECP obtained higher energy savings than the WEBSO (between 10 and 31 %) in both irrigation districts when theoretical irrigation requirements were considered.

However, both methodologies (WEBSO and WECP) were developed for branched networks with a single water supply point and cannot be applied to networks with multiple water sources, also common in irrigation areas. The optimization of looped water networks is more complex because the pressure head in each pumping station must be estimated simultaneously. Fernández García *et al.* (2013) addressed this problem and proposed a useful methodology to identify the optimum sectoring strategy for this sort of networks (WEBSOM) using the multiobjective genetic algorithm NSGA-II (Non-dominated Sorting Genetic Algorithm) (Deb *et al.* 2002) in the optimization process. Conversely, methodologies to detect critical points when the water is supplied from several sources have not been developed yet.

In this work, a methodology based on the control of critical points for multiple source networks is developed and applied to a real irrigation district in Southern Spain. Then, the results are compared with those obtained by Fernández García *et al.* (2013) when sectoring was considered as energy saving strategy.

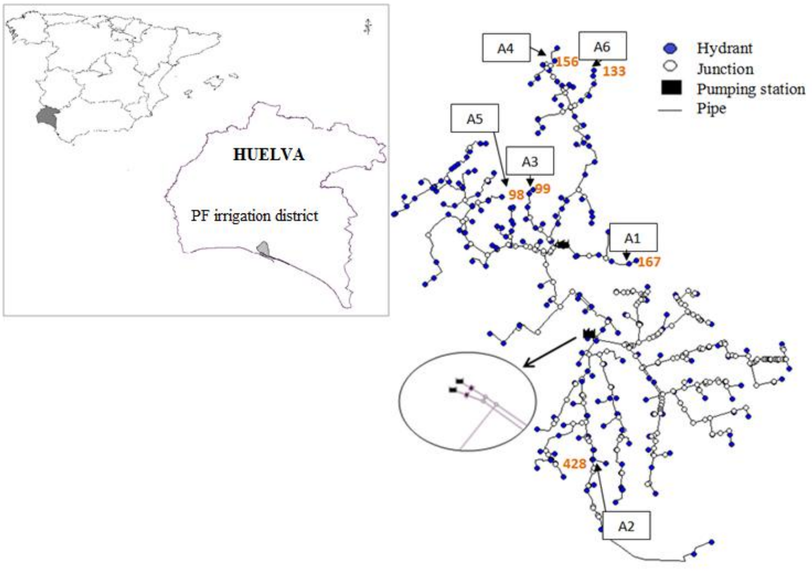
4.2. Methodology

4.2.1. Study area

The Palos de la Frontera (PF) irrigation district is placed in the Guadiana river basin in Southern Spain (Fernández García *et al.* 2013) (Fig. 4.1). The area is mainly flat, with elevations between 5 to 48 m. The total cropped area is 3,343 ha where strawberry accounts for nearly 75 %. Other crops in the area are citrus, fruit trees and winter vegetables. The irrigation network has three pumping stations that can provide maximum pressure heads of 85 m, 45 m and 55 m, respectively. Irrigation is organized on-demand and it is monitored by a telemetry system that records in real time information related to volumes, flows and pressures (Pérez Urrestarazu *et al.* 2009).

4.2.2. Critical points detection for multiple source networks

The WECP algorithm, proposed by Rodríguez Díaz *et al.* (2012b), was modified to cope with multiple water source networks. Thus, a new algorithm, WECPM (Water and Energy optimization by Critical Points control for Multiple supply sources), was developed. WECPM included a heuristic multiobjective optimization procedure to identify the best management of the critical points.



Booster stations	Pipe change: replacement by bigger pipes
A3: 10 m of elevation	A1: 158 m from 129.2 mm to 200 mm
A4: 10 m of elevation	A2: 284 m from 104.6 mm to 200 mm
A5: 10 m of elevation	
A6: 10 m of elevation	

Fig. 4.1. Location of Palos de la Frontera irrigation district and energy saving actions in the irrigation network

Genetic algorithms (GA) constitute one of the most used heuristic techniques to solve problems related to the operation and design of water distribution networks (Montesinos *et al.* 1999, Moradi- Jalal *et al.* 2004; van Dijk *et al.* 2008; Jamieson *et al.* 2007). The main stages of GA are briefly described as follows. First, a random initial population is generated. Then, all individuals of the initial population are evaluated and ranked according to their values of the objective function. Finally, selection, crossover and mutation processes are carried out until the convergence criterion or the fixed number of generations is achieved (Goldberg 1989). A typical GA minimizes or maximizes a single objective function and gives a unique optimal solution. However, to solve problems with several conflicting objectives, a multiobjective genetic algorithm (MOGA) can be used. The result of a multiobjective problem is not a single solution, but a set of optimal solutions known as Pareto optimal front (Savic 2007; Chandapillai *et al.* 2012; Siew and Tanyimboh 2012). The NSGA-II has been adapted to detect critical points in multiple source networks linked to the hydraulic model EPANET (Rossman 2000) by using its dynamic link library (DLL). The optimization algorithm was developed in MATLAB (Pratap 2010). The flow chart of WECPM is shown in Fig. 4.2 and its main features are described next.

- Initial Population

Firstly, the initial population was randomly generated. In this work, individuals or chromosomes that contained n_v variables corresponding to the daily pressure heads of the pumping stations during the peak demand month formed this population.

– Objective functions

The individuals previously generated were evaluated, that is, the values of the objective functions for each individual were calculated. The objective functions used in this work were the minimization of the daily energy consumption (Eq. 4.1) and the minimization of the pressure deficit (Eq. 4.2) considering that the network was operated on demand:

$$F1 = EC_{norm} \qquad [4.1]$$

$$F2 = Pf + CMPD_{norm} \qquad [4.2]$$

Where EC_{norm} is the normalized daily energy consumption, *Pf* the pressure failure percentage and $CMPD_{norm}$ the normalized term that shows the magnitude of the pressure deficit.

The calculation of the term EC_{norm} (Eq. 4.1) requires the previous estimation of *EC* (kWh day^{-1}), that was calculated as follows:

$$\mathrm{EC} = \frac{1}{1000}\frac{1}{\eta} \cdot \gamma \cdot t_{rs} \sum_{i=1}^{N} Q_i \cdot H_i \qquad [4.3]$$

Where *i* is the pumping stations index, *N* the number of pumping stations, η the global efficiency of pumps (assuming a pumping efficiency of 0.8), γ water specific weight (9800 Nm^{-3}), Q_i the pumped flow by station *i* (m^{3}s^{-1}), H_i the pressure head of pumping station *i* (m) and t_{rs} the daily irrigation time (h) to satisfy crop irrigation requirements estimated as described in Allen *et al.* (1998).

Regarding *F2*, the term *Pf* was determined as the ratio between the number of hydrants that did not reach the service pressure and the number of operating hydrants. In this equation, $CMPD_{norm}$ was derived from *CMPD,* calculated as the difference between the pressure in the most critical hydrant and the service pressure.

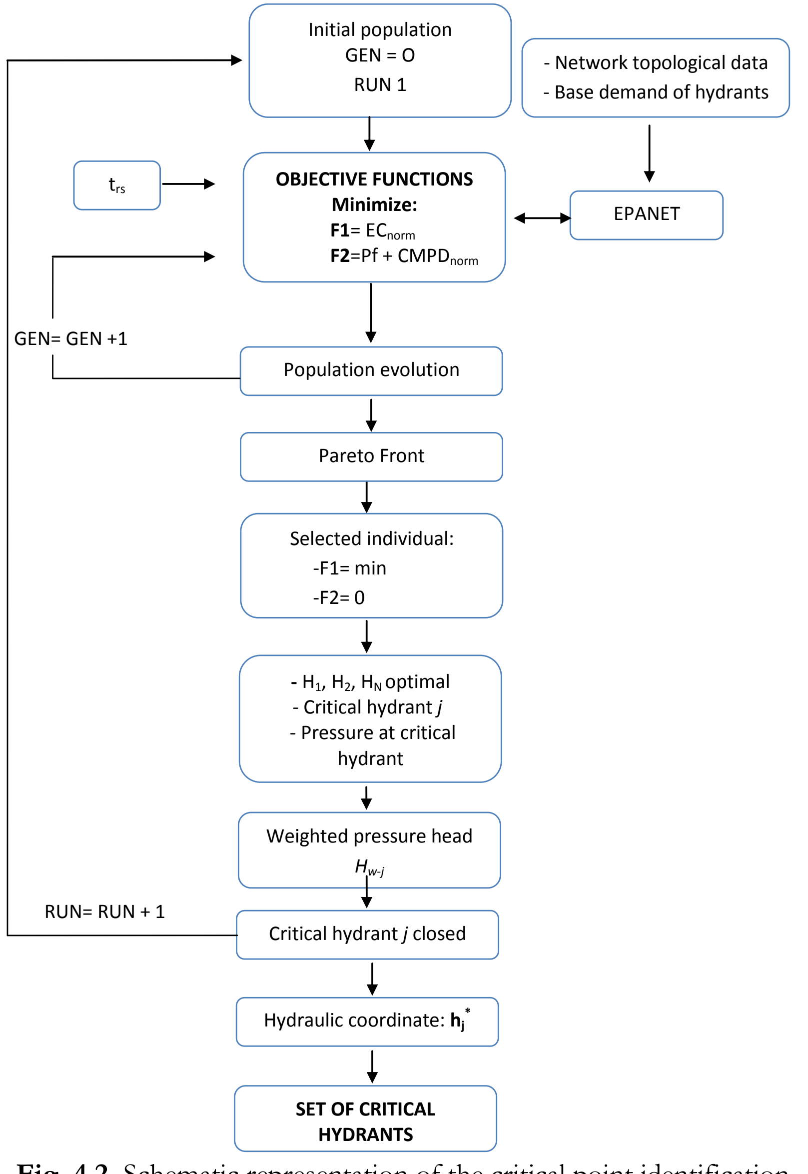


Fig. 4.2. Schematic representation of the critical point identification

In order to compare the values of *F1* and *F2*, the terms *EC* and *CMPD* were normalized (EC_{norm} and $CMPD_{norm}$) by the continuous uniform distribution U (0,1). EC_{norm} varied from 0 to 2 while *Pf* and $CMPD_{norm}$ ranged from 0 to 1, respectively.

The constraints of this minimization problem were the physical laws of energy and mass conservation.

To determine the objective functions and their constraints, the hydraulic simulation of the network was carried out using EPANET, a free and widely used software in the evaluation of water distribution systems (Chandapillai *et al.* 2012; Siew and Tanyimboh 2012). Also, the EPANET engine can be easily integrated into external programs through its Dynamic Link Library (DLL). The required data were the network's topology, the pressure head of the N pumping stations of every individual created by NSGA-II and the hydrant base demand (Carrillo Cobo *et al.* 2011). The flows supplied by each pumping station and the pressures at every hydrant were obtained from the hydraulic simulator.

– Selection, crossover- mutation, recombination

The processes of selection, crossover- mutation and recombination were performed as described in Deb *et al.* (2002) for a number of generations (*GEN*) fixed at the beginning of the process.

– Critical point detection

The optimization process finished providing the set of individuals (Pareto front) whose hydrants worked at least with the service pressure and their energy consumptions were the lowest. Among the individuals in the Pareto front, the most frequent critical hydrant was identified and then, the individual that having that hydrant as critical involved the minimal energy consumption was selected. This individual contained information of the optimal pressure heads of the *N* pumping stations and, as result of the hydraulic simulation, the energy consumption during the maximum demand month and the pressure in the most limiting hydrant (critical point or hydrant with the lowest pressure).

From these results, the weighted pressure head provided by the set of pumping stations when hydrant *j* was the most critical, H_{w-j}, was determined by the following equation:

$$H_{w-j} = \frac{\sum_{i=1}^{N} Q_i \cdot H_i}{\sum_{i=1}^{N} Q_i} \qquad [4.4]$$

Once the first critical point was detected, all the optimization process described above was carried out again. However, in this case, the detected critical point was considered closed and its base demand was set to zero. Thus, a second critical point and its weighted pressure head were obtained. This process continued until the differences in energy consumption in several consecutive critical hydrants was negligible. Then all critical points were identified and their weighted pressure heads were calculated.

Finally, a dimensionless coordinate (h_j^*) associated to each critical hydrant, was defined to characterize its hydraulic behaviour and was calculated as follows:

$$h_j^* = \frac{H_{w-j}}{H_{w-mch}} \qquad [4.5]$$

Where $H_{w\text{-}mch}$ is the weighted pressure head of the first detected critical point (run 1). Thus, the maximum value of h_j^* was 1 for the first detected critical point and it was gradually reduced for the following critical hydrants. In the end, all hydrants were ranked according to this criterion. Hydrants with highest h_j^* were selected (critical points) and improvement measures to reduce their energy demand were proposed.

4.2.3. Sectoring Strategy for Multiple Source Networks

To optimize the energy demand, Fernández García *et al.* (2013) developed a methodology based on multiple sources networks sectoring (WEBSOM). The sector configuration was performed by grouping hydrants according to the network's topology. Thus, two dimensionless coordinates, z_j^*, related to the hydrant elevation, and l_j^*, related to the distance between the source nodes and demand nodes, were proposed for every hydrant:

$$z_j^* = \frac{\sum_{i=1}^{N} \frac{z_j - z_i}{|z_j - z_i|_{max}}}{N} \qquad [4.6]$$

$$l_j^* = \frac{\sum_{i=1}^{N} \frac{l_{j-i}}{l_{max-i}}}{N} \qquad [4.7]$$

Where z_j is the hydrant j elevation, z_i is the pumping station i elevation and $|z_j\text{-}z_i|_{max}$ is the maximum elevation difference between each hydrant and the pumping station i (absolute value).

$l_{j\text{-}i}$ is the distance between the hydrant *j* and the pumping station *i*, determined by the Dijkstra's graph search algorithm (Dijkstra 1959) and $l_{max\text{-}i}$ is the distance between the furthest hydrant and the pumping station *i*.

Once the possible sectors were determined, the monthly optimal sectoring operation calendar for irrigation networks with several supply points that required the minimum energy consumption could be identified. The optimal network operation was established using a procedure based on NSGA-II.

Once the possible sectors were determined, the monthly optimal sectoring operation calendar for irrigation networks with several supply points that required the minimum energy consumption could be identified. The optimal network operation was established using a procedure based on NSGA-II.

4.2.4. Selection of Best Energy Saving Strategy

After the detection of the critical points and assuming that the network improvement strategies to reduce their energy demand were implemented, WECPM was run for every month of the irrigation season and the potential annual energy savings were compared with those achieved by WEBSOM. Thus, both methodologies' results were compared and the best energy saving strategy could be selected.

4.3. Results and Discussion

4.3.1. Irrigation Water Demand

The WECPM was applied to the PF irrigation network for the peak water demand month (May) assuming that the irrigation requirements were fully satisfied. As shown in Table 4.1, the peak crop water requirements occurred in May (4.1 mm day^{-1}), while January and December were the lowest water demanding months (0.7 mm day^{-1}). Thus, the maximum daily irrigation time required per month, which directly affects the energy consumption, was 9.5 hours in May.

4.3.2. Critical Points Detection

Three decision variables (n_v=3) were contained in each individual since this irrigation district has three pumping stations. The minimum values of pressure head at each pumping station were 55, 50 and 45 m while the maximum values were 95, 65 and 55 m, respectively. Concerning the NSGA-II parameters, 100 individuals and 50 generations were considered in each run. The crossover probability was 0.9 and the mutation probability 0.1 (Deb *et al.* 2002).

Table 4.1. Monthly crop water requirements, *IN*, irrigated area, *IA* and daily irrigation time required per month, t_{rs}

	IN, mmday^{-1}	IA[a], %	t_{rs}, hours
Jan	0.7	79	1.7
Feb	1.1	79	2.5
Mar	2.1	91	4.8
Apr	2.9	94	6.7
May	4.1	94	9.5
Jun	1.5	94	3.5
Jul	0.9	16	2.0
Aug	2.0	21	4.4
Sep	1.7	95	3.9
Oct	2.0	79	4.7
Nov	0.9	79	2.2
Dec	0.7	79	1.5

[a]Percentage of the total area that is irrigated every month

Fig. 4.3 represents the Pareto Front obtained in the first run when all hydrants were open. The minimum value of F1 was 0.52 that implies an energy consumption of 623.2 MWh. However, this value was associated to the maximum value of F2, 0.46, which indicated that 13 hydrants did not get the pressure service and the pressure in the most critical hydrant was only 18 m. In contrast, the maximum value of F1 was 0.62 (energy consumption of 744.6 MWh) corresponding to the minimum value of F2 (0). This value is related to an individual that ensured the service pressure in all hydrants. From this set of solutions, we selected the individual with F2 equal to 0. In this run, the detected critical point was hydrant 167. In order to identify the next critical point, hydrant 167 was removed and a second run was performed. Thus, in every run a new critical point was sequentially detected and removed (hydrant 428 was eliminated after the second run) and while the critical points were eliminated, the network's pressure requirements were progressively reduced.

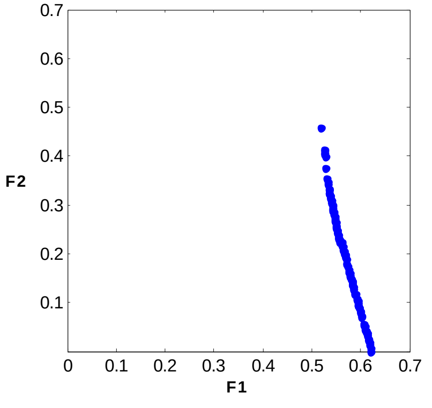


Fig. 4.3. Pareto Front of the first run when all hydrants are considered open.

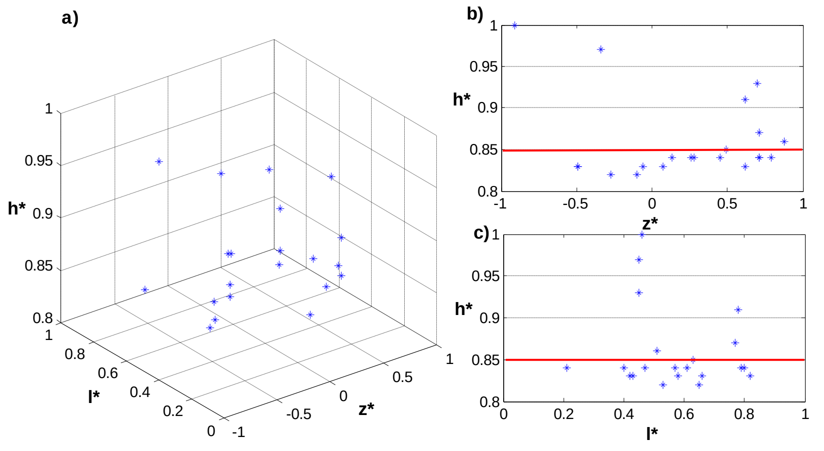
Table 4.2 summarizes the WECPM's outputs for 20 consecutive runs: 20 critical points, which are ranked according to their weighted pressure head. This table also shows the corresponding pressure heads for the three pumping stations when each critical hydrant was open, the pressure in each critical hydrant, the daily pumped flow, the energy consumption and the energy consumption per unit of supplied water in each run.

As critical points were removed from the analysis, the pumped flow was progressively reduced. Thus, to obviate the effect of the reduction in pumped flow on the decrease of energy consumption, the energy consumption per unit of supplied water was evaluated. The weighted pressure head was reduced in the consecutive runs as well as the energy consumption and the energy consumption per unit of irrigation water supplied. However, after run 8 (hydrant 155), $H_{w\text{-}j}$ was reasonably constant because the following critical points had similar pressure requirements. Considering the first 8 runs, $H_{w\text{-}j}$ was reduced from 62.8 to 52.6 m after disabling 7 critical points, which were responsible of 20 % of the energy consumption (4,794 kWh day^{-1}). Likewise, the unit energy demand (kWh m^{-3}) diminished from 0.21 to 0.17 when these critical hydrants were not operating.

After obtaining the $H_{w\text{-}j}$ for all the critical hydrants, the hydraulic dimensionless coordinate h_j^* was calculated and plotted against both topological coordinates, z_j^* and l_j^* (Fig. 4.4). The seven detected critical points had h_j^* values over 0.85. The two first critical hydrants (167 and 428) show low values of z_j^* (negative values denote that the point is below the pumping stations) and medium values of l_j^* (this indicates that the hydrants are located at an intermediate distance from the water sources). Therefore, the high values of h_j^* are due to the existence of undersized pipes. The other critical points (99, 156, 133, 115 and 38) show high values of z_j^*, hence these hydrants were located in the highest areas.

Table 4.2. Critical hydrants, optimal pressure heads of the pumping stations H_i, weighted pressure head $H_{w\text{-}j}$, pressure P in the critical hydrants, pumped flow $\sum Q_i$, energy consumption EC and energy consumption per unit of irrigation water supplied E_w

Run	Hydrant	H_1 m	H_2 m	H_3 m	$H_{w\text{-}j}$ m	P m	$\sum Q_i$ $m^3 day^{-1}$	EC $kWh\ day^{-1}$	E_w $kWh\ m^{-3}$
1	167	66.3	57.5	0.0	62.8	30	112388	24019	0.214
2	428	62.6	59.7	45.9	61.1	30	110387	22941	0.208
3	99	62.6	50.0	0.0	58.6	30	109319	21796	0.199
4	156	61.2	50.0	51.4	57.3	30	108762	21188	0.195
5	133	57.9	50.0	47.1	54.6	30	108495	20163	0.186
6	115	57.1	0.0	49.8	54.0	30	108171	19866	0.184
7	38	55.8	50.0	0.0	53.1	30	107701	19458	0.181
8	155	55.1	50.0	0.0	52.6	30	107235	19225	0.179
9	120	55.0	50.1	0.0	52.6	31	106806	19114	0.179
10	114	55.1	50.0	0.0	52.6	31	106635	19089	0.179
11	119	55.0	50.0	0.0	52.6	32	105796	18916	0.179
12	382	55.2	50.1	0.0	52.7	33	105158	18860	0.179
13	152	55.0	50.0	0.0	52.6	33	103922	18576	0.179
14	98	55.0	50.0	50.3	52.4	34	103365	18421	0.178
15	213	55.1	0.0	49.7	52.4	30	103056	18373	0.178
16	106	55.0	50.0	0.0	52.5	34	102556	18329	0.179
17	186	55.1	0.0	48.2	52.0	30	102222	18090	0.177
18	202	55.0	0.0	47.7	51.9	30	101540	17915	0.176
19	182	55.0	0.0	45.0	51.5	32	100106	17532	0.175
20	467	55.4	0.0	45.0	51.9	32	98765	17447	0.177



BEFORE				AFTER			
Hydrant	z_j^*	l_j^*	h_j^*	**Hydrant**	z_j^*	l_j^*	h_j^*
167	-0.91	0.46	1.00	428	-0.34	0.45	1.00
428	-0.34	0.45	0.97	99	0.70	0.45	0.96
99	0.70	0.45	0.93	156	0.62	0.78	0.94
156	0.62	0.78	0.91	98	0.62	0.43	0.91
133	0.71	0.77	0.87	133	0.71	0.77	0.90
115	0.88	0.51	0.86	115	0.88	0.51	0.89
38	0.49	0.63	0.85	213	0.49	0.63	0.88

Fig. 4.4. Dimensionless coordinates z_j^*, l_j^* and h_j^* of the critical points detected and comparison for the first seven critical hydrants before and after the proposed measures.

