Agricultural Water Management 164 (2016) 212–222

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Rehabilitating pressurized irrigation networks for an increased energy efficiency

I. Fernández García[a,*], E. Creaco[b], J.A. Rodríguez Díaz[a], P. Montesinos[a], E. Camacho Poyato[a], D. Savic[c]

[a] Department of Agronomy, University of Cordoba, Campus Rabanales, Edif. da Vinci, 14071 Cordoba, Spain
[b] Dipartimento di Ingegneria Civile e Architettura, University of Pavia, Via Ferrata 5, 27100 Pavia, PV, Italy
[c] Centre for Water Systems, University of Exeter, Harrison Bldg., North Park Rd., Exeter EX4 4QF, UK

ARTICLE INFO

Article history:
Received 13 June 2015
Received in revised form 19 October 2015
Accepted 29 October 2015
Available online 11 November 2015

Keywords:
Network rehabilitation
Optimization
Energy efficiency
Water distribution systems

ABSTRACT

This paper presents a methodology aimed at assisting irrigation district managers in the optimal rehabilitation of pressurized irrigation networks. The methodology uses a multi-objective approach and finds optimal trade-off between investments and long term operational costs. The approach is based on two steps: 1—application of two alternative optimization algorithms to determine optimal trade-offs between installation costs and pump power absorption; 2—post-processing of the optimal solutions in terms of long term costs under various possible scenarios generated featuring various values of the useful construction life and of the capital recovery factor. Applications were carried out on a real case study, considering a pre-fixed electricity tariff and the on-demand operation of the network.

After analyzing the results, the most cost-effective solution, with a redesign cost of 205,627 €; and overall cost varying from 6,019,447 €; to 11,498,053 €; according to the scenarios considered, was selected.

1. Introduction

Reducing greenhouse gas emissions by 20%, increasing the use of renewable energy sources by 20% and incrementing the energy efficiency by 20% within year 2020 are the objectives pursued in the Energy Strategy of the European Commission (European Commission, 2010). The enhancement of energy efficiency must also be applied to pressurized irrigation networks, large users of energy after the modernization of the open channel systems and the adoption of pressurized irrigation systems (sprinkler or drip) (Corominas, 2010). Thus, the European countries have to assume water management strategies focused on the water-energy-environment nexus in the agricultural sector (European Commission, 2012).

Spain, Italy and Portugal, with a strong agricultural sector, are the most water-consuming countries in the European Union. Thus, different measures to reduce water and energy use and operational costs in irrigation networks have been developed in these countries. Strategies focused on network sectoring by grouping hydrants in irrigation turns (Carrillo Cobo et al., 2011; Moreno et al., 2010), control of critical points (hydrants with high energy requirements) (Rodríguez Díaz et al., 2012; Fernández García et al., 2014), or optimization of pumping stations (Moreno et al., 2009; Lamaddalena and Khila, 2013) assuming different water consumption patterns, are the most successful strategies for reducing the energy consumption and optimizing the water use in this type of networks. Previous research on the control of critical points in irrigation networks considered the detection of the most unfavorable hydrants and their subsequent control by performing several improvements in the network (Rodríguez Díaz et al., 2012; Fernández García et al., 2014). However, in these works, the actions to enhance the operation of the critical points were assumed without applying any optimization procedure. In these cases, measures such as network rehabilitation could involve an effective tool to improve the operation of the critical points and hence, to reduce energy consumption.

The aforementioned strategies have been focused on the development of optimization procedures to minimize energy consumption in irrigation networks. Other works have analyzed the effects of the electricity tariff on operational costs, concluding that avoiding the irrigation in peak hours, significant energy cost

---

[*] Corresponding author.
E-mail addresses: g52fegai@uco.es (I. Fernández García), creaco@unipv.it (E. Creaco), jarodriguez@uco.es (J.A. Rodríguez Díaz), pmontesinos@uco.es (P. Montesinos), ecamacho@uco.es (E. Camacho Poyato), d.savic@exeter.ac.uk (D. Savic).

http://dx.doi.org/10.1016/j.agwat.2015.10.032
0378-3774/

savings can be achieved (Rocamora et al., 2013; Córcoles et al., 2015; Fernández García et al., 2015).

In the context of water distribution system optimization, many algorithms have been developed using both the single (e.g., Savic and Walters, 1997; Vairavamoorthy and Ali, 2000) and multi-objective approach (e.g., Baños et al., 2009; Siew and Tanyimboh, 2012; Creaco and Franchini, 2012). The advantages of considering a multiobjective optimization are (1) a wider range of solutions is obtained; (2) the decision maker is the ultimately responsible for selecting the best solution according to his preferences and (3) the problem definition is more realistic (Cohon, 1978).

In irrigation networks, the optimization of the design has also been considered using both single and multi-objective procedures. For example, Farmani et al. (2007) carried out the optimization of the design of pressurized irrigation systems taking into account two possible management scenarios: on-demand operation (farmers can irrigate whenever they want) and -rotation scheduling (farmers are organized in irrigation turns). They concluded that the optimal redesign cost can be reduced by 50% when different irrigation turns are considered during the optimization process. On the other hand, González-Cebollada et al. (2011) proposed a new method, recursive design, to determine the minimum redesign cost of pressurized irrigation networks, highlighting that their new methodology required less simulation time than other known optimization techniques.

However, the disadvantage of the above mentioned methodologies lies in the fact that they do not consider jointly optimization of design and operational costs of the network. This aspect is very important since in pressurized irrigation networks with pumping stations, the major cost is related to the pump operation. Thus, optimizing the pump performance to reduce the operational cost should be taken into account at the same time as the optimization of the network pipes.

In addition, these methodologies focus on the determination of optimum network designs, which can entail huge installation costs for farmers. Hence, the rehabilitation of irrigation networks by changing certain pipes and improving the operation of the pumping station can imply significant savings in cost and energy consumption, with installation costs affordable for farmers.

In this work, a methodology based on a multi-objective approach is then proposed to simultaneously optimize installation and operational costs. These two objectives are conflicting. The laying of new pipes in the network with different sizes and lower roughness, compared to the existing ones, leads to an increased installation cost. However, this entails a decrease in network head losses and hence, lower energy is required to