4.3.3. Improvement Actions

After analyzing the hydraulic and topological coordinates, several energy saving actions were proposed for every critical point in order to improve the network operation (Fig. 4.1). These measures implied changes in pipe sizes when z_j* was low and the installation of booster pumps for the hydrants with the highest elevations. These measures were sequentially applied in order to analyze their potential impacts in the network operation. Fig. 4.1 details the improvement actions and shows their location.

4.3.4. Potential Energy Savings after the Improvement Actions

To estimate the potential energy savings after the improvement actions, the new optimal pressure heads at pumping stations were recalculated using a new network's model which included all these changes. Then, following a similar approach, the new critical points for the improved network were detected (Fig. 4.4). These changes affected to the coordinate h_j^* but did not modify z_j^* and l_j^*, which depend on the network's topology only.

Hydrants 167 and 38 were not identified as critical points after the improvement actions and hydrants 98 and 213, which were not in the original list, appeared in the new set of the 7 most critical hydrants. In fact, after the introduction of the four first energy saving actions, hydrant 98 (which was not in the initial list of critical points) was detected as critical point and an improvement measure was designed for this hydrant. Furthermore, the values of coordinate h_j^* after the measures were significantly higher than before the changes and the difference between the first and the seventh critical point was smaller. This increase in h_j^* was related to the decrease of $H_{w\text{-}mch}$, which was now much closer to the $H_{w\text{-}j}$ values.

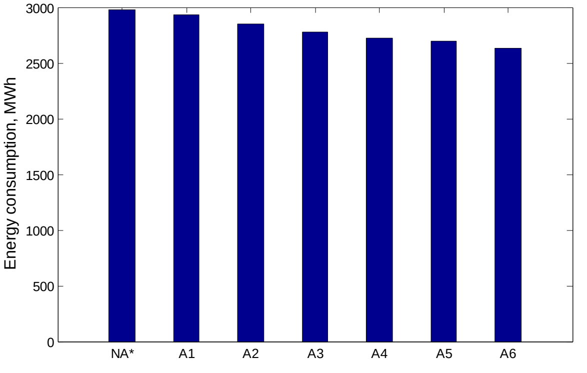
In order to estimate the monthly and annual energy savings achieved if these measures were adopted, a similar analysis was carried out for all the months of the irrigation season. Thus, the monthly energy requirements were included in the WECPM model and a new set of optimal pressure heads for the three pumping stations (those with the minimum value of F1 and F2=0) was obtained for every month. Pumping pressure heads before and after the improvement actions are shown in Table 4.3.

Table 4.3. Optimal pressure heads (m) of the three pumping stations and weighted pressure head (m) obtained with WECPM, before and after the proposed actions

	BEFORE				AFTER			
	H_1	**H_2**	**H_3**	**H_{w-j}**	**H_1**	**H_2**	**H_3**	**H_{w-j}**
Jan	59	0	53	57	55	0	48	52
Feb	59	50	0	56	55	0	48	52
March	63	56	48	60	56	0	48	53
April	66	58	48	63	57	51	53	54
May	66	58	0	63	57	0	50	54
Jun	66	58	0	63	57	50	53	54
Jul	0	0	50	50	0	0	48	48
Aug	0	0	51	51	0	0	49	49
Sept	67	58	48	64	57	50	50	54
Oct	59	0	48	56	55	50	48	53
Nov	59	0	48	56	55	0	45	52
Dec	59	50	0	56	56	0	45	53
Average				58				52
Max				64				54
Min				50				48

In all months, $H_{w\text{-}j}$ decreased after the improvement actions. The average value of $H_{w\text{-}j}$ was reduced from 58 m to 52 m whereas the peak value of $H_{w\text{-}j}$, obtained in September, decreased from 64 m to 54 m. Although May is the peak demand month, September has the largest irrigated area because most of the crops coincides in the field (Table 4.1). It should be noted that the simultaneous operation of all hydrants, each one supplying the volume of water required to irrigate its associated area, was considered in this work. Thus, the $H_{w\text{-}j}$ values were very similar in the peak demand months because more crops are simultaneously in the field. However, the daily volume of pumped water was higher in May than in other peak demand months since more irrigation time was needed (Table 4.1). Because of this, the control of critical points is the most appropriate management measure for the highest water demand months (related to both irrigated area and irrigation requirements). In this case, months with higher $H_{w\text{-}j}$ (April, May, June and September) were associated to the largest irrigated area as well as irrigation needs (Table 4.1). Moreover, the control of critical points resulted more effective in these months because the decrease in $H_{w\text{-}j}$ after the actions was more significant. The minimum value of $H_{w\text{-}j}$ occured on July with 50 m and 48 m before and after the actions, respectively (only 16 % of irrigated area).

The annual energy consumptions obtained when the improvements actions were sequentially introduced are shown in Fig. 4.5. Thus, the relation between the number of improvement actions and energy savings was obtained. The three first actions entailed almost 60 % of the energy savings achieved when all measures were introduced. Hence, managers of irrigation districts can decide the number of actions to be applied taking into account the energy saving versus the investment cost linked to each of them.



*NA: WECPM no actions

Fig.4.5. Annual energy consumption after the sequential introduction of the energy saving actions

4.3.5. WEBSOM vs. WECPM

Table 4.4 shows the monthly energy consumptions obtained when WEBSOM and WECPM strategies were adopted and compared with the monthly energy demand required for the current operation of the network. WECPM with improvement actions achieved lower energy requirements than WEBSOM in all months. In contrast to the current operation of the network, anual energy savings of 1195.4 MWh (29 %) and 1483.7 MWh (36 %) were obtained when WEBSOM and WECPM were considered, respectively. Therefore, WECPM with actions was more effective than WEBSOM in the PF irrigation district which has a flat topography with 43 m as maximum difference between hydrant elevations. Using the strategy of critical point control Rodríguez Díaz *et al.* (2012b) also achieved higher energy savings than with sectoring in irrigation districts with flat topography (the maximum elevation difference among hydrants was 45.6 m). Assuming the WECPM with actions, the peak energy demand month was May with an energy consumption of 640.8 MWh while the lowest energy demand occurred in July (20.3 MWh).

Table 4.4. Monthly energy consumption (MWh) required for the current operation of the network, after sectoring and after WECPM with and without improvement actions

	Actual operation	**WEBSOM**	**WECPM**	
			No actions[a]	**Actions**
Jan	151.4	135.0	102.6	94.7
Feb	217.2	159.9	131.0	122.9
Mar	470.2	320.4	345.6	304.7
Apr	676.3	508.8	506.6	438.5
May	962.8	707.4	744.6	640.8
Jun	352.8	241.9	264.3	228.3
Jul	36.0	27.5	21.3	20.3
Aug	104.8	68.1	62.8	59.8
Sep	402.0	281.7	306.5	260.8
Oct	415.3	265.1	278.1	262.5
Nov	191.1	119.1	124.1	115.3
Dec	135.2	84.9	90.4	82.6
Total	4115.0	2919.6	2977.9	2631.3

[a]Optimal pressure heads detected using WECPM

Comparing the potential energy savings of WECPM without actions versus the current operation of the network, the annual energy saving was the 28 % (1137.1 MWh). Moreover, this strategy achieved lower energy requirements than WEBSOM in some months (January, February, April, July, August) and the annual energy consumption was only 2 % higher than the obtained by WEBSOM. Additionally, the sectoring strategy implies irrigation in turns while WECPM with and without actions allows on demand irrigation. The annual energy demand optimized by WEBSOM is 10 % higher than the value obtained by WECPM with actions. A cost/benefit analysis is required before selecting the best management option for any irrigation network according to its particular conditions (e.g. availability of telecontrol systems and only its set up would be required). The investment cost of the improvement actions (e.g. pipe replacement) must be compensated with the economical value of the energy savings.

4.4. Conclusions

A useful methodology to detect and control critical points for multiple source networks has been proposed. This methodology is based on the algorithm WECPM, which uses the NSGAII genetic algorithm along with a hydraulic simulation model.

The analysis of WECPM on a real irrigation network has provided a potential annual energy saving of 36 % in relation with the current operation of the network, if minor improvement measures, such as the replacement of two pipes and the installation of four booster pumps, were adopted. Even without

improvement actions, WECPM could reduce 12 % of the energy consumption of the current network operation.
The strategy of controlling critical points has been compared with sectoring. The energy savings were 10 % higher compared to the results obtained by WEBSOM.

A cost/benefit analysis is required before selecting the best energy saving strategy for any irrigation network according to its particular conditions (e.g. topography, availability of telecontrol systems). Furthermore, farmers' management preferences should also be considered.

The adoption of a sectoring strategy implies the organization of the farmers in turns, losing one degree of flexibility while the control of critical points allows farmers to irrigate on demand. In contrast to sectoring, the critical points control strategy involves investment costs to perform the proposed energy saving actions. The incorporation of the energy tariff to these algorithms would help to determine which methodology achieves higher economic savings for each particular network, that is the main target for farmers and it is not always linked to the reductions in energy consumption.

Acknowledgments. This research is part of the AMERE project (AGL2011-30328-C02-02), funded by the Spanish Ministry of Economy and Competitiveness.

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5. Energy Cost Optimization in Pressurized Irrigation Networks

This chapter is currently under review in the journal "Irrigation Science", Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014)

Abstract. The increasing pressure on energy is involving higher prices of this resource, with significant implications on irrigated agriculture. This sector has undergone substantial transformations to improve water use efficiency by adapting its gravity irrigation systems to pressurized networks, with greater energy consumption and hence higher costs. Thus, farmers are demanding measures leading to reduce energy costs and ensure the profitability of their farms. In this paper, previous energy optimization models focused on the network sectoring (WEBSOM) and critical points control (WECPM) are improved by incorporating an electricity tariff module, that considers different energy prices according to the hour of the day and the day of the year, to determine the minimum energy cost taking also into account different operation conditions of the network. This methodology has been tested in an irrigation network located in Southern Spain evaluating different operation scenarios: operation with and without sectors and with and without critical points control. The results show that assuming the critical points control, combining the network operation

without sectoring in the peak energy demand months and the operation by sectors in the others, an economic saving of 13 % with respect to the scenario that does not consider the measures of sectoring and critical points control can be achieved. The proposed model is a decision-making support system that integrates alternative irrigation network operation scenarios with the structure of the electricity tariff.

Keywords. Cost optimization, electricity tariff, water supply systems, Spain

5.1. Introduction

The population growth and the associated rise of food demand involve greater pressures on the planet resources. Hence, both energy and water consumption could increase by 40 % over the next twenty years (European Commission 2011).

Irrigated agriculture plays an important role in securing food production. Thus, the world area equipped for irrigation is expected to rise in 32 M ha over the period 2005-2050 (Conforti 2011). However agriculture is a sector with high water consumption. Water diverted for irrigation has reached up to 90 % of the total water resources in arid developing countries (Brazilian *et al.* 2011). In Europe, irrigated agriculture consumes around 33 % of total water used although, in countries of Southern Europe, this figure may represent over 80 % (EEA 2012). Spain has one third of the irrigated area of Europe which consumes 80 % of the National freshwater (Tarjuelo *et al.* 2010). The productivity of a single irrigated hectare is six time higher than the obtained by rainfed production (Camacho 2005). Moreover, the irrigated agriculture sector accounts for 60 % of the total agricultural production and 80 % of total exports (López Gunn *et al.* 2012). Nonetheless, the availability of water resources for irrigation is limited in most of its regions. Thus, the switch from open channel systems to pressurized water distribution networks has been contemplated in the two National Irrigation Modernization Plans (MAPA 2001, MARM 2006). This modernization process has enhanced the conveyance efficiency and increased the flexibility in the water supply. But, in contrast, the energy demand has boosted considerably (Rodríguez Díaz *et al.* 2011).

In addition to higher energy consumption, the energy price for irrigation has risen in the last years because of both the liberalization of the electricity market since 2003 and the elimination of the special rates for irrigation in 2008, involving higher power and energy charges. In the liberalised electricity market, users (farmer or irrigation district) can directly purchase the energy in the daily market or get it by a bilateral agreement with the energy producers which is the most frequent option (Rocamora *et al.* 2012). Due to the higher energy demand and the increased energy prices, Rodríguez Díaz *et al.* (2012a) determined that management operation and maintenance costs are almost fivefold higher after the network modernization of an irrigation district case study located in Southern Spain. Therefore, farmers' profits are becoming even more reduced since they have to pay the amortization costs of both the modernization of water distribution networks and on-farm irrigation systems. The same trends are observed in other countries, like South Africa, with increases in electricity tariff of 31 % from 2009 to 2010 and expected increment of 25 % for the next three consecutive years (Brazilian *et al.* 2011).

Several authors have noted these raised energy requirements and have proposed measures to reduce them. Some of these measures have been based on the implementation of energy audits in irrigation districts (Abadía *et al.* 2012), sectoring (Carrillo Cobo *et al.* 2011, Fernández García *et al.* 2013), critical points control (Rodríguez Díaz *et al.* 2012b) or better management of pumping stations (Moreno *et al.* 2007, Lamaddalena & Khila, 2012).

Sectoring and critical points control strategies may lead to significant energy savings. When sectoring, farmers are organized in irrigation turns according to their energy demand. Carrillo Cobo *et al.* (2011) estimated energy savings of 27 % and 9 % for two case studies (Southern Spain). Regarding the critical points control (hydrants with high energy requirements), Rodríguez Díaz *et al.* (2012b) determined energy savings around 10 % and 30 % in two irrigation district located in Southern Spain. To apply the sectoring and critical points control strategies in irrigation networks with several supply points, Fernández García *et al.* (2013 and 2014) developed methodologies based on heuristic techniques which led to energy savings between 29 % and 36 %. However, in the above works, the energy cost has been estimated assuming an average energy price without considering the structure of electricity tariff. Usually, in Spain, the electricity tariffs are structured in 3 or 6 periods that vary according to the hour of the day and the day of the year. Moreover, the electricity tariff includes two terms, one related to the energy consumption and another that considers the power consumption, with different prices according to the period. The power term has undergone an average price increase of 288 % from 2008 to 2014 (MINETUR 2008, 2014) and its impact on electricity bill is increasingly growing.

In this paper, the electricity tariff is integrated within the sectoring and critical points control strategies developed by Fernández García *et al.* (2013 and 2014). Thus, possible network operation scenarios that take into account the electricity tariff are analyzed and compared to determine the minimal electricity cost, ensuring pressure requirements at hydrants.

5.2. Methodology

5.2.1. Study area

The Palos de la Frontera irrigation district (PF) is located in Huelva (Southern Spain). In this area, the annual average rainfall is 490 mm and the average reference evapotranspiration is 1145 mm (Pérez Urrestarazu *et al.* 2009). Strawberry is the main crop and covers the 75 % of the irrigated area (3343 ha). The PF irrigation network is a multi-source network and consists of 513 pipes and 227 hydrants, fed by 3 pumping stations. Each hydrant is designed to supply 1.2 Ls-1ha-1 with a service pressure of 30 m. The maximum delivery capacity of each pumping station is 1584, 1056 and 1372 Ls-1 with a pressure head of 85, 45 and 55 m, respectively.

5.2.2. Water and Energy use optimization combined with energy cost minimization

The algorithm WECO (Water, Energy and Cost Optimization) has been developed to get the optimal operation of an irrigation network taking into account the minimization of both energy cost and pressure deficit at hydrants, ensuring as well the water requirements of crops. A new module comprising the electricity tariff has been incorporated into the optimization algorithms proposed by Fernández García *et al.* (2013 and 2014): WEBSOM (Water and Energy Based Sectoring Operation for Multiple Supply Sources) and WECPM (Water and Energy optimization by Critical Points control for Multiple supply sources).

Genetic algorithms (Goldberg 1989) are heuristic techniques widely applied to many optimization problems of water distribution systems (Montesinos *et al.* 1999, Reca *et al.* 2008, Jiménez-Bello *et al.* 2010, Fallah-Mehdipour *et al.* 2012). These algorithms provide a set of optimal solutions of the considered optimization problem by minimizing or maximizing one objective function. However, many decision making problems need to achieve several conflicting objectives (Savic 2007). In a multiobjective approach the set of optimal solutions are known as the Pareto front and it is made out of solutions with a wide range of accomplishment of the different objectives. WEBSOM and WECPM were developed using the NSGA-II multiobjective algorithm (Non-dominated Sorting Genetic Algorithm) (Deb *et al.* 2002) because of its successful application in the optimization of this type of problem (Farmani *et al.* 2006, Consoli *et al.* 2008).

The algorithm WECO links WEBSOM and WECPM by means of the electricity tariff module to analyze and compare the following optimal network operation scenarios:

- Scenario 1: Operation of the irrigation network by sectors (WEBSOM).
- Scenario 2: Irrigation network operation without sectors (WECPM without actions).
- Scenario 3: Operation of the irrigation network without sectors and considering improvement actions after the critical points identification (WECPM with actions).
- Scenario 4: Operation of the network when sectoring and critical points control (with actions) strategies are implemented simultaneously (combination of scenario 1 and 3).

Thus, WECO enables to compare and determine which operation scenario achieves the highest economic saving. WECO has been implemented in MatLabTM (Pratap 2010) using EPANET as hydraulic simulator (Rossman 2000). A general overview of the WECO algorithm is shown in Fig. 5.1.

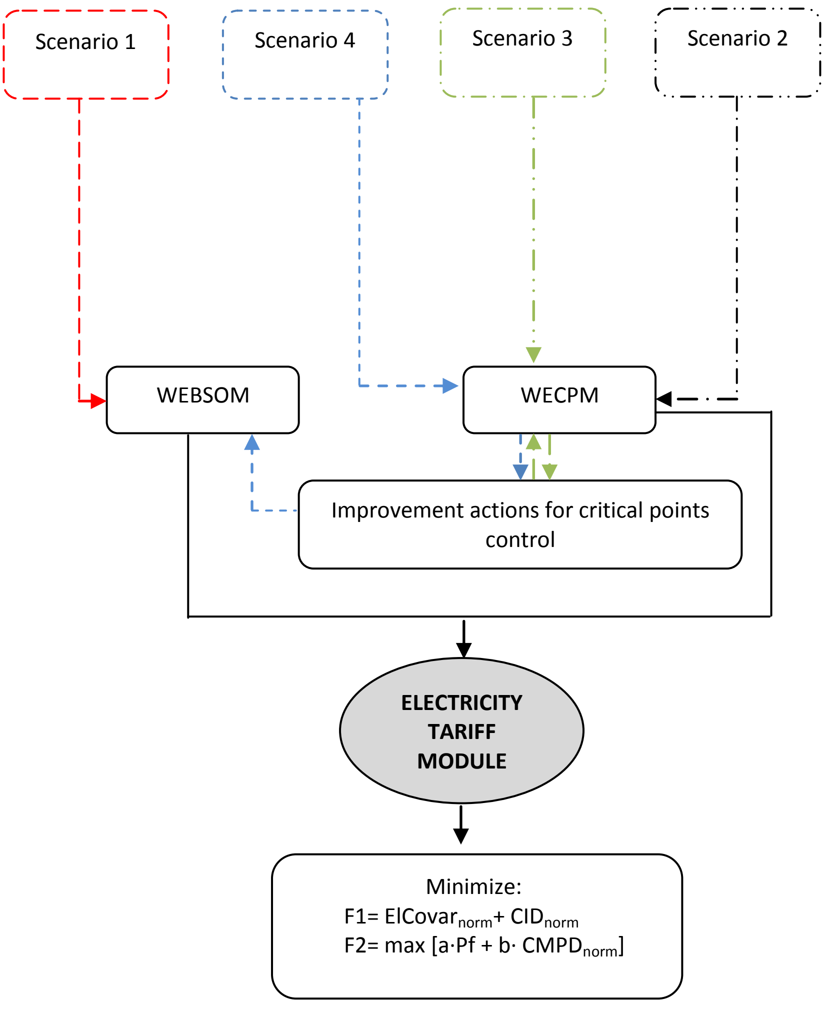

Fig. 5.1. Schematic representation of WECO algorithm

5.2.2.1. Electricity tariff module

The electricity tariff data are stored in this module to integrate them in the network operation scenarios. The structure of the electricity tariff is strongly related to the electrical market and regulations of each country. Two types of tariff schedules are commonly offered to the users: one with a flat rate in which the same energy price is considered all day and another one with different prices according to the time of energy consumption. These time-of-use tariffs consider different periods, each one with a specific energy price. The number of periods and the length of each of them can vary according to the day. Normally, peak demand periods involve higher rate for electricity while off peak periods entail lower energy price.

Time-of-use tariffs are often contracted by the irrigation district. Thus, for a certain tariff, the annual electricity cost (€ $year^{-1}$) is obtained by summing two terms: a fix cost concerning the contracted power ($ElCo_{fix}$) and a variable cost linked to the energy consumption ($ElCo_{var}$), both according to the energy price in each period:

$$ElCo = ElCo_{fix} + ElCo_{var} \qquad [5.1]$$

$ElCo_{fix}$ (Eq. 5.2) and $ElCo_{var}$ (Eq. 5.3) are determined as follows:

$$ElCo_{fix} = \sum_{p=1}^{np} Power_{maxp} \cdot Ppower_p \qquad [5.2]$$

Where p is the period index, np is the number of periods, $Power_{maxp}$ is the contracted power according to the maximum demanded value in period p and $Ppower_p$ the power term price in period p.

$$ElCo_{var} = \frac{1}{1000} \cdot \frac{1}{\eta} \cdot \gamma \cdot \sum_{d=1}^{nd} \sum_{w=1}^{nsect} \sum_{p=1}^{np} t_p \cdot Pec_p \sum_{i=1}^{N} (Q_{ipwd} \cdot H_{ipwd}) \quad [5.3]$$

Where d, w, and i are the day index, the sector index, and the pumping station index, respectively. nd is the number of operation days, n_{sect} the number of possible sectors (when the network is operated by sectors), N the number of pumping stations, η the global efficiency of pumps, γ the water specific weight (9800 Nm^{-3}), t_p the daily irrigation time (h) during period p, Pec_p (€ kWh^{-1}) the energy price according to period p and Q_{ipwd} (m^3s^{-1}) and H_{ipwd} (m) are the pumped flow and the pressure head supplied by station i during period p when sector w operates during day d.

Using this general tariff, the annual electricity cost can be obtained for a wide range of real cases.

5.2.2.2. Network operation scenarios

- Scenario 1

This scenario is evaluated with the WEBSOM algorithm (optimal sectoring) linked to the electricity tariff module. Hydrants are grouped according to two dimensionless topological coordinates that relate hydrant elevation and distance from the pumping stations. According to the topology of the network, hydrants may be classified into 2 to n_{sect} sectors. WEBSOM establishes an optimum sectoring calendar according to minimum energy cost and minimum both irrigation and pressure deficits. Thus, the optimum number of irrigation sectors varies from one month to another.

Then, the customized NSGA-II proposed by Fernández García *et al.* (2013) was applied after including several modifications related to the generation of the initial population and the objective functions, described as follows:

- Initial population

In this case, the number of variables of each chromosome, n_v, (Fig. 5.2a) was obtained as follows:

$$n_v = N \cdot n_{sect} \cdot n_d \quad [5.4]$$

- Objective functions

The following objective functions, determined for each month of the irrigation season, were minimized:

$$F1_{sce1} = ElCo_{var\,norm} + CID_{norm} \quad [5.5]$$

$$F2_{sce1} = \max\left[a \cdot Pf + b \cdot CMPD_{norm}\right] \quad [5.6]$$

Where $ElCovar_{norm}$ is the normalized total energy cost and CID_{norm} is the normalized maximum irrigation deficit obtained by the difference between the theoretical irrigation requirements of all crops (estimated according to Allen *et al.* 1998) and the supplied flow by all pumping stations, both for day *d* (Fernández García *et al.* 2013). The normalization of both terms by the distribution U (0,1) was carried out to perform their summation. $ElCovar_{norm}$ and CID_{norm} varied from 0 to 1. Therefore, the minimum and maximum value of F1 was 0 and 2, respectively.

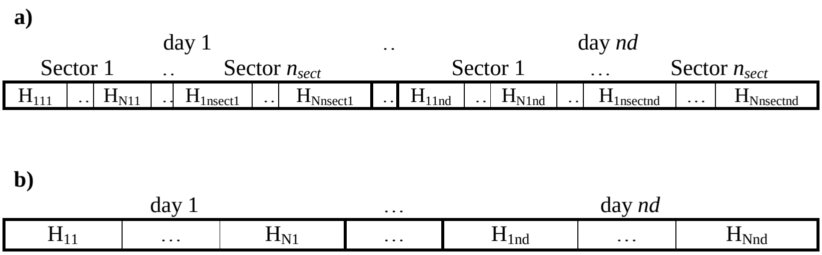

Fig. 5.2. Schematic representation of a chromosome for scenarios 1 and 4 **(a)** and for scenarios 2 and 3 **(b)**

In Eq. 5.6, *Pf* is the pressure failure percentage which ranged from 0 (all hydrants get the service pressure) to 1 (all hydrants get a pressure lower than the service pressure) and $CMPD_{norm}$ is the normalized term that evaluates the monthly magnitude of pressure deficit (Fernández García *et al.* 2013). *a* and *b* are coefficients with values 0.5 and 1.5 to penalize those solutions with an increased *CMPD* term. *Pf* and *CMPD* were calculated for all operating sectors in a certain day. The value of $F2_{sce1}$ was the maximum value obtained by summing up these terms for each sector. The minimum and maximum value of $F2_{sce1}$ was 0 and 2, respectively.

The minimal value of the term $ElCo_{var}$ depends on the optimal combination of Q_{iwks} , H_{iwks}, and Pec_p. Thus, the daily power demand of the operating sectors was determined. Then, sectors were sorted in descending order of power demand and electricity tariff periods were sorted in increasing order of energy price (Pec_{np}, Pec_{np-1}, …, Pec_1). Starting with the most power demanding sector, if the daily time required to satisfy the crop irrigation requirements (t_{rs}) was lower than the number of hours of the upper period (t_{np}), the energy cost of this sector was determined by multiplying its power demand by the term t_{rs} and by Pec_{np}. In contrast, if t_{np} was lower than t_{rs}, the energy cost in this period of the sector considered was calculated by multiplying its power demand by t_{np} and by Pec_{np}. The remaining hours (t_{rs}-t_{np}) were assigned to the next tariff period (*np-1*) and the energy cost of this sector in this period was obtained by multiplying the power demand by (t_s-t_{np}) and by Pec_{np-1}. Therefore, the energy cost of the aforementioned sector was the sum of the energy costs obtained in each period. The energy cost of the following operating sectors was calculated by the same procedure but starting in the tariff period in which the previous power demanding sector finished. When t_{rs} was greater than the water availability time according to the sectoring option (t_a), the irrigation requirements were not fully satisfied (Fernández García *et al.* 2013).

- Scenario 2

This scenario can be evaluated with the WECPM algorithm linked to the electricity tariff module to determine both the minimum energy cost and pressure deficit. The crop water requirements were indirectly considered in the calculation of the energy cost. Using this algorithm, the optimal pressure heads in pumping stations when all hydrants operate simultaneously were obtained. The NSGA-II algorithm has been adapted to the current problem:

- Initial population

The number of variables of each chromosome, n_v, (Fig. 5.2b) was determined as follows:

$$n_v = N \cdot n_d \quad [5.7]$$

- Objective functions

The objective functions stated in Eq. 5.5 and 5.6 were minimized. However, in this case the term CID_{norm} was 0 in all cases because WECPM does not consider the sectoring operation and the irrigation time required to satisfy the crop water demand is always enough.

The electricity tariff module was integrated in this scenario as follows: in a certain day, irrigation started in the period with the lower energy price, *np*. If t_{rs} was lower than t_p, the daily energy cost of network operation was obtained by multiplying the power demand by t_{rs} and by Pec_{np}. In contrast, when t_{rs} was greater than t_p, irrigation occurred during several tariff periods. Therefore, the energy cost in *np* period was calculated by multiplying the power demand by t_p and by Pec_{np}. The energy cost in the following tariff period, *np-1*, was determined by multiplying the power demand by (t_{rs} - t_p) and by Pec_{np-1}. Hence, the daily energy cost was the sum of the energy costs obtained in each period.

- Scenario 3

In this case, the optimization process described in scenario 2 was applied but considering the proposed energy saving actions to control the critical points identified in the network (Fernández García *et al.* 2014). These improvement measures implied changes in pipe sizes and the installation of booster pumps.

- Scenario 4

WECPM and WEBSOM algorithms were sequentially applied in combination with the tariff module to determine the minimum energy cost when the irrigation network was managed by sectors and the measures to improve the operation of critical points were implemented. The process of detection and control of critical points was carried out by WECPM (scenario 3) followed by the application of WEBSOM (scenario 1).

5.3. Results and Discussion

The proposed scenarios were evaluated in the PF irrigation network assuming a pumping efficiency of 0.8. As strawberry (with the largest irrigated area) is a low water stress tolerance crop, the term CID_{norm} was 0 when irrigation deficit did not occur and 1 when CID_{norm} was de 5 % of theoretical crop irrigation requirements (Q_{req}). Irrigation deficits higher than 5 % of Q_{req} were penalized with *F1* and *F2* values of 2 and 1.9, respectively. Lower values than those above could remove possible solutions of the optimization problem while the value 2 for both objective functions was set to unfeasible solutions that can be generated during the optimization process.

As regards the algorithm parameters, 50 individuals and 100 generations and crossover and mutation probabilities of 0.9 and 0.1, respectively, were set for the four scenarios. Table 5.1 shows the number of variables in each scenario. The values of the total head of the three pumping stations ranged from 0 (the pumping stations were not operating) and a random number between 45 to 95 m.

Table 5.1. Number and value of variables of the optimization process for each scenario

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Parameters	N=3 n_{sect}=5	N=3	N=3	N=3 n_{sect}=5
n_v	June	45	9	9	45
	Rest of months	30	6	6	30

5.3.1. Electricity tariff effects

						1-15	15-30						
Time	Jan	Feb	Mar	Apr	May	Jun		Jul	Aug	Sep	Oct	Nov	Dec
00-01	1	3	1	1	1	1	1	1	3	1	3	1	1
01-02	1/3	3	1	1	1	1	1	1	3	1	3	1	1/3
02-03	3	3/1	1	1	1	1	1	2	3	1	3	1/3	3
03-04	3/2	1	1	1	1	1/2	1/3	2	3	1	3	3	2
04-05	2	1	1/3	1	1	2	3		3/1		3/1	3/4	2/4
05-06	2	2	3	1	1	2	3		1		1	4	4
06-07		2	3	1	1	2	3		1		1	4/2	
07-08		2	3		1		2		1		1	2	
08-09			3		1		2		1/2		1	2	
09-10			3/4		1		2		2		1/2		
10-11			4						2		2		
11-12			4						2		2		
12-13			4						2		2		
13-14			4						2		2		
14-15			4/2								2		
15-16			2										
16-17			2										
17-18			2										
18-19													
19-20							2/4						
20-21							4						
21-22							4						
22-23			2				4						
23-24			2										

		Energy price, c€ kWh^{-1}	Power Price, c€ kW^{-1}
	P6	6.99	169
	P5	9.33	370
	P4	9.97	370
	P3	11.03	370
	P2	11.37	505
	P1	13.18	1009

* Weekends are always in P6

Fig 5.3. Periods and energy and power price in the 6-period tariff (for the 2009 irrigation season) and scheduling of operating sectors (working days) in scenario 1

The 6-period Spanish tariff was applied to the studied irrigation district since the contracted power exceeds the value of 450 kW (ME 2001). Period 1 (P1) is the most expensive and both the energy and power price is progressively reduced to P6, the lowest price period. Two different types of days, working days and weekends (Saturdays and Sundays) are proposed in each month in this tariff but in June, in which three different types of days (first and second half and weekends) were considered. Hence, we optimized the annual cost (energy and power cost) taking into account two different types of days in every month (three in June). Weekends are charged according to the P6 (Fig. 5.3).

The electricity tariff structure particularly affected the network operation by sectors since the irrigation in turns involved up to 19 operating hours (Table 5.2). Thus, irrigation in expensive hours could occur.

Table 5.2. Operating hours per day in each scenario

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Jan	5.1	1.7	1.7	5.1
Feb	7.5	2.5	2.5	7.5
Mar	19.2	4.8	4.8	4.8
Apr	6.7	6.7	6.7	6.7
May	9.5	9.5	9.5	9.5
Jun	7/14	3.5/3.5	3.5/3.5	3.5/3.5
Jul	4	2	2	6
Aug	13.2	4.4	4.4	13.2
Sep	3.9	3.9	3.9	11.7
Oct	14.1	4.7	4.7	14.1
Nov	8.8	2.2	2.2	6.6
Dic	6	1.5	1.5	7.5

When the electricity tariff was included in the analysis, the optimal number of sectors differed from those obtained in the original WEBSOM model. Furthermore, two sectoring options per month (three in June), working days and weekends, were obtained after including the electricity tariff. Table 5.3 compares the optimal sectors operation calendar obtained by Fernández García *et al.* (2013) and the new calendar obtained for scenarios 1 and 4. Using WEBSOM without the energy tariff, 5 sectors could operate in June and October. When the electricity tariff was considered the maximum number of operating sectors (working days) was 4, in scenario 1, and 5 (December) in scenario 4.

Table 5.3. Optimal sectors operation calendar obtained by the original WEBSOM (A), WECO scenario 1 (working days and weekends) (B) and WECO scenario 4 (working days and weekends) (C)

	t_{rs}	A	B	C
Jan	1.7	2	3/3	3/5
Feb	2.5	2	3/5	3/3
Mar	4.8	3	4/5	1/4
Apr	**6.7**	**3**	**1/3**	**1/3**
May	**9.5**	**2**	**1/3**	**1/1**
Jun	3.5	5	2/4/4*	1/1/4*
Jul	2	3	2/3	3/3
Aug	4.4	2	3/2	3/5
Sep	3.9	4	1/4	3/4
Oct	4.7	5	3/4	3/4
Nov	2.2	4	4/4	3/4
Dec	1.5	3	4/3	5/5

* The first, second and third value are associated to the first half, second half and weekends of June

Moreover, the number of operating sectors in working days in peak water demand months (greatest t_{rs}), April and May, was reduced because a larger number of operating sectors were led to irrigate in expensive hours. Thus, energy cost could be higher if the number of operating sectors increased. Related to this, Table 5.4 reports the values associated to two possible solutions derived from scenario 1 in March, October and November. Solution 1 showed energy consumptions lower than solution 2 in those months. However, energy costs associated to solution 1 were higher than in solution 2. This effect is explained observing the number of operating sectors (working days) in both solutions. In solution 1, with lower energy consumptions, the number of sectors was greater than in the solution 2, implying the network operation in expensive hours. Therefore, energy cost was higher. This seems to indicate that the electricity tariff structure does not promote the reduction of energy consumption. As an example, Casado (2012) studied the water and energy management in a Southern Spain irrigation district. The network was operated only in P6 period in the irrigation season 2009/2010. He reported an energy cost reduction in 2009/2010 with regard to 2008/2009 (when the demand concentration in P6 did not occur). However, energy consumption between both irrigation seasons increased because the demand concentration, higher pumped flows, involved a reduction of the pumping efficiency and higher friction losses in pipes. Related to this, Rocamora *et al.* (2012) indicated that the proper selection of the energy contract may increase the economic efficiency but not necessarily the energy efficiency.

Table 5.4. Energy consumption, EC (MWh month^{-1}), energy cost, ElCo (€ month^{-1}) and operating sectors (in working days) in two possible solutions obtained in scenario 1

	Solution 1			Solution 2		
	EC, MWh	**ElCo, €**	**Sectors**	**EC, MWh**	**ElCo, €**	**Sectors**
Mar	327	25,837	4	346	25,040	2
Oct	253	19,012	3	257	18,553	2
Nov	110	7,799	4	111	7,771	3

The electricity tariff involved a significant step forward in obtaining a realistic optimum sectoring calendar since it provided the scheduling and the operation sequence of the sectors during the day according to their power demand and the energy cost (Fig. 5.3). When the network was managed without sectors (scenarios 2 and 3), the electricity tariff established an irrigation scheduling concentrated in the lowest price periods.

5.3.2. Scenario comparison

Fig. 5.4 shows the Pareto fronts obtained in each scenario for the peak water demand month (May). In order to compare the scenarios, priority was given to the minimization of pressure deficit (F2) over the minimization of energy cost (F1) in the selection of the solution from the Pareto front. This criterion was assumed since the minimum energy cost solution of the Pareto front in scenarios 1, 2 and 4 involved unacceptable pressure deficits.

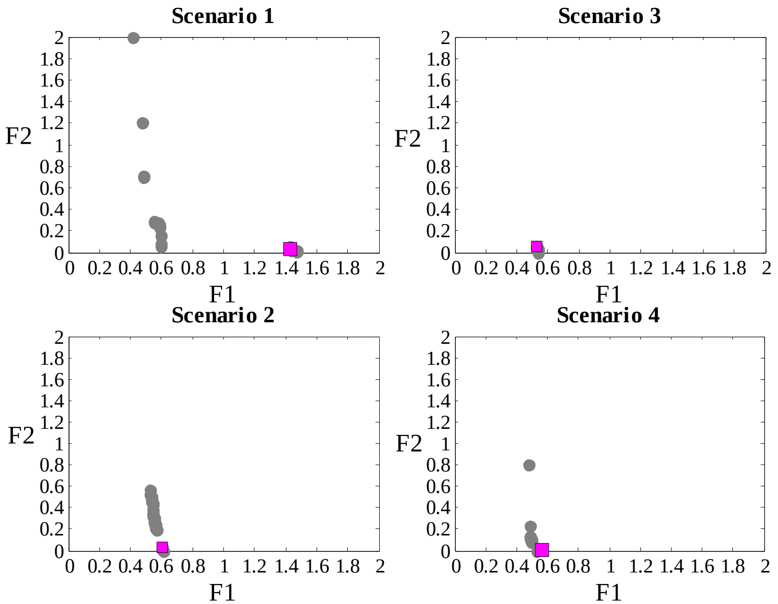

Fig 5.4. Pareto front obtained for May in every scenario

In scenario 1, the adopted solution (square marker) had $F1_{sce1}$ and $F2_{sce1}$ values of 1.43 and 0.02, respectively. However, other solution (S2) in the Pareto front had $F1_{sce1}$ and $F2_{sce1}$ values of 0.60 and 0.06, respectively. *A priori*, S2 seemed to be better than the selected solution. Nevertheless, the terms $ElCovar_{norm}$ and CID_{norm} in the chosen solution were 0.53 and 0.91 while these terms in S2 were 0.59 and 0.01, which implied higher energy demand (814 MWh and 59,027 € compared to 728 MWh and 52,791 € in the selected solution) but with similar quality of service.

Table 5.5 reports the values of energy cost, energy consumption, irrigation deficit, pressure in the critical hydrant and number of critical hydrants (hydrants with pressure lower than service pressure) associated to each selected solution (square marker) of the Pareto fronts plotted in Fig. 5.4.

Table 5.5. Values associated to the selected Pareto front solution in May

	Sce. 1	Sce. 2	Sce. 3	Sce. 4
ElCo, € month^{-1}	52,791	54,670	47,524	55,405
Energy consumption, MWh month^{-1}	728	754	656	768
ID (% of $Qreq_{May}$)	5	-	-	-
Number of critical hydrants (working days)	-	-	4	-
Number of critical hydrants (weekends)	-	2	-	-
Pressure in the critical hydrant (working days), m	30	30	29	30
Pressure in the critical hydrant (weekends), m	30	29	30	30

Improvement actions performed in scenarios 3 and 4 consisted in the replacement of 442 m of pipes and the installation of 3 booster stations (one of them supplied two critical points) (Fernández García *et al.* 2014) and the investment costs and energy cost of operation of the booster pumps were included in the analysis of these scenarios. Investment costs amounted 13,951 € and the annual cost (1,895 €) was determined considering a payback period of 10 years and an interest rate of 6 % (Table 5.6). Thus, the annual cost per hydrant was estimated in 8.35 €.

Table 5.6. Energy consumption, energy cost (operation costs and amortization costs of improvement actions), contracted power and power cost in each scenario

	Energy consumption, MWh				**Energy cost, €**			
	Sce 1	Sce 2	Sce 3	Sce 4	Sce 1	Sce 2	Sce 3	Sce 4
Jan	93	102	97	86	6,484	7,142	6,807	5,983
Feb	122	131	127	115	8,496	9,153	8,886	8,007
Mar	327	354	318	313	25,837	24,756	22,245	21,909
Apr	512	512	433	455	35,809	35,791	30,281	31,801
May	728	754	656	768	52,791	54,670	47,524	55,405
Jun	270	289	229	283	19,912	20,183	15,997	19,778
Jul	20	23	21	20	1,388	1,621	1,469	1,363
Aug	58	67	62	57	4,032	4,685	4,321	3,977
Sep	314	304	264	252	21,949	21,237	18,473	18,554
Oct	253	284	275	242	19,012	19,840	19,193	18,145
Nov	110	127	124	108	7,840	8,884	8,688	7,529
Dic	79	91	92	77	5,504	6,331	6,401	5,353
	2885	3037	2698	2774	209,054	214,294	190,284	197,805
Amortisation costs					-	-	1,895	1,895
	Contracted power, kW				**Power cost, €**			
P6	2,650	2,920	2,410	3,460	4,479	4,935	4,072	5,847
P5	2,540	2,600	2,180	2,270	9,398	9,620	8,066	8,399
P4	530	200	200	370	1,961	740	740	1,369
P3	400	200	200	200	1,480	740	740	740
P2	380	200	200	200	1,919	1010	1,010	1,010
P1	200	200	200	200	2,018	2018	2,018	2,018
					21,255	19,063	16,647	19,383
Total electricity cost					**230,309**	**233,357**	**208,826**	**219,083**

Scenario 3 achieved both lowest energy consumption and cost although a slight pressure deficit (only 1m) was obtained in four hydrants during working days on May that could be acceptable for farmers as 29 m of pressure is sufficient for drip irrigation systems.

Scenario 2 obtained the highest values although it should be noted that scenario 2 determines the optimal pressure heads in the pumping stations and does not consider measures such as sectoring or critical points control. However, this scenario has wider applicability because investment costs and establishment of irrigation turns are not necessary.

Comparing monthly energy consumptions, scenario 1 achieved lower values than scenario 3 in all months but March, April, May, June and September, the months with higher instantaneous water demand (Fernández García *et al.* 2014). In these months, scenario 3 was better. Likewise, scenario 3 achieved lower energy consumption than scenario 4 in April, May and June. However, unlike scenario 1, scenario 4 performed better than scenario 3 in March and September.

Taking into account the energy cost, scenario 3 achieved the lowest value, increasing gradually in scenarios 4 (4 %), 1 (9 %) and 2 (11 %). However, scenarios 1 and 4 were more effective than scenario 3 in off-peak months.

5.3.3. Additional economic savings related to contracted power

The four scenarios analyzed by WECO algorithm considered the simultaneous operation of hydrants. Thus, the maximum power demand in each tariff period was determined. This information is the key to adjust the fix term in Eq. 5.1, the contracted power. In

Spain, the contracted power must be at least equal to the maximum power demand in each tariff period to avoid cost penalties. For this reason, irrigation districts often contract an increased value of power, higher than the strictly required value and hence, the power cost is higher. WECO provided the optimized value of power demand, and consequently the recommended values of the contracted power for the different periods. The maximum power requirements occurred in period P6: 2650 kW, 2920 kW, 2410 kW, and 3460 kW in scenarios 1, 2, 3 and 4, respectively (Table 5.6). These values were significantly lower than the contracted power of 7522 kW indicated by Rodríguez Díaz *et al.* (2011) for this irrigation district in this tariff period. The annual power cost in every scenario is shown in Table 5.6. The lowest power cost was achieved in scenario 3 and this cost increased gradually in scenarios 2, 4 and 1. Scenario 1 showed the greatest cost since power was contracted in all periods, but period P1. In scenario 4, power was contracted in periods P6, P5 and P4 while scenarios 3 and 2 involved power contracting in periods P6 and P5, with the lowest power prices. In the tariff periods in which the irrigation network did not operate, a minimum power of 200 kW was contracted to the maintenance of facilities.

Analysing these results, the strategy that leads to the minimum electricity cost, both the energy cost (also the minimum energy consumption) and the power cost, could be a combination of scenarios 3 and 4 during the irrigation season. According to this, improvement measures on critical hydrants would be performed. Then, all hydrants could irrigate at the same time in April, May, June and September while in the other months, the irrigation network would be operated in sectors. Thus, the annual energy consumption would be 2598 MWh and the energy cost 184,541 €. Hence, an additional reduction of 100 MWh (3 %) in energy consumption and 5743 € (3 %) of energy cost with respect to scenario 3 (scenario with the lowest energy consumption and cost) could be achieved. The contracted power would be the same as the proposed in scenario 3 and hence, the power cost would achieve 16,647 €. Thus, taking into account the energy and power cost and the amortization cost, the total electricity cost associated to this strategy would be 203,083 €.

5.4. Conclusions

The higher energy requirements in pressurized irrigation networks along with the increase of the energy prices have meant an important reduction of farm profits.

The algorithm WECO provides the optimal operation of irrigation networks that minimizes both energy cost and pressure deficit at hydrants according to different scenarios: all the hydrants in the network work simultaneously or the network is operated by sectors and with and without critical points control. The WECO algorithm upgrades the previous models (WEBSOM and WECPM) including the electricity tariff structure to determine the irrigation scheduling associated to the minimum total electricity cost according to the price of energy and power in each tariff period.

The algorithm has been applied to a real irrigation network. The network operation without sectoring and taking into account the measures that improve the operation of critical points achieves the minimum annual cost in the network studied. However, if the energy cost analysis is carried out per month, the sectoring operation combined with measures to ameliorate the hydraulic behavior of the critical hydrants performs better in months with low irrigation requirements. Thus, if measures to control the critical points are assumed, combining the network operation without sectoring in peak energy demand months and the operation by sectors in the others, an additional reduction of the energy cost is achieved. WECO also enables the optimization of the contracted power, the fix term of the electricity tariff whose proper selection involves significant economic savings, providing optimal irrigation scheduling with the lowest electricity cost per year.

WECO is a decision-making support system that can analyze alternative irrigation network operation scenarios. Water managers and farmers can choice the scenario according to their preferences: from the simplest applicable scenario with the optimization of pressure heads in the pumping stations only that entails smaller economic savings up to another scenario with improvement actions in critical points and irrigation scheduling in turns that can provide the lowest operation and power costs.

Acknowledgments. This research is part of the AMERE project (AGL2011-30328-C02-02), funded by the Spanish Ministry of Economy and Competitiveness.

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6. Optimum Pumping Station Management for Irrigation Networks Sectoring. Case of Bembezar MI (Spain)

This chapter has been published entirely in the journal "Agricultural Water Management", Fernández García I, Moreno MA, Rodríguez Díaz JA (2014)

Abstract. Changing from old open channel distribution systems to pressurized irrigation networks to improve water use efficiency has involved an increase in energy consumption. As total energy costs have significantly increased in recent years, modernization is sometimes an additional problem for farmers because it has led to increased water-related costs. Several authors have highlighted that irrigation system sectoring, where hydrants are grouped in sectors with similar energy requirements, is one of the most efficient energy saving measures. However, with sectoring the pumping station may have to work under flow and pressure conditions that are very different from its optimum operational point, which would make it impractical from an operational standpoint. In this study, a new model (WEBSOMPE), which optimizes the sectoring operation and pressure head, has been developed and applied in a typical irrigation district in Southern Spain. The benefits of the installation of up to three variable speed drives have been modeled and analyzed. The joint use of

sectoring and VSDs (Variable Speed Drives) would lead to energy savings of up to 26 % and guarantee the service pressure at the hydrant level. One major benefit over the alternative of replacing pumps is that the installation of VSDs would not represent major investments in infrastructure.

Keywords. Energy, variable speed drive, irrigation, water

6.1. Introduction

In 2012, the European Commission published a report entitled "Blueprint to safeguard Europe's waters" (European Comission, 2012). In support of this, the European Environment Agency (EEA) published a number of reports highlighting the pressures on European water resources. In these reports the water-energy nexus were one of the priorities, stating that water distribution systems should be analyzed in a smart regional energy management. In Spain, the change from old open channel distribution systems to pressurized irrigation networks to improve water use efficiency has involved higher energy consumption. The energy demand per unit of water was estimated by Rodríguez Díaz *et al.* (2011) to be 0.41 kWh m^{-3}, but this value can be much higher where water is diverted from deep aquifers or supplied to steep areas with large differences in elevation from the water source to the point of supply (hydrant). Over the last years, the energy tariffs have dramatically increased. As total energy costs have significantly grown in recent years, modernization is sometimes an additional problem for farmers because it has led to a nearly four-fold increase in water prices, from 100 to 400 € ha^{-1} (Rodríguez Díaz *et al.* 2011). Similar trends have been observed in other countries such as South Africa and Australia (Brazilian *et al.* 2011; Jackson *et al.* 2010). Several authors have highlighted the high energy requirements in pressurized irrigation networks and have proposed measures to reduce them (Abadía *et al.* 2012; Jiménez Bello *et al.* 2010). CarrilloCobo *et al.* (2011) developed a methodology based on sectoring (grouping hydrants according to their energy demand) which would lead to potential energy savings of 9–27 % in two Andalusian irrigation districts (Southern Spain). For the same irrigation areas, Rodríguez Díaz *et al.* (2012) determined energy savings of 10 % and 30 % by controlling critical points (hydrants with especial energy requirements). These previous studies analyzed optimum network management without considering the interactions between the network and the pumping station. Nevertheless, one criticism is that the efficiency of pumping stations, designed to supply water on demand, could be extremely low after adopting energy saving strategies in which the pumping system would work under different pressure head and flow conditions (Pérez Urrestarazu and Burt, 2012). In order to save energy when the pumping station is included in the optimization process, the pumping system must be modified and adapted to efficiently supply water for a wide range of pressure heads.

Pumping for water distribution and groundwater extraction are the main energy consumers in pressurised water networks. There are two main actions for reaching the objective of reducing energy consumption in pumping systems: 1) proper design and sizing of new pumping systems and 2) proper management of pumping systems based on the actual demand of the system. For both actions, it is necessary to model the pumping station and carry out a theoretical (applicable to design) or real (for improving management) performance analysis of the pumping station. Adjusting pumping station regulation to the actual demand is particularly complex for an on-demand network where the pumping station must supply a very wide range of flows and pressures. Pumping stations supply mostly low or medium discharge and not maximum discharge (Moreno *et al.* 2007, Lamaddalena and Khila, 2012). Thus, it is necessary to improve the efficiency for low and medium discharge, not only high discharge (design flow). Another aspect to consider in the regulation of pumping stations is the use of variable speed drives (VSD) for fitting energy consumption to energy demand. Ait Kadi *et al.* (1998) demonstrated that around 25 % of energy consumption can be saved in an irrigation district in Morocco by using variable-speed pump technology. Lamaddalena and Khila (2012) reported that energy savings of 27 % to 35 % could be achieved using an appropriate average speed regulation in two Italian on-demand irrigation districts. However, most of these analyses do not take into account the effect of VSD efficiency on the final result. In previous studies, this efficiency has been analyzed as an independent issue and has not been considered in modeling pumping systems. Thus, it is crucial to consider the VSD efficiency in accounting for energy savings and not assume that it will be always high.

The aim of this study is to reduce energy demand, using modeling techniques to analyze the feasibility of combining optimal network management and pumping station performance in Bembézar MI (BMI, Southern Spain) which was originally designed to supply water on demand. Thus, a sectoring strategy is developed for BMI and the required improvements in the pumping station based on the installation of VSD are estimated.

6.2. Methodology

6.2.1. Study area

The BMI irrigation district is located in the Guadalquivir River Basin, (GRB; Andalucía, Southern Spain). Average annual rainfall in GRB is 550 mm and potential evapotranspiration is 1335 mm (Rodríguez Díaz *et al.* 2007). 50 % of the irrigated area (4000 ha) is devoted to citrus fruits, which are becoming increasingly important in the basin.

BMI is characterized by a steep topography with hydrant elevations ranging from 58 m to 103 m (Fig. 6.1). The irrigation network is comprised of 28 hydrants designed to supply 1.2 $Ls^{-1}ha^{-1}$ with a service pressure of 30 m. Water is conveyed through 220 pipes with a total length of 32 km. Currently the irrigation network is operated on-demand, which means that water is continuously available to farmers.

The pumping station (elevation of 93 masl) was originally designed to supply water on demand and is composed of seven split case horizontal centrifugal pumps. There are 2 types of pumps: A, with lower power to supply water when a few hydrants are open, and B, higher power pumps (Table 6.1). There are 3 pumps of type A and four of type B. One of the A pumps is activated with a VSD, and the remainder work as fixed pumps. The sequence of activation is the variable speed pump (VSP) followed by all A and B pumps, consecutively.

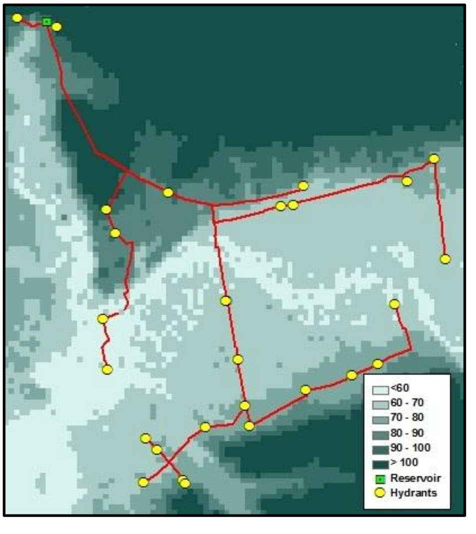

Fig. 6.1. Land topography (m) and layout of the BMI irrigation network

Table 6.1. Main characteristics of the pumps

Type A	Type B
Power: 315 kW	Power: 800 kW
Frequency 50 Hz	Frequency 50 Hz
Voltage 6000 V	Voltage 6000 V
Rotation speed: 1488 r.p.m	Rotation speed: 992 r.p.m

6.2.2. Energy and pumping efficiency management scenarios

The aim of this study is to determine the optimal operation of irrigation networks when they are operated in sectors and to adapt the pumping station by including VSDs to achieve maximum pumping efficiency. With this aim, four scenarios were analyzed:

- Scenario 1: This scenario corresponds to the current management of the irrigation district in which one of the pumps is activated with a VSD and all other pumps work as fixed pumps. The network is organized on-demand; hence, water is continuously available to farmers.
- Scenario 2: This is similar to scenario 1 but the network is operated by sectors.
- Scenario 3: One additional VSD is included in the pumping station and the network operation is by sectors.
- Scenario 4: Similar to scenario 3 but the pumping station includes three VSDs (the current variable speed drive and two additional speed drives).

6.2.3. Pumping station modeling

Every group of hydrants (sector) has different demands of pressure head, thus involving variations in pumping efficiencies. Hence, modifications in the performance of the pumping station can give rise to high efficiency at different head pressures. This can be achieved by the inclusion of more VSDs to fit the energy supplied to energy demand. In this study, we evaluate the number of VSDs that should be included in the pumping station to obtain the maximum efficiency. Activation of the VSPs and automated control are also considered in the applicability of the methodology.

The developed pumping station simulation model reproduces the performance of all pumps for different activation sequences. This model was implemented in MATLAB™ (Pratap, 2010) and considers the characteristic pressure head and efficiency curves of the pumps (Q-H and Q-η). The model was run considering both the discharge interval of 25 l min^{-1} and the head pressure required. These parameters can be modified by the user. Pressure head was set at a constant value for manometric pumping station regulation or a variable value in other types of regulation. Using affinity laws for those pumps controlled by VSD and the working point (Q-H) for fixed speed pumps, the pumping station efficiency for each amount of flow demanded could be obtained. This model is useful for establishing the best working conditions of pumping stations, for evaluating their efficiency, and for studying the effect of pump ageing on the performance of the station. It also enables the user to select which pumps work as VSPs and which are fixed pumps. In all cases, a sequential activation of the different VSPs, the most efficient option, is performed (Moreno *et al.* 2007, Moreno *et al.* 2010).

For accurate analysis, all components of pumping station efficiency should be considered (Eq. 6.1):

$$\eta = \eta_p \cdot \eta_m \cdot \eta_c \cdot \eta_v \cdot \eta_l \qquad [6.1]$$

where η is the total pumping station efficiency, η_p is the pump efficiency, η_m is the motor efficiency, η_c is the cables efficiency, η_v is the variable speed drive efficiency, and η_l is the efficiency related to head losses in pump pipes.

Only the total efficiency can be measured, so the other components are calculated or estimated. Most of these components can be obtained from the technical documentation for the pumps.

When several VSPs are activated sequentially, it is crucial to evaluate VSD efficiency. Manufacturers typically specify that this efficiency is higher than 95 %. However, the authors have measured this efficiency in many VSDs commonly installed in pumping stations for irrigation (Moreno *et al.* 2010), resulting in efficiencies similar to those shown in Fig. 6.2. Thus, these measured values have been considered as the reference efficiency pattern for this kind of equipment. If the user has the real VSD curve, this can be included in the model. However, it is usually difficult to obtain because it is necessary to install two perfectly synchronized electrical network analyzers during a long period of time such that data are recorded across the whole range of frequencies of the VSD. It is even more difficult to obtain in medium voltage networks, which requires special instrumentation to take these measurements, as in the case of the system analyzed here. The VSD efficiency curve provided offers a good approximation.

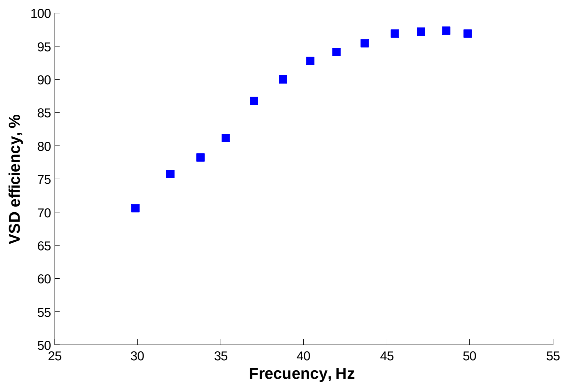

Fig. 6.2. Measured efficiency of a variable speed drive installed in a pumping station

6.2.4. The WEBSOMPE algorithm

The WEBSOMPE (Water and Energy Based Sectoring Operation for Multiple supply sources considering Pumping Efficiency) algorithm optimized the following parameters simultaneously: minimizing energy consumption according to network management (with or without sectors); ensuring the pressure requirements at hydrants; and adapting the pumping station operation according to the energy demand by including VSDs.

It is based on the WEBSOM (Water and Energy Based Sectoring Operation for Multiple Supply Sources), developed by Fernández García *et al.* (2013), which uses multiobjective optimization techniques to obtain the optimal monthly sectoring operation calendar, giving both minimum energy consumption and pressure deficit.

The only difference between WEBSOMPE and WEBSOM is in the pumping efficiency. In WEBSOM, this value was assumed to be constant, while in the new model, the pumping efficiency was obtained from the pumping station model described above. Regarding network operation by sectors, groups of hydrants (sectors) were previously identified according to an elevation criterion. The land topography is quite steep (Fig. 6.1) and elevation predominates over the friction losses in pipes, especially considering that this network was originally designed to supply water with 100 % simultaneity with small friction losses. Three sectoring options were proposed: one sector, two sectors and three sectors. To attain our objectives, minimization of the following objective functions was considered:

$$F1 = EC_{norm} + CID_{norm} \quad [6.2]$$

$$F2 = \max\,[Pf + CMPD_{norm}] \quad [6.3]$$

The first objective function (*F1*) addresses the minimization of both energy consumption (*EC*) and irrigation deficits (*CID*). Both terms were normalized by the continuous uniform distribution *U* (0, 1) for summation. EC_{norm} and CID_{norm} ranged from 0 to 1. Hence, the minimum and maximum value of *F1* were 0 and 2, respectively.

EC (kWh/ irrigation season) was determined by the following equation:

$$EC = \frac{1}{1000} \cdot \frac{1}{\eta} \cdot \gamma \sum_{s=1}^{Ns} t_s \cdot D_s \sum_{w=1}^{Nsect} Q_{ws} \cdot H_{ws} \qquad [6.4]$$

Where *w* and *s* are the sector and the month index, respectively, N_{sect} the number of possible sectors, N_s the number of operating months of the irrigation network, Q_{ws} (m^3s^{-1}) and H_{ws} (m) the pumped flow and the pressure head, respectively, when sector *w* operates during month *s*; D_s the number of days in month *s*, t_s the daily irrigation time in month *s* (h) and γ is the water specific weight (9810 Nm^{-3}). In this case, η_t was not assumed to be a fixed value and was obtained by the pumping station model according to the demanded flow and the pressure head for each operating sector. The irrigation deficit term *CID* was the maximum monthly difference between the theoretical irrigation requirements of all crops (estimated as described in Allen *et al.* 1998) and the flow supplied by the pumping station, both for month *s*. A maximum allowed irrigation deficit of 5 % was assumed. Hence, CID_{norm} varied between 0 (irrigation deficit did not occur) and 1 (irrigation deficit was 5 % of the theoretical irrigation requirements). Irrigation deficits higher than 5 % of the irrigation needs were penalized with *F1* and *F2* values of 2 and 1.9, respectively.

The second objective function (*F2*) considered minimization of the pressure deficit. *Pf* (the pressure failure percentage) is the ratio between the number of hydrants with pressure below the service pressure and the number of operating hydrants. This term ranged from 0 to 1. *CMPD* evaluated the magnitude of pressure deficit by the difference between the service pressure and the pressure at the critical hydrant (hydrant with the lowest pressure). *CMPD* was also normalized using the continuous uniform distribution U (0, 1). The terms *Pf* and $CMPD_{norm}$ were calculated for each operating sector and month. The value of *F2* was the maximum value obtained by summing these terms. *F1* and *F2* varied between 0 and 2.

6.2.5. Multiobjective optimization

The Non-dominated Sorting Genetic Algorithm (NSGA-II) (Deb *et al.* 2002) has been used in the optimization process due to its successful application in problems related to water distribution systems (Siew and Tanyimboh, 2012; Shokri *et al.* 2013). The first step is the generation of the initial population. In this problem, the population was formed by N_{ind} individuals or chromosomes, each with (N_{sect} x N_s) variables. Each variable was associated to the pressure head of the pumping station for each operating sector and month. The number of operating sectors can be different for each month. Next, the individuals are ranked according to the values of the objective functions indicated above. In order to calculate the objective functions, topological data from the network and the hydrant base demand must be estimated, which was performed according to Fernández García *et al.* (2013). Each run was carried out assuming that all hydrants within each operating sector were open. The irrigation network was simulated in EPANET (Rossman, 2000) and its Dynamic Link Library (.dll) was included in the model to obtain the flow supplied by the pumping station and the pressure at hydrants according to each operating sector and month. Then, the "selection, crossover and mutation" processes are carried out until the convergence criterion is achieved (Deb *et al.* 2002). As a result, a set of compromised solutions, named as Pareto front, is generated. The optimization process was performed in MATLAB™ and a flow chart of the algorithm is shown in Fig. 6.3. In our work, the parameters of the optimization procedure are as follows. The "population size" and the "number of generations" were set to 100 and the "crossover" and "mutation probabilities" were 0.9 and 0.1, respectively. The number of variables of each "chromosome" was 27 (3 possible sectors x 9 operating months) grouped in sets of three. Each variable of every set of three identified the pressure head of the pumping station when sector 1, 2 and 3 operated, respectively. 2 sectors operated when the value of one of the variables was 0 and only 1 sector operated when the value of two variables was 0.

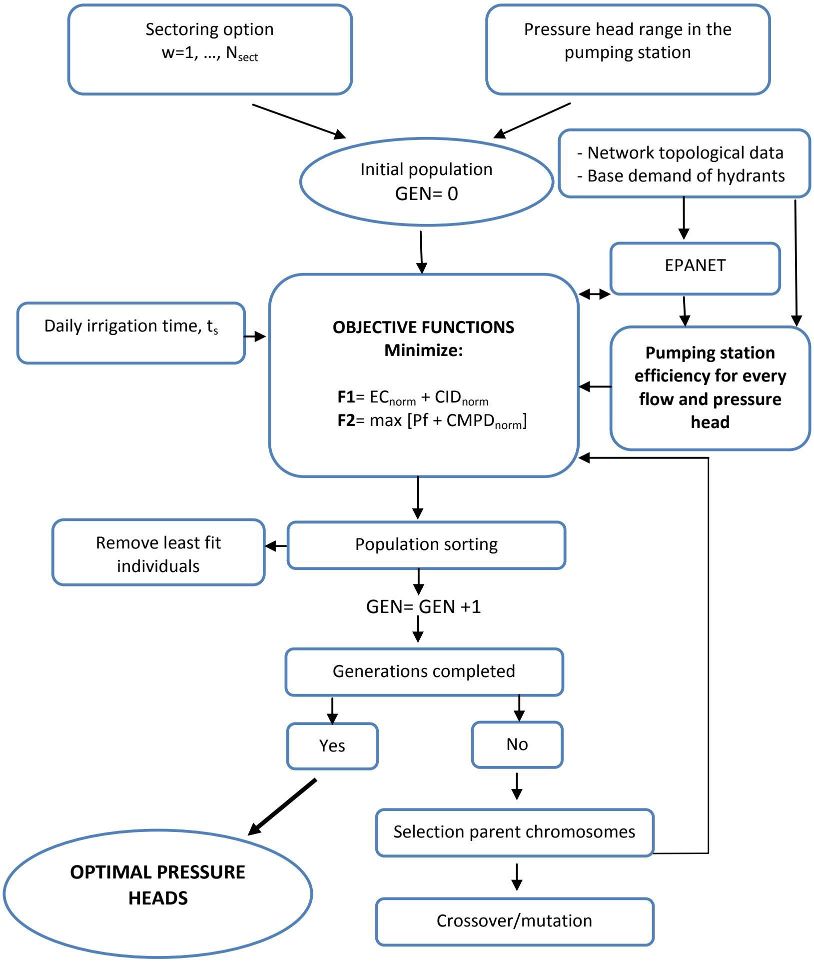

Fig. 6.3. Schematic representation of the optimization process using the WEBSOMPE algorithm

6.3. Results and discussion

6.3.1. Sectoring strategies

The WEBSOMPE methodology was applied to the BMI irrigation district for the four scenarios analyzed. The number of hydrants within each group according to the sectoring option (1, 2 or 3 sectors) and basic statistics of elevation in every sector are provided in Table 6.2. When 2 sectors were considered, sector 1 grouped hydrants with the highest elevations (average elevation of 84 m) while the average elevation for the hydrants in sector 2 was 66 m. Likewise, the option with 3 sectors grouped the hydrants with the highest elevation in sector 1 (92 m) and the average elevation of hydrants was progressively reduced in sectors 2 (73 m) and 3 (64 m).

Table 6.2. Number of hydrants, maximum (Z_{max}, m), average (Z_{ave}, m) and minimum (Z_{min}, m) elevations of hydrants in every sector for the three sectoring strategies (on-demand, two and three sectors)

	Strategy	**On-demand**	**2 sectors**	**3 sectors**
Sector 1	Hydrants	28	14	8
	Z_{max}	103	103	103
	Z_{ave}	75	84	92
	Z_{min}	58	72	79
Sector 2	Hydrants	-	14	10
	Z_{max}	-	71	76
	Z_{ave}	-	66	73
	Z_{min}	-	58	69
Sector 3	Hydrants	-	-	10
	Z_{max}	-	-	68
	Z_{ave}	-	-	64
	Z_{min}	-	-	58

The upper and lower limits for each variable used in the optimization procedure (in this case pressure head in every sector) according to each scenario are shown in Table 6.3.

Table 6.3. Upper and lower limits for the variables and required pressure head (m) for every sector in each scenario

	Sce. 1	Sce. 2	Sce. 3	Sce.4
Min	[27]	[27,27,27]	[35,27,27]	[35,27,27]
Max	[80]	[80,80,80]	[60,60,60]	[52,52,52]

Different values of the variables were considered in each scenario to adjust them to the operation range of the variable speed pumps.

6.3.2. Efficiency of the pumping station after adding variable speed pumps

Fig. 6.4 shows the efficiency of the pumping station for each discharge demanded considering a regulation with one (current management), two and three VSPs for head pressure ranging from 27 m to 52 m and flows from 0 to 4000 Ls^{-1}.

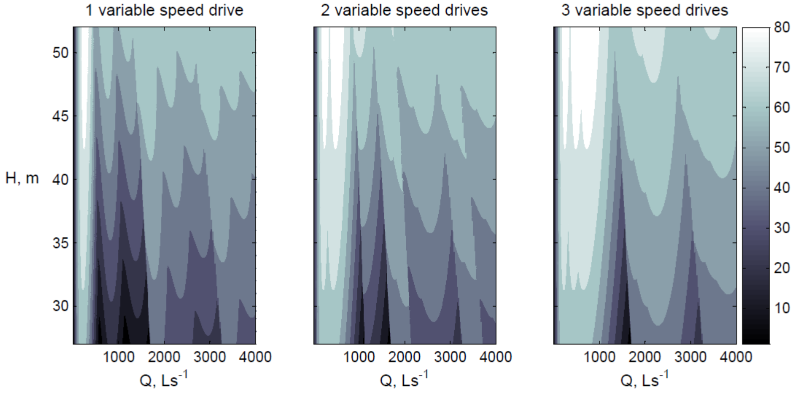

Fig. 6.4. Pumping efficiency (%) for 1, 2 and 3 VSDs

In general, the efficiency was greater when 3 VSPs were installed in the pumping station. For high head pressures, there were no significant differences in pumping efficiency in the three options (typically over 60 %). However, when the required head pressure was reduced, the differences increased and the installation of 3 VSPs activated sequentially achieved higher values than 1 VSP, where inefficiency was less than 10 %. Thus, the pumping station would work more efficiently after the installation of more VSPs because energy savings would be achieved, especially in the operation of the sectors demanding less pressure.

6.3.3. Analysis of the current management

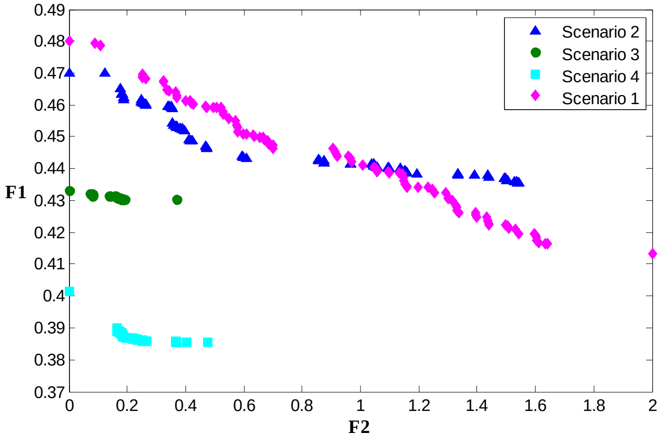

Fig. 6.5. Pareto Fronts obtained for the four modeled scenarios

Scenario 1 represents the current network operation. On-demand operation with one VSD gives rise to one of the Pareto Fronts shown in Fig.6.5. In a multiobjective optimization, the decision maker may select the solution of the Pareto Front according to their criterion (Savic, 2007). In this study, priority was given to solutions with small pressure deficits (F2) over solutions with lower energy consumptions.

The selected solution of the Pareto Front had values of 0.48 and 0.11 for F1 and F2, respectively. This solution involved a seasonal energy consumption of 5258 MWh (Table 6.4) and a pressure deficit of 2 m (7 %) in only one hydrant in October (Fig. 6.6a). The theoretical irrigation requirements were fully satisfied. The average monthly pumping efficiency in scenario 1 is shown in Fig. 6.7a. Pumping efficiencies above 70 % were obtained in all months. The on-demand operation entailed high pressure heads and pumped water (Fig. 6.8). Thus, the pumping station worked with the maximum efficiency.

Table 6.4. Energy consumption and optimal weighted pressure head in each scenario

	Energyconsumption, MWh				**Optimal weighted pressure head, m**			
	Sce 1	Sce 2	Sce 3	Sce 4	Sce 1	Sce 2	Sce 3	Sce 4
Mar	55	58	46	42	60	69	38	38
Apr	512	449	462	360	69	43	57	34
May	929	914	775	696	62	62	41	37
Jun	1132	1121	990	854	61	60	41	37
Jul	1154	1143	1019	819	63	61	49	32
Aug	938	929	814	677	64	63	47	35
Sep	454	433	395	345	69	61	44	42
Oct	54	54	53	47	58	56	44	47
Nov	29	27	24	25	71	59	37	40
Total	**5258**	**5130**	**4578**	**3865**				
Average					**64**	**59**	**44**	**38**

6.3.4. Potential energy savings after sectoring and improving the pumping system

Scenario 2 considers sectoring but using the current pumping station with only one VSD. Scenario 2 achieved lower values of F1 for the same values of F2 than Scenario 1 (Fig. 6.5). The *CID* term was 0 in all solutions of the Pareto Front. The selected solution of the Pareto had values of F1 and F2 of 0.47 and 0, respectively. This corresponded to energy consumption of 5130 MWh, only 2 % lower than Scenario 1 (Table 6.4). However, pressure deficits did not occur in any month. For the optimal sector operation calendar, 2 sectors were operating in April and November and 3 sectors in May, September and October. Only one operating sector was proposed for all other months. A weighted pressure head was determined in scenarios 2, 3 y 4 in months with network operation by sectors (Table 6.4). A weighting based on the flow supplied by each operating sector was performed. The optimal weighted pressure head in scenario 2 was lower than in Scenario 1 in all months except March.

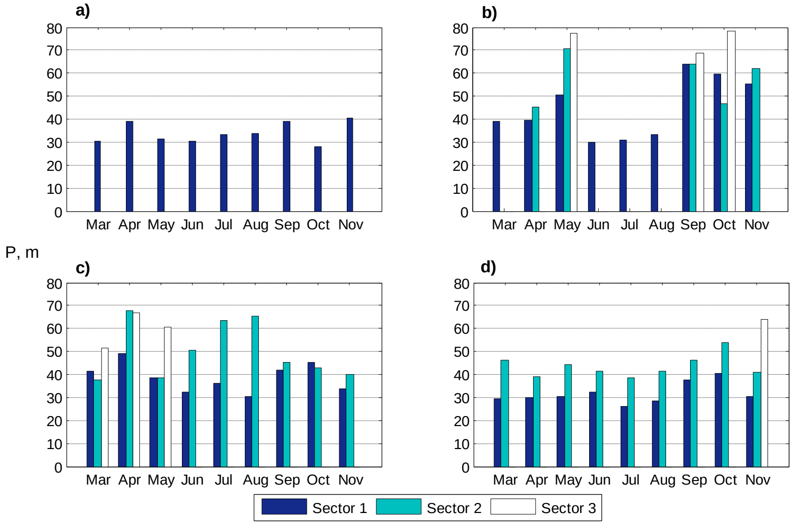

Fig. 6.6. Pressure in the worst hydrant according to each operating sector in Scenario 1 **(a)**, Scenario 2 **(b)**, Scenario 3 **(c)** and Scenario 4 **(d)**

This month showed a raised weighted pressure head because the pumping efficiency was higher than in Scenario 1 (pumping efficiencies of 79 % and 73 % were obtained in Scenarios 2 and 1, respectively). Nevertheless, the network operation by sectors did not imply significant reductions of the weighted pressure head with respect to Scenario 1. When the network is managed by sectors, the pressure head and the pumped volume can be reduced (Fig. 6.8). However, in that case, the pumping station may work with low pumping efficiency and the energy consumption may increase. Fig. 6.7b shows the average monthly pumping efficiency for Scenario 2, where raised pumping efficiencies were obtained in all months (except April). The optimal weighted pressure head obtained in April was 43 m in Scenario 2 and 69 m in scenario 1. The lower value of the optimal pressure head in Scenario 2 gave rise to lower pumping efficiencies. In contrast, in May, September and October (months with operation by sectors) high pumping efficiencies were obtained maintaining a weighted pressure head greater than the required. Thus, pressure in the critical hydrant in these months exceeded significantly the required pressure (Fig. 6.6b).

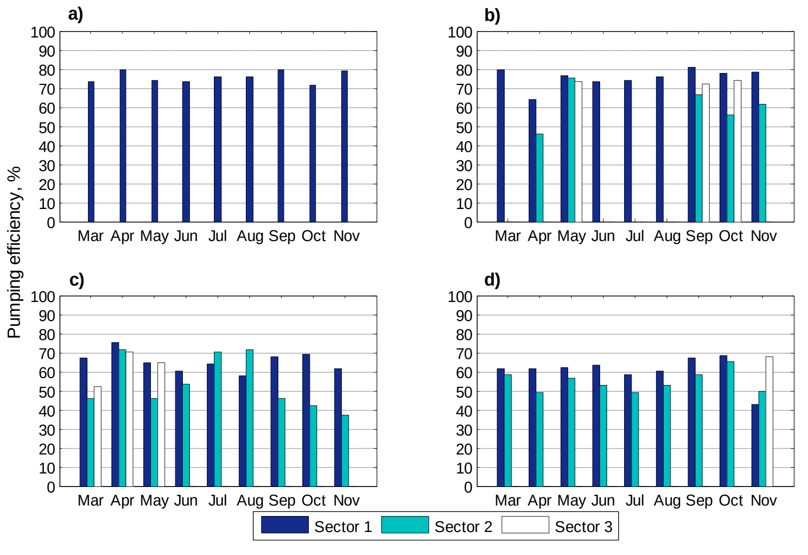

Fig. 6.7. Average monthly pumping efficiency according to each operating sector in Scenario 1 **(a)**, Scenario 2 **(b),** Scenario 3 **(c)** and Scenario 4 **(d)**

In Scenario 3 (network operation by sectors and one additional VSD), solutions with high values of F2 were removed and the F2 values ranged from 0 to 0.37 (Fig. 6.5). The solution selected had a F1 value of 0.43 and a F2 value of 0. The *CID* term was 0 in this solution. The energy consumption was 4578 MWh, involving energy savings of 551 MWh (11 %) with respect to Scenario 2 and 680 MWh (13 %) compared to Scenario 1 (Table 6.4).

Moreover, this solution implied that the pressure in all hydrants was higher than the service pressure in all months (Fig. 6.6c). Concerning the optimal sectoring operation calendar, 3sectors operated in March, April and May and 2 sectors operated in all other months. Thus, the inclusion of one additional VSD allowed the network operation by sectors in all months. In terms of pumping efficiencies, high values were achieved in this scenario (Fig. 6.7c) and the average optimal weighted pressure head decreased in 15 m compared to Scenario 2 (Table 6.4). However, the pressure in the critical hydrant was too high in most cases (Fig. 6.6c). This means that the pressure head could be even more reduced and additional energy savings could be achieved.

In Scenario 4 (network operation by sectors and three VSDs), a significant reduction in F1 occurred and all solutions of the Pareto Front satisfied the theoretical irrigation requirements (Fig. 6.5). From this Pareto Front, a solution with F1 and F2 values of 0.39 and 0.27 were selected, respectively. Thus, energy consumption was 3865 MWh, involving energy savings of 1393 MWh (26 %) compared to Scenario 1 (Table 6.4). Regarding the optimal sectoring operation calendar, 2 sectors operated in all months except in November, with 3 operating sectors. Hence, the most appropriate number of operating sectors was 2 in this irrigation district. Fig. 6.6d shows the pressure in the critical hydrant according to the operating sectors and month of the solution selected. Small pressure deficits occurred in March, July and August when sector 1 operated: 2 hydrants presented a pressure deficit of 3 % (1 m) in March, of 7 % (2 m) in August and of 13 % (4 m) in July. Although a solution with pressure deficits was selected, the irrigation network could operate properly with pressure in the range of 25- 30 m. The average optimal weighted pressure head decreased in 6 m, 21 m and 26 m compared to scenarios 3, 2 and 1 without reducing the pumping efficiency (Fig. 6.7d).

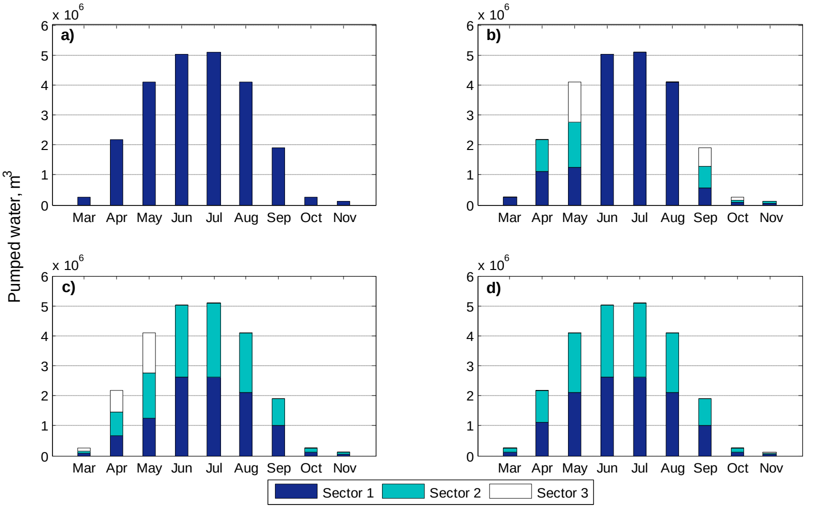

Fig. 6.8. Pumped water according to each operating sector in Scenario 1 **(a)**, Scenario 2 **(b)**, Scenario 3 **(c)** and Scenario 4 **(d)**

The management option proposed in Scenario 4 involves energy savings of 26 % by installing only two VSDs. If the WEBSOM algorithm is applied to this irrigation district assuming a fixed pumping efficiency of 0.7, similar energy savings are obtained (1360 MWh, 26 %) but the replacement of pumps would be required to keep efficiency constant, leading to higher investment costs.

6.4. Conclusions

Several authors have highlighted that sectoring is one of the most efficient energy saving measures. However, the pumping station may have to work under flow and pressure conditions that are very different from the optimum operation point.

In this study, a new model (WEBSOMPE) has been developed to optimize the sectoring operation and pressure head, taking into account the pumping efficiency according to energy demand. The benefits of installing variable speed drives are also modeled and analyzed. In the irrigation network studied, the combined use of sectoring and VSDs can lead to energy savings of up to 26 %, guaranteeing the service pressure at the hydrant level. Contrary to other options, such as replacing pumps, this change would not represent major investments in infrastructure.

The analysis performed here confirms that substantial energy savings can be achieved when sectoring measures are adopted, but the pump station must be adapted to work under different flow and pressure requirements. Otherwise, energy consumption will not be significantly reduced (in BMI energy savings of only 2 % would be expected when the pump station is not upgraded). However, an in-depth study must be undertaken for each individual network because the optimum measures may differ substantially from one case to the next.

Acknowledgments. This research is part of the AMERE project (AGL2011-30328-C02-02), funded by the Spanish Ministry of Economy and Competitiveness. The authors gratefully acknowledge the anonymous reviewers for their valuable comments.

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7. Incorporating the Irrigation Demand Simultaneity in the Optimal Operation of Pressurized Networks with Several Water Supply Points

This chapter is currently under review in the journal "Water Resources Management", Fernández García I, Montesinos P, Camacho Poyato E, Rodríguez Díaz JA (2014)

Abstract. Network sectoring is one of the most effective measures to reduce energy consumption in pressurized irrigation networks, something of extreme importance to farmers. In this work, the previous model focused on the irrigation networks sectoring with several supply points (WEBSOM), which assumed simultaneous operation of all hydrants, has been improved by integrating an analysis of multiple random demand patterns and their effects on variability in hydrant pressure (extended WEBSOM). The extended WEBSOM has implied a multiobjective optimization, followed by a Montecarlo procedure to analyze different flow regimes using quality of service indicators. This innovation has involved energy savings ranging from 9 % to 15 % with respect to the consideration of the concurrent operation of all hydrants, which rarely occurs in the on-farm irrigation systems. These energy savings were associated to maximum values of pressure deficit of 21 % and 34 % in the most critical hydrant with a deficit frequency of 27 % and 36 % in the peak month. However, smaller and less frequent deficits

were achieved in the rest of the months. Thus, substantial energy savings can be obtained in irrigation districts without significant losses in the service quality provided to farmers.

Keywords. Energy efficiency, genetic algorithms, water distribution systems, Spain

7.1. Introduction

In irrigation agriculture higher water use efficiencies may be achieved by the modernization of hydraulic infrastructures from open channel systems to pressurized irrigation networks (Boelens & Vos 2012). In most cases pumping groups are required for the operation of pressurized networks and hence, energy is a key resource in these systems (Carrillo Cobo *et al.* 2014).

The continuous growth of world population is raising pressure on scarce resources like water and energy (Malano *et al.* 2004). Furthermore, from the perspective of climate change, an increase of pressures on these resources is expected to occur (Martín Ortega *et al.* 2011). As stated previously, the adoption of pressurized systems has involved lower conveyance losses and higher application efficiency and consequently, the water use efficiency has increased in recent years (Lal 2004, Jackson *et al.* 2011). However, the operation of these irrigation systems entails higher energy consumptions, with increases up to 163 % after the modernization of gravity fed irrigated areas (Jackson *et al.* 2010). In addition, the energy cost has also grown significantly because of the disappearance of special rates for irrigation and the liberalization of the electricity market in countries like Spain (Rocamora *et al.* 2012), with the highest percentage of irrigated land in the European Union, 30 % (BIO Intelligence Service 2012). This directly affects the farmers' incomes who demand measures aimed at the reduction of both the energy consumption and the energy cost.

One of the more effective measures to improve energy efficiency has consisted in network sectoring, focused on the establishment of irrigation turns. By this strategy, considerable energy savings have been estimated in several irrigation districts (Jiménez Bello *et al.* 2010, Moreno *et al.* 2010, Navarro *et al.* 2012). For irrigation networks with several source nodes, a new sectoring methodology based on heuristic approaches was developed by Fernández García *et al.* (2013). However this methodology provided the optimal sectoring operation calendar and the pressure heads in the pumping stations assuming the simultaneous operation of all hydrants in each sector. This circumstance represents the most adverse loading condition. In many cases pressurized networks have been designed to operate on-demand, increasing farmers' flexibility to irrigate during their working hours. Consequently, the concurrent operation of all hydrants is not frequent in irrigation districts. Different flow regimes may occur during any day of the irrigation season due to the combination of crop rotations and farmers' irrigation scheduling. This fact causes changes in hydrants pressure and hence, the proper operation of the network can be affected (Khadra & Lamaddalena 2010).

This work represents a step forward in the methodology proposed by Fernández García *et al.* (2013) incorporating in their model an analysis of multiple random demand patterns. Thus, we evaluate the variability in hydrant pressure according to the discharge flow and the strategy that leads to the minimum energy consumption and pressure deficit while satisfying crop irrigation needs. The paper is structured as follows: first the case study is presented, then the extended WEBSOM algorithm (Fernández García *et al.* 2013) is described, including the selection of representative solutions from the Pareto front to be evaluated under multiple random demand patterns. The changes in hydrant pressure will be assed using service quality indicators. Finally the new procedure will be applied to the case study, comparing the selected solutions and discussing the better operation conditions of the network.

7.2. Methodology

7.2.1. Study area

The methodology proposed has been applied to Palos de la Frontera (PF) irrigation district (Huelva, Southern Spain). This irrigation district consists in a multi-source network with 3 pumping stations supplying water to 227 hydrants through 79 km of pipes. The irrigation network is designed to guarantee service pressures of 30 m and unit flow of 1.2 $Ls^{-1}ha^{-1}$ in all hydrants. The maximum flow delivery capacity of each pumping station is 1584, 1056 and 1372 Ls^{-1} with pressure heads of 85, 45 and 55 m, respectively (Fernández García *et al.* 2013).

The climatic conditions with annual average rainfall of 490 mm and average reference evapotranspiration of 1145 mm (Pérez Urrestarazu *et al.* 2009) are conducive to strawberry-growing. For this reason, strawberry is the main crop in this irrigation district. It covers 75 % of the irrigated area (3343 ha).

7.2.2. The extended WEBSOM

The original WEBSOM algorithm provides the optimal monthly sectoring operation calendar that leads to the minimum energy consumption assuming that all hydrants within each operating sector are open. WEBSOM uses a customized version of the non-dominated sorting genetic algorithm (NSGA-II) (Deb *et al.* 2002) as multi-objective optimization procedure based on the evolution of a random population of solutions generated initially. Then, the set of objective functions is evaluated for each individual of the population and selection, crossover and mutation processes are carried out until the convergence criterion is satisfied (Deb *et al.* 2002). The specific characteristics of WEBSOM are related to the generation of the initial population, the evaluation of objective functions and the crossover process. Individuals that make up the initial population of solutions contain information about both the total head of pumping stations, H_{iws} and the number of operating sectors per month during the irrigation season, N_{sect}. Sectors were previously established grouping hydrants according to two dimensionless topological coordinates of elevation and distance to the pumping stations (Fernández García *et al.* 2013). The search of the optimal operation of networks is based on the minimization of the two objective functions:

$$F1 = EC_{norm} + CID_{norm} \quad [7.1]$$

$$F2 = \max\left[Pf + CMPD_{norm}\right] \quad [7.2]$$

The first objective function (*F1*) is obtained by summing the normalized total energy consumption (EC_{norm}) and the normalized maximum monthly irrigation deficit (CID_{norm}). Both terms were normalized by the distribution U (0, 1). *EC* in (kWh/irrigation season) was calculated as follows:

$$EC = \frac{1}{1000} \cdot \frac{1}{\eta} \cdot \gamma \sum_{s=1}^{Ns} t_s \cdot D_s \sum_{w=1}^{Nsect} \sum_{i=1}^{N} Q_{iws} \cdot H_{iws} \quad [7.3]$$

Where *i* is the pumping stations index, *w* the sector index, *s* the month index, *N* the number of pumping stations, N_s the number of months of the irrigation season, η the global efficiency of pumps, γ water specific weight (9800 Nm^{-3}), t_s the daily irrigation time (h) during month *s*, D_s the number of days in month *s* and Q_{iws} the pumped flow by station *i* when sector *w* operates during month *s* (m^3s^{-1}).

The term CID_{norm} is formulated as follows:

$$CID_{norm} = max \cdot \left[\frac{RIS_s \cdot Qreq_s - Qsupply_s}{a \cdot RIS_{sp} \cdot Qreq_{sp}} \right] \quad [7.4]$$

Where $Qreq_s$ is the monthly theoretical crop irrigation requirements (m^3s^{-1}), $Qreq_{sp}$ is the theoretical crop irrigation requirements during the peak month *p* and $Qsupply_s$ is the monthly supplied flow by all pumping stations (m^3s^{-1}). The terms $Qreq_s$ and $Qreq_{sp}$ are affected by RIS_s indicator that relates the monthly volume of water pumped and the monthly theoretical crop irrigation needs (Navarro *et al.* 2012). Thus, different deficit irrigation strategies, i.e. deficit irrigation, can be adopted using this model. *a* is a coefficient ranging from 0 to 1 that enhances the penalty introduced by CID_{norm}. This term is calculated for every month of the irrigation season and the maximum value is CID_{norm}.

F2 considers the maximum monthly pressure deficit that occurs in the irrigation season. *Pf* is the pressure failure percentage (ratio between the number of hydrants with pressure below the service pressure and the number of operating hydrants) and $CMPD_{norm}$ is the normalized magnitude of pressure deficit (service pressure, P_{ser} – actual pressure at each hydrant, divided by P_{ser}). Unlike the standard NSGA-II, a multiple-point crossover mechanism is considered in WEBSOM. This algorithm was implemented in MATLAB™ (Pratap 2010) using EPANET (Rossman 2000) as hydraulic simulator. A detailed description of the original WEBSOM can be found in Fernández García *et al.* (2013). Fig.

7.1 shows the flow chart of the Extended WEBSOM algorithm with the new modules that are described next.

7.2.2.1. Module for flow regime analysis

The original algorithm provides the Pareto optimal front, i.e. the set of quasi-optimal solutions that involves the operation of the network with minimum energy consumption. Solutions in the Pareto front have been identified assuming that all hydrants within each operating sector are concurrently open and hence, pipe flows throughout the network are constant for each sector and month. This situation is the most energy demanding, however it is not the most frequent. To take into account the influence of the occurrence of different demand pattern in the energy requirements, an additional analysis module has been incorporated in the WEBSOM algorithm. A set of solutions selected from the Pareto front is evaluated under several loading conditions in this new module. To select representative solutions, the following criterion is assumed. Once the repeated solutions are removed from the optimal Pareto front, the remaining individuals are sorted in descending order according to F2 or F1 values. Then, the first and the third quartile of the set of solutions are determined and the individuals are divided in three groups: one group is associated to the first quartile, the second one corresponds to the intequartile range (third quartile minus first quartile) and the third group is associated to the fourth quartile. Finally, the median value of the three groups is calculated, thus setting up six sub-groups. From every sub-group, at least one individual is selected according to the decision maker's criterion.

Each selected solution of the Pareto front reports on the optimum pressure heads of the pumping stations according to each operating sector and month. To analyze different random demand patterns, the solutions selected from the Pareto from (sets of pressure heads of pumping stations) are fixed and then, the operation of the network is evaluated under a wide range of loading conditions according to different combinations of open and closed hydrants.

Clément (1966) proposed a methodology to consider the different flow regimes in the network, by defining two possible states for hydrants (open and closed). Thus, hydrants can be open, with a probability p_{ws}, or closed, with a probability (1- p_{ws}). The probability p_{ws} is defined as (Clément, 1966; Lamaddalena and Sagardoy, 2000):

$$p_{ws} = \frac{t_{rs}}{t_{dw}} \quad [7.5]$$

Where t_{rs} (h) is the daily irrigation time to match the crop irrigation requirements per month and t_{ds} (h) the available irrigation time according to the number of operating sectors (24 hours when the network is not organized in sectors and [24/N_{sect}] when N_{sect} sectors operate) (Fernández García *et al.* 2013).

k Montecarlo simulations were performed to generate *k* random demand patterns (configurations of open and closed hydrants) for each month (*s*) and operating sector (*w*) based on the [0,1] uniform distribution. For each random demand pattern, the open or closed state of each hydrant was related to both the probability of open hydrant per sector and month (p_{ws}) and a random number (R_{kws}). Thus, hydrant was assumed to be open when p_{ws} was greater or equal to R_{kws} and closed when p_{ws} was lower than R_{kws}. The base demand for the open hydrants was determined by multiplying the maximum flow allowed per hydrant by the irrigated area associated to each hydrant.

For each month and operating sector, *k* simulations were carried out and critical hydrants (hydrants with the lowest pressure) and their pressures were collected in every simulation. This module was also performed in MATLAB™ using EPANET for the hydraulic simulation.

7.2.2.2. Module with service quality indicators

The use of indicators (simple relations between variables) simplifies the analysis of large amount of information through single numbers (Rodríguez Díaz *et al.* 2008). Three service quality indicators were proposed to analyze the changes in pressure at hydrant level according to the demanded flows in the network. These indicators were calculated for the critical hydrants where the pressure dropped below P_{ser} in any of the simulations performed. For each critical hydrant, with an associated pressure failure, *FPH*, simulated pressures under different loading conditions were collected and evaluated by the following indicators:

- Pressure equity at FPH_j, PE_{FPHj}. This indicator assesses the distribution of pressure at hydrant FPH_j according to the supplied flow by the pumping stations. It is calculated by the interquartile ratio, which relates the average pressure of the first, $\overline{Plq_{FPHj}}$, and the fourth quartile, $\overline{Pbq_{FPHj}}$, for each FPH_j in all the open/closed hydrant patterns evaluated (Pérez Urrestarazu *et al.* 2009, Rodríguez Díaz *et al.* 2009).

$$PE_{FPHj} = \frac{\overline{Plq_{FPHj}}}{\overline{Pbq_{FPHj}}} \qquad [7.6]$$

- Pressure deficit at FPH_j, PD_{FPHj} (%). This indicator is determined by the same procedure as used to calculate $CMPD_{norm}$ (Eq. 2). However, in this case, it is only calculated for *FPH* hydrants. This indicator has been previously used to estimate the relative pressure deficit at hydrant by Khadra & Lamaddalena (2010) and Daccache *et al.* (2010).

$$PD_{FPHj} = \frac{\overline{Plq_{FPHj}} - P_{ser}}{P_{ser}} \cdot 100 \qquad [7.7]$$

- Monthly frequency of pressure deficit at FPH_j, FPD_{FPHjs} (%). Unlike the hydrant reliability indicator (Lamaddalena & Sagardoy 2000, Khadra & Lamaddalena 2010) that evaluates the number of times that a hydrant obtains a pressure higher than the required, FPD_{FPHjs} indicates the monthly number of loading conditions where pressure at FPH_j is below P_{ser}, according to the total number of loading conditions per month, Nld_s.

$$FPD_{FPHjs} = \frac{\sum_{k=1}^{Nld}(P_{FPHj} < P_{ser})_{ks}}{Nld_s} \cdot 100 \qquad [7.8]$$

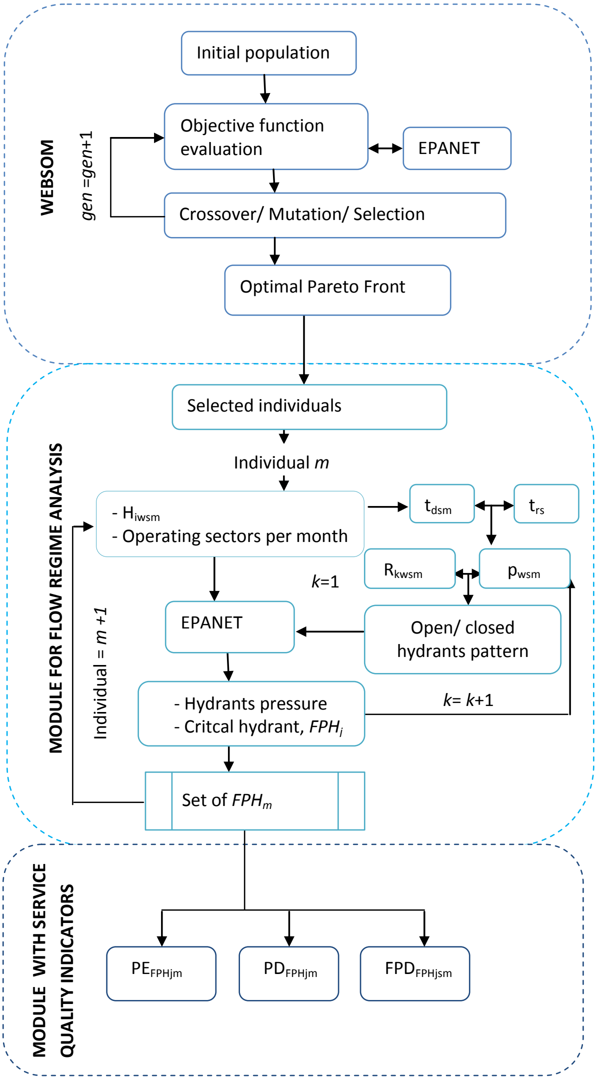

Fig. 7.1. Flow chart of extended WEBSOM algorithm

7.3. Results and discussion

7.3.1. Pareto Optimal Front

The extended WEBSOM algorithm was applied to PF irrigation network assuming the total satisfaction of theoretical irrigation requirements during the whole season (6230 m^3ha^{-1}) (Fernández García *et al.* 2013). The N_{sect} value was set to 5. Hence, the number of decision variables was 180 (3 pumping stations x 5 operating sectors x 12 operating months) with values ranging from 45 to 55 m, from 50 to 65 m and from 55 to 95 m for the pumping stations 1, 2 and 3, respectively. If the gen associated to each pumping station is set to 0 entails the non-operation of that pumping station. A pumping efficiency of 0.7, a more realistic value (Fernández García *et al.* 2014), was considered in this work. As strawberry is a high value crop and hence, irrigation deficit is not assumed, the indicator RIS_s was set to 1 for every month. A value of 0.05 for the coefficient *a* was established to avoid the removal of feasible solutions at the beginning of the process.

The algorithm parameters were set to 100 individuals and 200 generations, with crossover and mutation probability of 0.9 and 0.1, respectively (Deb *et al.* 2002). The optimal Pareto front, after removing 42 repeated individuals, is shown in Fig. 7.2. F1 ranged from 0.41 to 0.66 and these values corresponded to EC_{norm} since CID_{norm} term was 0 in all solutions. Regarding F2, the minimum and maximum values were 0.04 and 0.89, respectively. As could be expected, solutions with lower F1 values (low energy consumption) involved the highest values of F2 (larger pressure deficits). The solution selection criterion was applied to extract from this Pareto front, the set of "optimal solutions" according to predefined preferences (Savic 2007). In this case, one solution from each sub- group was selected to undergo the analysis of simultaneity of demand (Fig. 7.2). Table 7.1 reports the optimal sectoring operation calendar associated to each selected solution. Different sets of operating sectors per month were obtained in every solution. However, as May is a peak strawberry-growing month, only 2 sectors could operate per day to fulfill the crop irrigation needs. The simultaneous operation of all hydrants (without sectors) was not the best option in any month as RIS_s was set to 1.

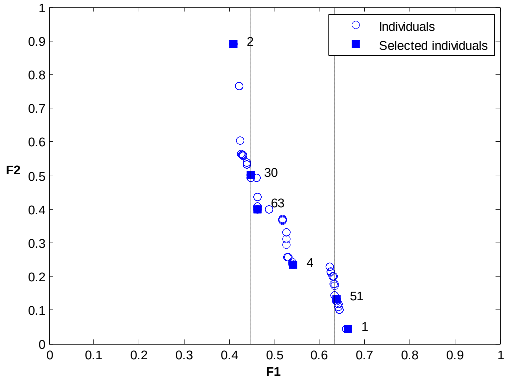

Fig. 7.2. Pareto optimal front and six selected individuals

The pressure heads in the pumping stations (H_1, H_2 and H_3) for each operating sector in the peak demand month are plotted in Fig. 7.3. Solutions 2, 30 and 63 involved the operation of the pumping stations 2 and 3 (the lowest power stations) when sector

1 operated. As F2 value was reduced (solutions 4, 51 and 1), the operation of pumping station 1 was required while station 3 stopped working. Likewise, the operation of station 3 was required in solutions 2 and 30 when sector 2 was operating while pumping stations 1 and 2 worked in the remaining solutions.

Table 7.1. Sectoring operation calendar for the selected solutions from the Pareto optimal front

	Number of sectors				
Solution	**1**	**2**	**3**	**4**	**5**
2	-	May-Sep	Jan-Feb-Apr-Oct-Nov	Jun-Jul	Mar-Aug-Dec
30	-	May	Jan-Feb-Apr-Sep-Oct-Nov	Jun-Jul	Mar-Aug-Dec
63	-	May	Jan-Feb-Apr-Sep-Oct-Nov	Jun-Jul	Mar-Aug-Dec
4	-	May	Jan-Feb-Apr-Oct-Nov	Jul-Sep	Mar-Jun-Aug-Dec
51	-	Apr-May	Jan-Feb-Jun-Jul-Oct-Nov	Sep	Mar-Aug-Dec
1	-	Apr-May	Jan-Jun-Oct-Nov	Feb-Mar-Jul-Sep	Aug-Dec

The energy consumption associated to the selected solutions ranged from 2979 MWh, with *pf* (pressure failure percentage) and $CMPD_{norm}$ (magnitude of pressure deficit) of 0.34 and 0.55 respectively, to 3666 MWh (pf = 0.02 and $CMPD_{norm}$ = 0.02) (Table 7.2). Solutions 2, 30, 63 and 4 showed too high pressure deficits to the proper operation of the irrigation network. Smaller pressure deficits were obtained in solutions 51 and 1.

7.3.2. Effects of flow regimes variability on hydrant pressures

The original WEBSOM offers optimum configurations for the worst situation when all the hydrants are simultaneously open. However this condition rarely occurs since farmers are free to open and close their hydrants during their irrigation turn. Thus, for each selected individual of the Pareto optimal front, pressure heads in pumping stations were fixed according to the outputs of the WEBSOM model and then an analysis of flow regimes variability was performed. In this case, the number of Montecarlo simulations was set at 1000 (k= 1000) because it provides enough random demand patterns to evaluate the effects of flow regimes variability on hydrant pressures.

Table 7.2. Energy consumption (*EC*), pressure failure percentage (*Pf*), normalized magnitude of pressure deficit ($CMPD_{norm}$) and pressure in the critical hydrant (*P*) for the selected individuals of the Pareto optimal front

Solution	EC, MWh	Pf	CMPD	P, m
2	2979	0.34	0.55	13
30	3081	0.29	0.21	24
63	3125	0.01	0.39	18
4	3335	0.01	0.22	23
51	3595	0.02	0.11	27
1	3666	0.02	0.02	29

The changes of pressure at the *FPH* according to the loading conditions through the irrigation network for each selected solution are shown in Fig 7.4. When the simultaneity of irrigation demand is taken into account, pressure deficits are reduced since lower flows reduce the energy losses in pipes. As it can be seen, the lower the energy consumption (solutions 2, 30, 63), the higher number of *FPH* and the greater pressure deficits. Solutions with larger pressure deficits (2, 30 and 63) implied the operation of 8, 9 and 8 *FPH*, respectively. In contrast, only 5 and 3 hydrants were FPH in any simulation for solutions 51 and 1, respectively. Furthermore, hydrant 167 obtained the lowest pressure in all cases and this hydrant, along with 99 and 428, appeared as *FPH* in all selected solutions. The height of the boxes in Fig. 7.4 denotes the interquartile range, i.e. the middle 50 % of the data. The upper limit of the box represents the upper quartile while the lower limit is the lower quartile. The horizontal line in the box corresponds to the median value. Outliers in the box plot are values outside the range defined by [Q1 (the first quartile) - 1.5·IQR (interquartile range)] and [Q3 (the third quartile) + 1.5·IQR] (Hiyama *et al.* 2011). Hence, the greater the height of the box, the greater pressure variation at the *FPH* and the greater sensitivity to changes in pressure which may have important implications in the irrigation system uniformity at farm level (Daccache *et al.* 2010). Thus, hydrants 167 and 428 (with greater height of the box in all solutions) suffered more pressure variation. Solution 2 (Fig. 7.4) implied a median value lower than 30 m for hydrants 167, 99 and 156. In fact, this solution led to the operation of hydrant 167 with pressure below the service pressure in almost 75 % of the cases in which hydrant 167 received the lowest pressure. A reduced interquartile range was obtained for hydrants 99, 115 and 133 and hence, small pressure variations were achieved in these hydrants. Moreover, multiple outliers (plus sign makers) were detected for these hydrants in solution 2. Considering the pressure deficits detected, the sectoring options and the pressure heads in the pumping stations proposed in solution 2 did not allow the proper operation of the irrigation network.

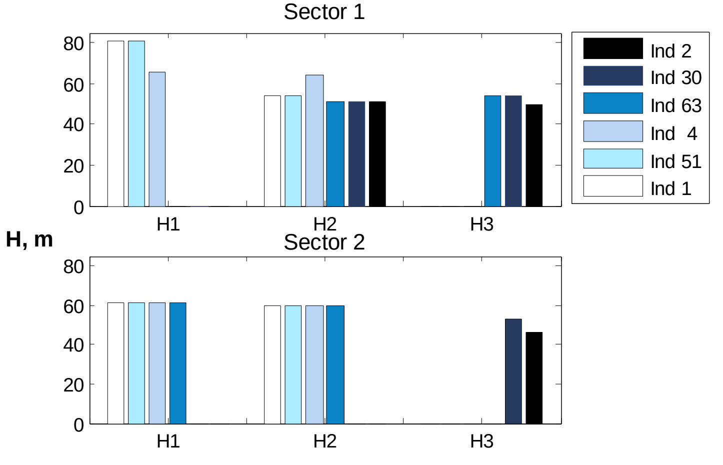

Fig. 7.3. Pressure heads in the pumping stations in May

In solutions 30 and 63, the median value was below the service pressure in 3 and 2 hydrants, respectively. Like in solution 2, hydrant 167 had pressure below 30 m in almost 75 % of the cases. However pressure would rarely be less than 25 m so managers would have to decide whether this small deficit in just one hydrant is admissible considering the important energy savings that would be achieved assuming this configuration. In solution 4, a median value greater than P_{ser} was achieved in all hydrants. In solutions 51 and 1, pressure was higher than 30 m for all hydrants in 75 % of the cases. Nevertheless solutions 4, 51 and 1 imply a considerably higher energy demand.

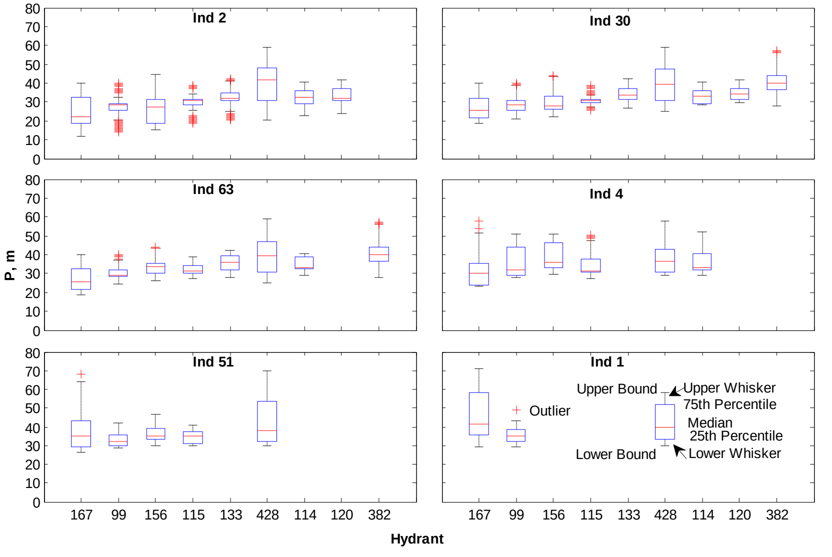

Fig. 7.4. Boxplot of variability of pressure at critical hydrants according to loading conditions into the irrigation network in the selected solutions (2, 30, 63, 4, 51 and 1)

7.3.3. Analysis of service quality indicators

In order to evaluate the feasibility of solutions 30, 63, 4, 51 and 1, the service quality indicators described above were used. Fig. 7.5 shows the pressure equity at the *FPH* in the analyzed solutions. Contrarily to branched networks with a single supply source where changes in pressure head in the pumping station lead to equivalent changes in pressure at hydrant (Rodríguez Díaz *et al.* 2012), in looped or branched networks with several supply nodes, pressures at hydrant varies depending on the pressure head in each pumping station. In all solutions, the higher the energy consumption and hence the lower the pressure deficit, the greater pressure equity, PE_{FPHj}. Thus, PE_{FPHj} values closer to 1 involved small pressure variations in FPH_j. However, solution 4 did not follow this trend and a slight decrease in PE_{FPHj} with respect to previous solution (solution 63) was obtained to hydrants 99, 156, 115 and 114. The size of the box of these hydrants in solution 4 was greater than in solution 63 (Fig. 7.4) since the average pressure of the best quartile increased considerably (hence the interquartile range). PE_{FPHj} values for hydrants 167 and 428 were below or close to 0.5 in all solutions. Thus, significant pressure variations were estimated for these hydrants.

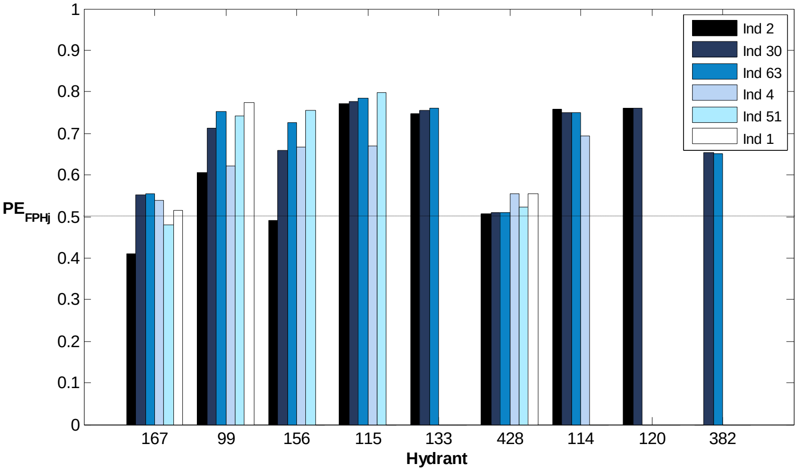

Fig 7.5. Pressure equity at FPH_j, PE_{FPHj}, in the selected solutions

Pressure deficits, PD_{FPHj} at FPH for each solution is shown in Fig. 7.6. Negative values of PD_{FPHj} indicated pressure deficit while the positive values of this indicator corresponded to average pressures over 30 m. However even when the average is above the service pressure, there are loading conditions with high irrigation demand where pressure at hydrant drops below 30 m. Large negative PD_{FPHj} values were obtained for hydrants 167, 99 and 156 in solutions 2, 30 and 63 while small pressure deficits were achieved in the other critical hydrants. As it has already discussed, solution 2 hindered the proper operation of the network since pressure deficits higher than 50 % in hydrant 167 were achieved. Solution 30 involved pressure deficits of 35 %, 19 % and 18 % in hydrants 167, 99 and 156, respectively. For the same hydrants, PD_{FPHj} values were – 34 %, – 11 % and – 6 % in solution 63. In solution 4, only hydrant 167 obtained a PD_{FPHj} of – 21 % while the other hydrants showed smaller pressure deficits. Solution 1 showed positive values of PD_{FPHj} in all hydrants.

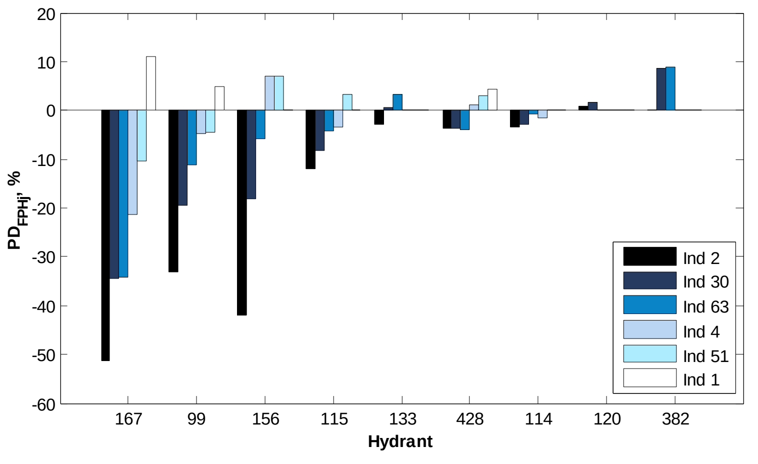

Fig. 7.6. Pressure deficit at FPH_j, PD_{FPHj}, in the selected solutions

In addition to above indicators, the analysis of *FPH* performance is improved by a deeper knowledge of the frequency of pressure deficit at these hydrants. Fig. 7.7 plots the maximum monthly frequency of pressure deficit in each FPH_j (number of monthly loading conditions where FPH_j received less than 30 m divided by the total number of monthly loading conditions) versus PD_{FPHj}. The peak values of FPD_{FPHjs} were obtained in April, May and September. As the energy consumption increased in all solutions, the frequency of pressure deficits in any hydrant was reduced. Hydrants 167 and 99 (with high PD_{FPHj}) had frequencies of pressure deficit greater than 20 % in solutions 2, 30, 63 and 4. Hydrant 428 showed an FPD_{FPHjs} value of 16 % in solutions 30 and 63 although small pressure deficits in this hydrant were obtained. In the rest of the cases, frequencies of pressure deficit below 10 % were estimated.

In view of the results showed above, the sectoring options and pressure heads in the pumping stations proposed in solutions 63 and 4 could be considered as quasi optimal operation rule of the network. Solution 63 achieves energy savings of 15 % with respect to solution 1 although hydrant 167 (the most critical FPH_j) entails a pressure deficit of 34 %. However, the maximum frequency of deficit in this hydrant is 36 %, an admissible value. Moreover, for the rest of hydrants, pressure deficits are below 20 % with frequencies lower than 20 %. This justifies the selection of solution 63 instead of solution 30, which entails increased both pressure deficits and frequencies. Conversely, solution 4 involves less energy saving than solution 63 (9 % of energy saving with respect to solution 1) but lower both PD_{FPHj} and FPD_{FPHjs} are achieved. Solution 51 implies increased degree of accomplishment of pressure requirements at hydrants although the energy saving obtained is only 2 % with regard to solution 1. Therefore, the extended WEBSOM enhances the farmer's flexibility to irrigate and enables to select individuals with high energy savings that could not be chosen by WEBSOM due to their significant pressure deficits. Furthermore, if pressure heads in pumping station were matched with the different flow regimes instead of fixing them, additional energy savings could be achieved.

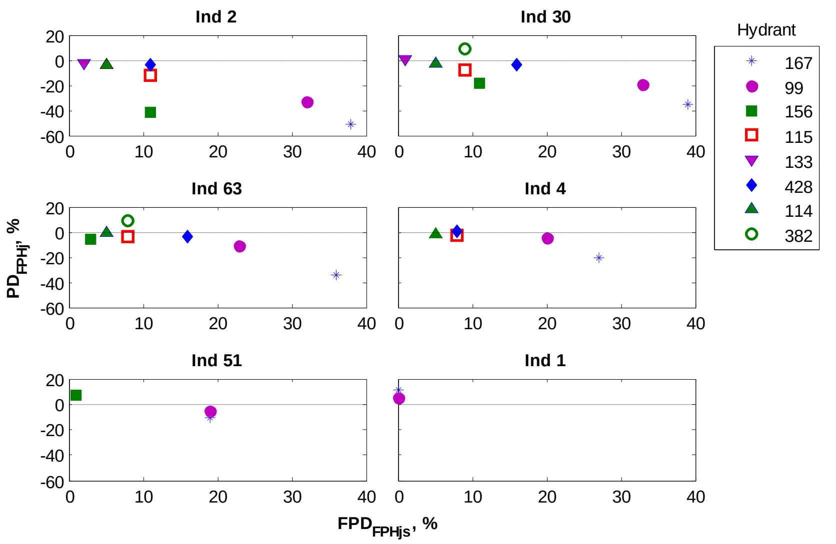

Fig. 7.7. Maximum monthly frequency of pressure deficit *vs.* pressure deficit at FPH_j

7.4. Conclusions

The adoption of pressurized irrigation systems has increased farmer's flexibility but, in return, energy consumption is considerably higher. In this paper we have presented an extended version of the WEBSOM algorithm for optimum sectoring of water distribution networks with more than one supply point. The new methodology incorporates the simultaneity of demand and analyzes the effects of pressure variability at hydrants in relation to the different loading conditions of the irrigation networks during the irrigation season.

The analysis of different flow regimes has allowed the selection of lower energy consumption solutions that would involve significant pressure deficits in some hydrants only when the demand simultaneity is 100 %. However, this peak water demand rarely occurs and most of the time the simultaneity is lower and therefore pressure deficits are smaller and not critical to the proper performance of the on-farm irrigation systems. Contrarily to branched networks which are more predictable because ranges of pressure at hydrant level are directly related to the pressure head ranges at the pumping station, in networks with several supply nodes, pressures at hydrant level vary widely depending on the regulation of every pumping station. This makes their management even more complex. In the particular case of PF irrigation district, we have selected two solutions that would lead to energy savings ranging from 9 % to 15 % with respect to other solution that entails the current operation of all hydrants while pressure deficits of 21 % and 34 % in the most critical FPH_j occurred only in 27 % and 36 % of the simulations performed in the peak month. However, in the rest of months smaller and less frequent pressure deficits occurred. Thus, unlike what happens with WEBSOM, when the simultaneity of the demand is considered (the extended WEBSOM), solutions that would imply considerable energy savings without significant losses in the quality in the service provided to farmers, could be adopted.

In future works, the analysis of the variability in hydrant pressures should be extended to the on-farm irrigation performance to check that significant energy savings can be achieved ensuring the proper management of the on-farm irrigation.

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8. Conclusions

8.1. General conclusions

- Sustainable management of both water and energy resources must be also considered in pressurized irrigation networks, which have undergone significant increases of the energy requirements in recent years.
- New strategies focused on network sectoring and critical points control, applicable to irrigation networks with one or more supply points, have been developed, leading to potential energy savings between 20 % and 36 % in the analyzed irrigation network (PF).
- The incorporation of the electricity tariff in sectoring and critical points control strategies has entailed the development of tools combining measures to reduce both energy consumption and operational costs, making up a decision support system for technical advisers and/or farmers.
- The joint optimization of sectoring operation, pressure heads and pumping efficiency, taking into account the installation of VSDs, has entailed potential energy savings of up 26 % in the studied irrigation network (BMI), without replacing any pump.

- The incorporation of the simultaneity of demand in the stated sectoring strategy enables to relax the pressure requirements set. Thus, additional energy savings compared with the concurrent operation of all hydrants can be achieved without significant losses in the quality of the service provided to farmers.

8.2. Avenues for future research

From the results presented in this thesis, the avenues for further research are listed below:

- The rehabilitation of irrigation networks focused on their redesign to reduce the energy consumption in critical points as an additional strategy to improve the energy efficiency.
- The integration of profit margin for farmer as well as irrigation deficit strategies as objectives in the stated methodologies, to achieve the optimum management of both water and energy and improve the profitability for farmers.
- Match the raised strategies with the on-farm irrigation system and the irrigation scheduling, to develop an integrated system that takes into account the whole hydraulic infrastructure, from the pumping stations to the on-farm irrigation systems through distribution networks.

8. Conclusiones

8.1. Conclusiones generales

- Las redes de riego a presión modernizadas recientemente han experimentado un importante aumento de la demanda energética, por lo que deben adoptar también medidas que contribuyan a una gestión sostenible tanto del agua como de la energía.
- Las nuevas estrategias de sectorización y control de puntos críticos, desarrolladas tanto para redes con un único punto de suministro como con varios, han supuesto ahorros energéticos potenciales entre el 20 % y el 36 % en la red de riego estudiada (PF).
- La incorporación de la tarifa eléctrica en las estrategias de sectorización y control de puntos críticos, permite diseñar un sistema de apoyo a la toma de decisiones para técnicos y/o agricultores en el que se contemplan medidas que permiten minimizar tanto el consumo de energía como los costes de operación de la red.
- La optimización conjunta del calendario de operación de sectores, de las presiones en las estaciones de bombeo y del rendimiento en las mismas, considerando la instalación de

variadores de velocidad, ha supuesto un ahorro energético potencial de hasta el 26 % en la red de riego analizada (BMI), sin necesidad de sustituir ningún grupo de bombeo.

- La incorporación de la simultaneidad de la demanda en la estrategia de sectorización permite relajar los condicionantes de presión impuestos. De este modo, se pueden alcanzar ahorros energéticos adicionales con respecto a la operación simultánea de todos los hidrantes, sin que la calidad en el servicio proporcionada a los agricultores se reduzca.

8.2. Nuevas vías de investigación derivadas de esta tesis

A la vista de los resultados presentados en este documento, las nuevas líneas de investigación se pueden enfocar de acuerdo a lo recogido en los siguientes puntos:

- Profundizar en el desarrollo de estrategias de mejora de la eficiencia energética en redes de riego, como el rediseño de las mismas para reducir las necesidades energéticas en los puntos críticos.
- Considerar el margen de beneficio del agricultor y distintas estrategias de riego deficitario como objetivos adicionales en las metodologías propuestas, con el fin de alcanzar un manejo óptimo del agua y la energía y un aumento del beneficio del agricultor.
- Vincular las estrategias planteadas tanto con el manejo óptimo como con la programación del riego en parcela,

diseñando un sistema integral en el que se englobe la gestión de toda la infraestructura hidráulica, desde las estaciones de bombeo hasta los sistemas de riego en parcela, pasando por la red de distribución.

Appendix A. Effects of modernization and medium term perspectives on water and energy use in irrigation districts

This appendix has been published entirely in the journal "Agricultural Systems", Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P, Berbel J (2014)

Abstract. Increasing of water use efficiency has been a key strategy for dealing with water scarcity in semiarid countries. In Spain modernization of irrigation schemes has consisted in the substitution of old open channels systems by pressurized networks. However, this improvement has represented a significant increase in water costs, mainly due to the higher energy requirements.

Five irrigation districts of Andalusia, Southern Spain, have been analyzed using performance indicators, before and after the improvement actions. Results indicate an average reduction in water diverted for irrigation of 23 %, but water costs increased in 52 %. Consequently, farmers are migrating to more profitable crops, such as citrus, with higher water requirements. Furthermore, managers' predictions about the cropping patterns for the 2020s suggest that the area devoted to citrus production will increase by 12 %, implying even higher potential maximum irrigation water demand. Hence, farmers will have to adapt to a

future scenario by using deficit irrigation and other water saving technologies. Consequently, the vulnerability of the irrigated agriculture to the typical droughts of the Mediterranean climate may increase.

Keywords. Benchmarking, performance indicators, water supply systems, Andalusia

A.1. Introduction

In semiarid countries, crop production must be ensured by irrigation. In Spain, characterized by Mediterranean climate with scarce and irregular rainfall, irrigation agriculture is essential and consumes around 58 % of the water resources (Hardy *et al.* 2012) and more than 80 % in the driest regions. In Spain, the irrigated area is around 3.5 M ha, accounting for almost a third of European Union irrigated land (Lopez-Gunn *et al.* 2012).

Excessive water consumption is the main problem in maintaining a good environmental status in water resources (European Commission 2012). Irrigation water saving technologies have been the main measure used to reduce quantitative water stress in Spain since the Spanish National Plan for Irrigated Areas (MAPA 2001). This plan consisted in the modernization of water distribution infrastructure from old open channel distribution systems to pressurized networks. Annual water savings of 3000 Mm^3 were expected (Lecina *et al.,* 2010a). Most of the analysis of the cost and efficiency of the investment to improve water distribution efficiency (called 'modernization') has been made by ex-ante models. Related to this, Berbel *et al.* (2011) studied the implementation of the Program of Measures according to Water Framework Directive in Guadalquivir river basin (Andalusia, Spain).

The objective of this research was to gain knowledge about the real cost and impacts of modernization in Southern Spain. Preliminary analyses of national data show that:

a) As a result of the modernization process, surface irrigation has decreased from 42 % in 2002 to 30 % in 2011 whereas drip irrigation has increased from 30 % to 47 % over the same period (MAPA 2002, MAGRAMA 2012). Thanks to the continuous efforts to improve the conveyance efficiency, water use for irrigation per unit of irrigated area has been reduced by 21 % from 1950 to 2007 (Corominas 2010).

b) However, the energy consumption has increased by 657 % over the same period involving higher energy costs for farmers (Corominas 2010).

c) Furthermore, farmers must face the amortization, operations and maintenance costs of the new irrigation infrastructures (Rodríguez Díaz *et al.* 2012a).

Several researchers have used performance indicators for the evaluation of the water use in irrigation districts (Alexander *et al,* 2004, Malano *et al.* 2004, Rodríguez Díaz *et al.* 2008). However, in most previous research these indicators have been applied to comparative benchmarking analyses of different irrigation districts within a single year.

Benchmarking is defined as 'a systematic process for securing continual improvement through comparison with relevant and achievable internal or external norms and standards' (Malano and Burton 2001). This methodology has been rarely used for the evaluation of modernization processes. Lecina *et al.* (2010a, 2010b) evaluated the effects of the transformation of hydraulic infrastructure on water quantity and quality in the Ebro river basin based on hypothetical scenarios. They concluded that the new pressurized systems lead to more intensive cropping patterns and, therefore, to increments in evapotranspiration.

The rise of energy consumption is becoming a major issue in the irrigation supply. Rodríguez Díaz *et al.* (2011) evaluated the joint use of water and energy in ten Andalusian irrigation districts with pressurized systems during one irrigation season. They confirmed the increased energy requirements of the pressurized networks (0.4 kWh m^{-3}) and highlighted that energy represents almost 40 % of the water costs. Rodríguez Díaz *et al.* (2012a) reported that in Bembézar Margen Derecha irrigation district (Southern Spain), water diverted for irrigation was reduced by 40 % after modernization due to the migration to more efficient conveyance and application systems. Conversely, water costs per hectare are four times bigger due to higher energy costs.

This research continues with the analysis of cost and impacts of modernized irrigated systems but innovates with a dynamic benchmarking exercise analyzing the effects of the ex-post situation (observed data). Then, a comparison is made with both pre-modernization situation and future scenario. In this paper, the impact of modernization in five irrigation districts of Andalusia (Southern Spain) is evaluated applying water, energy and economic indicators. These indicators have been calculated for the 1996 to 2002 irrigation seasons, before modernization was implemented and for two irrigation seasons (2010-2012), when the new hydraulic infrastructures (pressurized networks) were fully operating. Finally, a future scenario developed according to the perceptions of the irrigation district managers is forecasted for the horizon 2020.

A.2. Methodology

A.2.1. Selection of irrigation districts

The irrigation districts selected for this work were Bembézar Margen Izquierda (BMI), Bembézar Margen Derecha (BMD), Sector BXII (BXII), Genil Margen Derecha (GMD) and Guadalmellato (GU) (Fig. A.1). All of them were modernized in recent years when the collective pressurized networks replaced the old open channels systems, excepting BXII. This irrigation district already had a pressurized system but without water meters at farm level, so volumetric billing was not possible. In all the districts, before the improvement actions, the water pricing system was a fixed rate per irrigated hectare without considering the volume applied. After the modernization processes, users were charged according to a mixed water pricing system. Energy costs for pumping are paid according to a volumetric pricing system, whilst maintenance, operation and management costs are paid at a fixed rate per unit irrigated area.

Before the modernization, users received water without pressure, and more than 70 % of the area used surface irrigation, with only a small percentage using trickle irrigation for fruit trees. These farmers had their own reservoirs and pumping stations. The new infrastructure allows users to irrigate on-demand, so the flexibility has been hugely increased. Drip irrigation is the most widespread system and surface irrigation (predominant before modernization) has virtually disappeared. The total investment was € 123.8 M (€ 3,235 ha^{-1}).

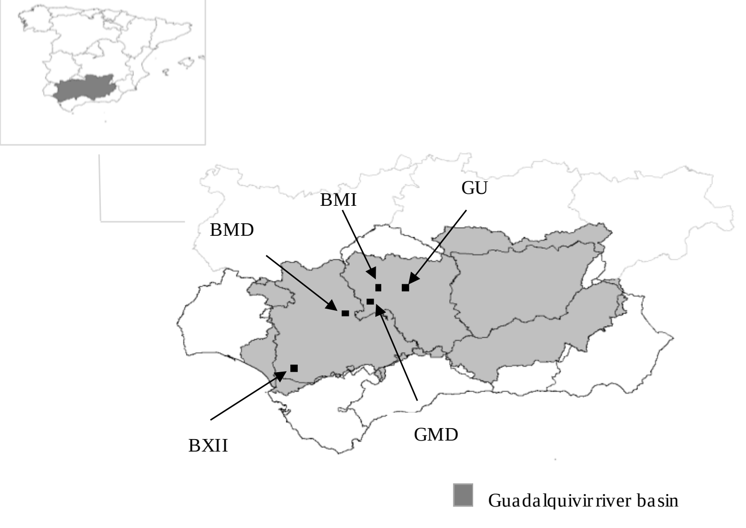

Fig. A.1. Location of the selected irrigation districts

The selected irrigation districts cover a total irrigated area of 38,285 ha, accounting for 11 % of the modernized area in Andalusia (Lopez-Gunn *et al.* 2012). All of them belong to the Guadalquivir river basin, characterized by Mediterranean climate with scarce and irregular rainfall (annual average around 550 mm) and high potential evapotranspiration rates, around 1335 mm as annual average (Rodríguez Díaz *et al.* 2007).

A.2.2. Water and energy use indicators

Water and energy use indicators selected in this work were mostly suggested by IPTRID (International Programme for Technology and Research in Irrigation and Drainage) (Malano and Burton 2001):

1. Annual irrigation water supply per unit irrigated area, *Is* (m^3ha^{-1}). This is the ratio of the total annual volume of water diverted or pumped for irrigation and the irrigated area.
2. Theoretical crop water requirements per unit irrigated area, *ETc* (m^3ha^{-1}). This indicator shows the ratio of the theoretical crop water requirements and the irrigated area. The crop evapotranspiration is estimated as described in FAO 56 (Allen *et al.* 1998).
3. Theoretical crop irrigation water requirements per unit irrigated area, *Ir* (m^3ha^{-1}). This is the theoretical volume of irrigation water required by the crops divided by the

irrigated area. The value of *Ir* is obtained by subtracting the effective rainfall (P_{ef}) from crop evapotranspiration.

4. Annual Relative Water Supply, *RWS*. This is the ratio of the total annual volume of water diverted or pumped in the irrigation district, *Is* (m^3) plus the effective rainfall, P_{ef} (m^3) divided by the theoretical crop water requirements, *ETc* (m^3).
5. Annual Relative Irrigation Supply, *RIS*. This indicator represents the total annual volume of water diverted or pumped in the irrigation district, *Is* (m^3) divided by the theoretical crop irrigation water requirements, *Ir* (m^3).
6. Cost related to the water agency tariff, C_C (€ha^{-1}). This is a fixed cost paid by farmers to the water authorities through the irrigation district for their water allocation withdrawn from reservoirs and delivered to the irrigation district. This cost is computed by hectare (Berbel and Gómez-Limón, 2000).
7. Maintenance cost, C_M (€ha^{-1}), also computed by hectare.
8. Energy cost. This represents the total annual energy cost divided by the total annual irrigation water supply, C_{EW} (€m^{-3}), o per unit of irrigated area C_{EA} (€ha^{-1}).
9. Total water costs per unit of irrigated area, C_{TA} (€ha^{-1}). This is the sum of all costs associated to irrigation (water agency tariff, maintenance and energy cost) per unit of irrigated area.

10. Total water costs per unit of supplied water, C_{TW} (€m^{-3}). This indicator represents the sum of all cost related to irrigation per unit of volume of water delivered to farmers.
11. Ratio of energy to total water costs, C_{EW}/C_{TW}. This is the proportion of total water costs related to the energy cost.
12. Output per unit irrigated area, O_A (€ha^{-1}). This indicator is obtained dividing the gross value of the agricultural production within the irrigation district by the irrigated area.
13. Output per unit irrigation supply, O_S (€m^{-3}). This represents the gross value of the agricultural production divided by the volume of irrigation water delivered to farmers.
14. Output per unit crop water transpiration, O_{ETc} (€m^{-3}). This is the ratio between the gross value of the agricultural production and the total volume of water required by crops, ETc (m^3).
15. Apparent labour productivity, P_L (€ AWU^{-1}). This indicator represents the gross value of the agricultural production divided by labour required in the irrigation district, estimated as annual work units (AWU). One AWU is equivalent to one person working full-time during a year. The labour input according to each crop has been obtained from Berbel and Gutiérrez (2004).

A.2.3. Data collection

In order to evaluate the modernization impacts on water and energy use, two different periods were analyzed for the five irrigation districts:

- 1996 to 2002 (pre-modernization period).
- 2010 to 2012 (post-modernization period).

To ensure consistency in the way the indicators were calculated across all irrigation schemes, IPTRID provides definitions and a methodology for their calculation (Malano and Burton 2001). In this study, all the data were collected in accordance with these guidelines using information routinely collected by the irrigation districts. Data required to calculate the indicators are typically recorded on a daily basis as part of management operations (for example, records on water use, costs and crops grown on each farm). Climate data were obtained from agroclimatic weather stations located in every irrigation district (Fig. A.2).

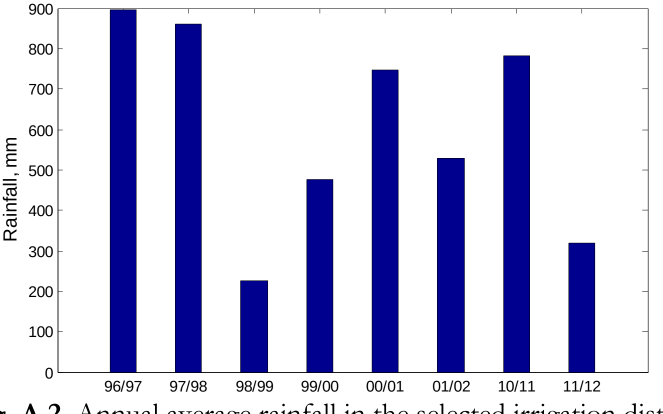

Fig. A.2. Annual average rainfall in the selected irrigation districts

A.2.4. Future scenarios

To provide medium-term trends for water demand, an estimation of the areas that may be devoted to each crop in 2020 was carried out. For this purpose, a survey was conducted among managers of irrigation districts asking about their predictions of growth / decrease of the area devoted to every crop in the next ten years. Then the crop water requirements for the 2020 scenario were estimated using the CROPWAT computer model (Clarke 1998). Afterwards, both the past and present water demand were compared with the 2020 synthetic trending scenario.

A.3. Results and discussion

The performance indicators were calculated for 1996 to 2002 irrigation seasons, related to pre-modernization period and for 2010 to 2012 irrigation seasons, corresponding to post-modernization period. Most of the data corresponding to the pre-modernization period were previously collected by Rodríguez Díaz *et al.* (2008). The obtained results are presented below.

A.3.1. Water use

The water allocations for the irrigation districts in the studied seasons are shown in Fig A.3. The average value obtained in pre-modernization period was 7164 m^3ha^{-1} whereas the average value in post-modernization period was 5508 m^3ha^{-1}.

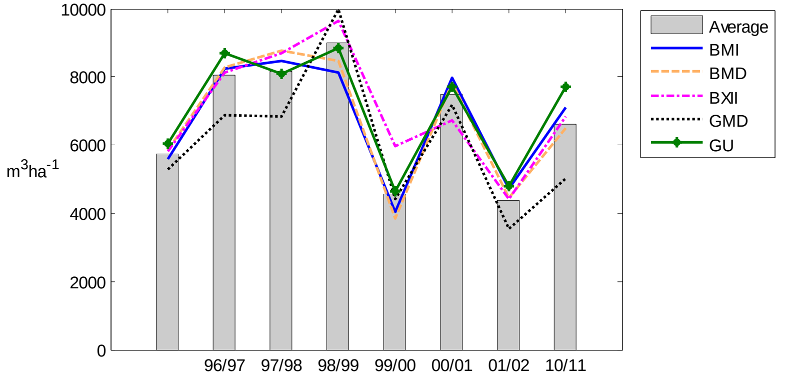

Fig. A.3. Water allocation for the irrigation districts.

Thus, the average allocations were reduced in 23 %. Concerning to annual irrigation water supply (Fig. A.4.a), a significant reduction of this indicator was obtained after the modernization process in all irrigation districts. The reductions in water use (water diverted for irrigation) were 2823 m^3ha^{-1} (37 %) in BMI, 1705 m^3ha^{-1} (22 %) in BMD, 1465 m^3ha^{-1} (20 %) in BXII, 2094 m^3ha^{-1} (33 %) in GMD and 1242 m^3ha^{-1} (16 %) in GU. On average, annual irrigation water supply was reduced by 1693 m^3ha^{-1} (23 %), similar figure to the reduction of average allocations. The transformation of the hydraulic infrastructures to pressurized networks is the main cause of the reduction of the irrigation supply. Furthermore, the new irrigation systems allow the use of trickle or sprinkler systems that enhance the water use efficiency at field scale (Carrillo Cobo *et al.* 2011).

Table A.1. Irrigated areas (ha), irrigation systems (%) and key crops (%) in the studied irrigation districts in pre-modernization and post-modernization periods

	BMI		BMD		BXII		GMD		GU	
Area, ha	3,900		11,912		14,643		2,235		5,500	
%	pre	post	pre	post	pre	post	pre	post	pre	post
gravity	80	1	75	25	*	30	90	10	90	*
drip	20	90	25	75	*	70	10	75	5	*
citrus	9	47	15	50			34	64		
maize	47	26	33	28		9	24	15	34	33
cotton	13		24	8	41	49	25	5	9	12
sunflower	10	3	8	3	5	4	9	6	10	13
wheat									17	18
sugar beet					44	20				
tomato					4	11				
olive tree		10								

*Not available

Fig. A.4.b shows the evolution of the total crop water requirements (*ETc*) before and after modernization. *ETc* decreased in BMI (from 8653 m^3ha^{-1} to 7076 m^3ha^{-1}) and GMD (from 8781 m^3ha^{-1} to 7546 m^3ha^{-1}), it was more or less constant in BMD (8385 m^3ha^{-1} in the pre-modernization period and 8410 m^3ha^{-1} in post-modernization) and it was increased in BXII (from 8310 m^3ha^{-1} to 9267 m^3ha^{-1}) and GU (from 7979 m^3ha^{-1} to 8430 m^3ha^{-1}). Differences on the *ETc* evolution are caused by the changes in the cropping patterns after the modernization (Table A.1). In BMI and GMD, maize and cotton, high water demanding crops, have been replaced by young citrus trees that are currently the main crops (47 % and 64 % of cultivated area respectively). Therefore, crop water requirements have diminished temporally in the post-modernization period. In

BMD, citrus (which most of them are young trees and therefore demanding less water) are now the main crops. However, the presence of cotton, which is the third most important crop, has meant that *ETc* has remained practically constant. Either way, in BMI, GMD and BMD, an increase of *ETc* over the coming years is expected because citrus trees that are currently young will be in full production and, therefore, will require more water. In BXII, the replacement of sugar beet by cotton has led to an increase of *ETc*. Although this irrigation district already had a pressurized network, after the installation of water meters (facilitated with the modernization), farmers pay according to the volume of water applied and hence, they try to maximize their benefits by growing most profitable crops. In GU, the rise of cotton area has increased crop water requirements.

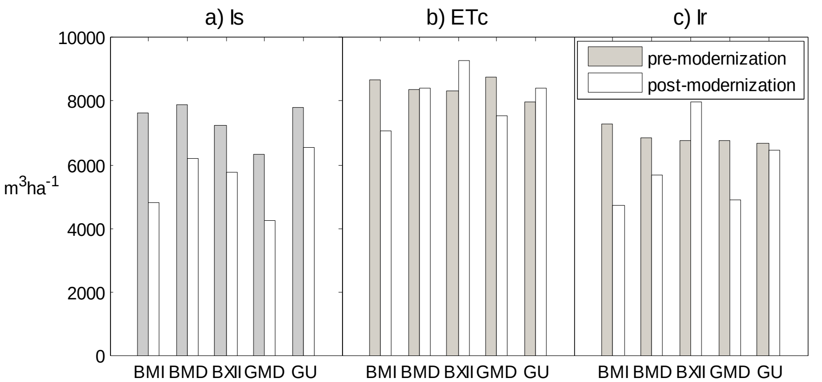

Fig. A.4.a Annual irrigation water supply (Is), **b** crop water requirements (ETc) and **c** crop irrigation requirements (Ir) in pre and post-modernization periods.

Crop irrigation water requirements (Fig. A.4.c) have decreased in most of the irrigation districts where spring-summer crops were replaced by annual crops, such as citrus. This change entails a greater rainfall use. In contrast, in BXII, the replacement of sugar beet (that uses an important fraction of the rainfall due to its cropping period) by cotton, has led to a raise of maximum irrigation requirements of 1209 m^3ha^{-1} (18 %). On average, crop irrigation water requirements have only decreased by 4 % while the reduction in water diverted for irrigation was up to 23 %. Hence, return flows have been reduced.

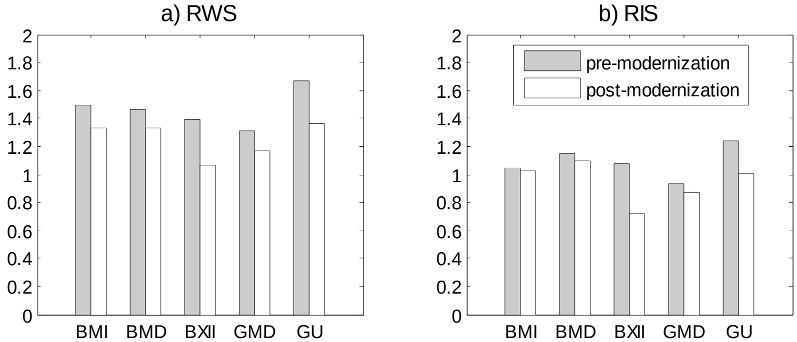

Fig. A.5.a RWS and **b** RIS for the irrigation districts before and after the modernization

However, adequacy indicators are needed to understand whether an improvement in the water use has occurred (Fig. A.5). The value of *RWS* has diminished in all irrigation districts. Likewise, *RIS* value, which relates irrigation water supply and theoretical irrigation water requirements (Rodríguez Díaz *et al.* 2008), has also been reduced in all irrigation districts: from 1.05 to 1.03 in BMI, from 1.15 to 1.10 in BMD, from 1.08 to 0.72 in BXII, from 0.93 to 0.87 in GMD and from 1.24 to 1.01 in GU. Theoretically, *RIS* values around 1.0 show that the full irrigation requirements were met. *RIS* indicator in BMI, BMD and GU showed values around 1 which means that water is used efficiently. In BXII and GMD, *RIS* was lower than 1, which entails deficit irrigation (Rodríguez Díaz *et al.* 2012b).

A.3.2. Water costs

Water cost has three items (Table A.2): the cost related to the water agency tariff, C_C, the maintenance cost, C_M and the energy cost, C_{EA} o C_{EW}. The amortization costs of the water distribution networks and on-farm irrigation systems are not included in the analysis.

Relating to C_C, an increase has been observed in all irrigation districts: 20.1 €ha^{-1} (40 %) in BMI, 16.8 €ha^{-1} (33 %) in BMD, 1.5 €ha^{-1} (2 %) in BXII and 1.8 €ha^{-1} (3 %) in GMD. However, in GU, C_C has reduced by 24 % (21.4 €ha^{-1}) since this irrigation district has now assumed responsibility for maintaining the hydraulic infrastructure. This task was previously carried out by the water authorities and the cost was included in C_C.

Table A.2. Water costs before and after the modernization process

	BMI		BMD		BXII		GMD		GU	
	pre	post	pre	post	pre	post	pre	post	pre	post
C_C, €ha^{-1}	49.9	70.0	50.2	66.9	87.5	89.0	64.5	66.2	88.3	66.9
C_M, €ha^{-1}	43.9	77.0	70.5	76.5	69.0	95.6	42.9	96.1	80.1	106.4
C_{EA}, €ha^{-1}	0.0	124.3	2.9	140	115.4	147.6	*	*	14.1	48.9
C_{TA}, €ha^{-1}	93.9	271.3	123.6	283.5	271.9	332.2	107.4	162.3	182.4	222.2
C_{EW}/C_{TW}, %	0	46	2	49	42	45			8	22

* Not available

The maintenance cost, C_M (Table A.2), has increased after the modernization because the upkeep of pressurized networks is more expensive and skilled labour is required (Rodríguez Díaz *et al.* 2012a). Thus, C_M has increased 33 €ha^{-1} (75 %) in BMI, 6 €ha^{-1} (9 %) in BMD, 53.2 €ha^{-1} (124 %) in GMD and 26.3 €ha^{-1} (33 %) in GU. In BXII, C_M has also risen by 26.6 €ha^{-1} (39 %) because of the maintenance of the new infrastructure to measure the volume of water used and the purchase of agricultural machine. Energy cost has evolved from values close to 0 in GU, BMD and BMI to values of 0.01, 0.02 and 0.03 €m^{-3}, respectively (Fig. A.6). In BXII, energy cost has increased from 0.02 to 0.03 €m^{-3}. The significant increment of energy cost is due to the combined effect of higher energy requirements of pressurized systems and the rise of energy price, that has been increased more than 100 % in the last years (Rodríguez Díaz *et al.* 2012c). In this regard, energy is the main contributor to irrigation cost in almost all the irrigation districts. Energy represents up to 50 % of the total water costs (e.g. BMD).

The rise of energy cost has led to higher total irrigation costs, C_{TA} (Table A.2). C_{TA} has risen 177.4 €ha^{-1} (189 %) in BMI, 159.9 €ha^{-1} (130 %) €ha^{-1} in BMD, 60.3 (22 %) €ha^{-1} in BXII, 54.9 €ha^{-1} (51 %) in GMD and 39.7 €ha^{-1} (22 %) in GU.

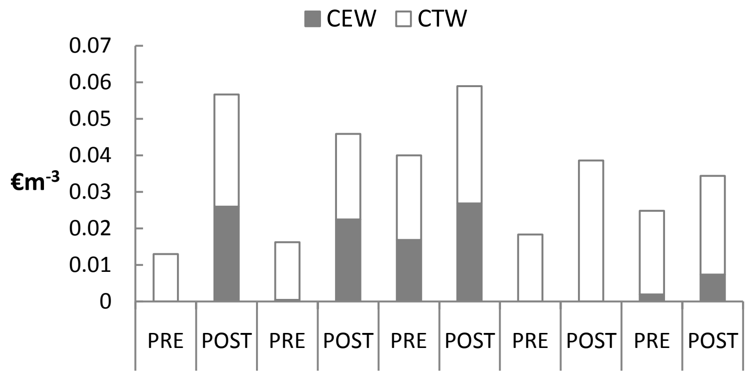

Fig. A.6. Energy cost (C_{EW}) and total irrigation cost (C_{TW}) in pre-modernization and post-modernization periods.

A.3.3. Productivity

The productivity indicators are shown in Table A.3. In BMI, BMD and GMD, the change to more profitable crops has entailed greater outputs per unit irrigated area. By contrast, in BXII and GU (irrigation districts with traditional crops) outputs per unit irrigated area have decreased mainly due to the market prices. In this work, possible increments in crop yield due to the adoption of pressurized irrigation systems, in which water use by crops is more efficient, have not been taken into account. Better irrigation systems increase the water availability, uniformity and flexibility and consequently, crop transpiration. Lecina *et al.* (2010b), estimated that the land productivity (€ha^{-1}) in sprinkler irrigation, with more intensive cropping patterns, was around 51 % higher than in surface irrigation. However, in some of the studied districts there was a significant percentage of drip irrigation before modernization (mainly for irrigation of fruit trees and citrus) and it has not been possible in our survey to distinguish between the previous and the current situation in terms of unit yields.

Table A.3. Apparent productivity indicators (output per unit irrigated area, OA, output per unit irrigation supply, OS; output per unit crop water demand, OETc; apparent productivity of the labour, PL) before and after the modernization processes

	O_A, € ha^{-1}		**O_S,** € m^{-3}		**O_{ETc},** € m^{-3}		**P_L**, € AWU^{-1}	
	pre	post	pre	post	pre	post	pre	Post
BMI	2,946	4,315	0.40	0.93	0.34	0.62	45,311	27,507
BMD	3,955	4,509	0.53	0.80	0.47	0.55	37,651	30,379
BXII	3,341	3,120	0.49	0.66	0.40	0.35	52,599	42,151
GMD	3,799	4,235	0.70	1.09	0.43	0.57	31,183	23,911
GU	2,740	2,029	0.37	0.36	0.37	0.24	41,974	34,363

Output per unit irrigation supply has also increased since the irrigation water supply was significantly reduced in all irrigation districts and the output per unit irrigated area increased in some cases. Carrasco *et al.* (2010), in their study about crop water productivity in the Guadalquivir river basin, obtained an increase of this indicator from 1989 to 2005 due to, among other factors, the more efficient use of irrigation water.

The value of output per unit crop water demand has increased after the modernization in BMI, BMD and GMD mainly due to the increase of output per unit irrigated area. In contrast, in BXII and GU, this indicator has reduced because of the increase of ETc and the reduction of output per unit irrigated area.

Productivity of labour has shown lower values in the post-modernization period in all irrigation districts. In BMI, BMD and GMD, the migration to citrus has involved a rise of input labour whereas in BXII and GU, the lower value of the output per unit irrigated area after the modernization, has entailed the reduction of the productivity of labour.

A.3.4. Perspectives about future cropping patterns and theoretical water requirements

In this analysis, the cropping patterns corresponding to the 2001/2002 and 2010/2011 seasons were assumed as representative of pre-modernization and post-modernization periods, respectively. The likely distribution of the key crops in 2020 was estimated from managers' perceptions about the evolution of the crop area in 2020 (Table A.4). The area devoted to citrus has significantly increased from 3511 ha in 2001/2002 to 8900 ha in 2010/2011 (153 %). The area devoted to citrus rises yearly (Montesinos *et al.* 2011) and the predictions for 2020 show an additional increase of 1063 ha (12 %) compared to the area devoted to citrus in 2010/2011. Consequently, traditional irrigated crops in these irrigation districts such as cotton, sunflower, wheat or sugar beet, will suffer substantial reductions. Considering only the influence of the cropping patterns change on evapotranspiration and irrigation requirements, an average hydrological year has been selected for every district (data taken from the long-time climate series). Thus, the cropping patterns of

2001/2002, 2010/2011 and the future scenarios were analyzed for the same climate conditions. Fig. A.7 shows that the progressive incorporation of citrus in the cropping patterns produces an increase in the maximum irrigation requirements when the trees reach their mature stage.

Table A.4. Predictions of change (%) in the irrigated areas devoted to the main crops for 2020 compared to the 2010/2011 irrigation season

%	BMI	BMD	BXII*	GMD	GU	Collectively
Cotton	10	-10	0	-10	-10	-2
Sunflower	-10	0	0	-25	0	-2
Wheat	10	0	0	-25	-25	-11
Maize	10	10	0	-25	0	5
Olive tree	-20			5	10	-2
Citrus	10	10		20	20	12
Sugar beet			0			0

* The manager of BXII estimated the same cropping pattern for 2010/2011 and 2020.

Comparing the 2010/2011 and 2001/2002 cropping patterns, the *ETc* decreases in BMI and BMD, remain constant in GMD and GU and increases in BXII. Collectively, the crop water requirements (*ETc*) increased by 2 %. Theoretical irrigation water requirements (*Ir*) are lower in 2010/2011 than in 2001/2002 for all irrigation districts, with the exception of BXII due to the replacement of sugar beet by cotton (Table A.1). For all districts jointly, *Ir* is reduced in 3 %. Thus, it can be assumed that the crop water requirements and irrigation needs remain practically constant in the short term. The result of our research regarding the behaviour of *Ir* and *ETc* is congruent with the results of the agro-economic model developed by Berbel and Mateos (2014) which analyses the impact of modernization in water use and consumption.

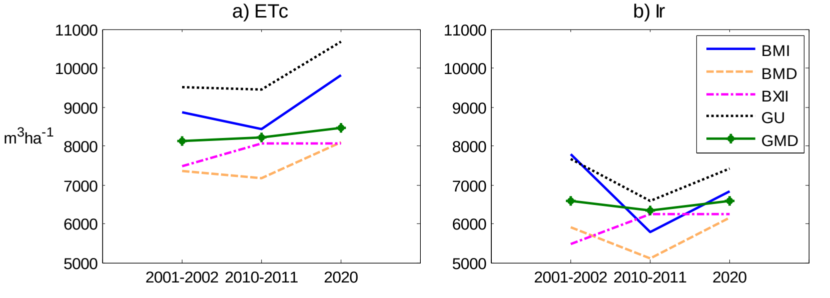

Fig. A.7. Crop water requirements (ETc) and irrigation water requirements (Ir).

Nevertheless, an increase of crop evapotranspiration for 2020 is expected compared to 2010/2011 irrigation season in all the irrigation districts excepting BXII, whose manager estimated the same cropping pattern for 2010/2011 and 2020. On average, the value of *Ir* is also expected to increase by 5 %. Although the comparison of 2001/2002 and 2010/2011 cropping patterns shows a decrease of *ETc* and *Ir* in most irrigation districts, it must be considered that high water requirement crops (cotton or maize) have been replaced by young citrus trees. However, in the 2020 scenario, the new citrus trees, that were already planted before the modernization processes plus the additional post modernization increment, will be in full production with maximum water requirements. Thus, the water savings that were obtained after modernization could be dramatically reduced and, in the next ten years, the net water losses (evapotranspirated water that goes to the atmosphere and cannot be reused by other users) could be even higher than before the improvement actions. The fact that water quota has been reduced in these irrigation districts by 25 % from previous levels may avoid the 'rebound' effect producing deficit irrigation as farmers cannot supply full irrigation needs.

The impacts of a changing climate on irrigation demand have not been included in the analysis and, as in other Mediterranean regions, any increase in evapotranspiration, coupled with changes in rainfall distribution, are expected to cause significant increases in irrigation demand. Increase in demand forecasts for the most common crops in the region for 2050 horizon estimates a range from +15 to +25 % for the 2050s and from +25 to +35 % for the 2080s (Rodríguez Díaz and Topcu 2010). These increases can aggravate the current situation.

A.4. Discussion and concluding remarks

In order to evaluate the impacts of irrigation system modernization on water and energy use, five irrigation districts, in the Guadalquivir basin with pressurized networks, have been analyzed.

The results show an average reduction of irrigation water abstraction of 23 %, mainly due to improvement of water distribution efficiency. Contrasting with the reduction of water diverted for irrigation, the energy cost was increased by 149 %, leading to an average rise of water costs of 52 %. Additionally the water tariff after the modernization process has become volumetric instead of the fixed land based (flat rate) previous system. All costs including operation and maintenance of new systems (pressurized distribution, metering etc.) are covered by the new tariff.

Farmers have carried out changes on their cropping patterns in response to the increased irrigation cost and the availability of a more flexible irrigation system. Area of more profitable crops, such as citrus, has increased productivity of land. Similar trends were observed for the outputs per unit of irrigation water supply, which have risen in 44 %. In contrast, these higher value crops require more water when they are irrigated at full requirement. Thus, the comparison of 2001/2002 and 2010/2011 irrigation seasons with the synthetic 2020 scenario, considering a standard hydrological year, shows a rebound effect in most irrigation districts. Current crop water requirements are just 2 % higher than in 2001/2002 irrigation season due to the substantial area devoted to young citrus trees (with reduced water demand). However, on 2020, increased area of citrus and maturity of those crops, will involve an increase in 9 % of crop water requirements compared to 2001/2002.

Thus, the higher water costs and the increased flexibility in the water availability after the modernization process, lead to the incorporation of more profitable crops (Playán *et al.* 2006; Lopez-

Gunn *et al.* 2012; Rodríguez Díaz *et al.* 2012a). The adoption of higher water demanding crops has been also indicated by Pfeiffer and Lin (2010), who have highlighted that more efficient irrigation systems improve the effectiveness of water, but the saved water is used to increment the crop yields, adopt more intensive crops or increase the irrigated areas.

Furthermore, the likely increment of crop yields due to the increased operational flexibility in the water conveyance system, which would entail further increase of *ETc*, has not been taken into account in this work. Therefore, the change to higher water demanding crops will enhance the dependence on irrigation water and the vulnerability of agricultural productions to droughts periods, typical of this region. Berbel *et al.* (2013) have described the process at basin level analysing the trajectory of Guadalquivir towards basin closure.

Modernization will probably not lead to net water savings at basin level as it has been already observed by Molle and Berkoff (2007), because of the change in crop plan and water use intensity. The solution adopted in Spain has been the reduction in water rights allotment that averages 25 % over the previous quota, e.g. most of the irrigation districts analyzed in this research has seen their water right allotment reduced from the previous 8.000 m^3ha^{-1} to 6.000 m^3ha^{-1} after the modernization were completed. This policy controls any possible rebound effect because even if maximum potential irrigation requirements increase, the water supply constraint will force farmers to use deficit irrigation and other water saving technologies.

This research has focused on the impact of water saving technologies (related to water delivery and application efficiency) in large irrigation schemes considering variables such as land use changes, energy use, water cost, and productivity factors. Further research should also study the impact of the reduction of water allocations on the return flows and also it should consider the impact on crop yields of the improvement of water supply, and consequently the higher uniformity and flexibility of water availability for farmers.

Finally, modernization allows the implementation of economic instruments such as those promoted by European Commission (2012) including an increase in water cost and metering as a pre-requisite to use water price as a signal to allow farmers efficient assignation of water resources.

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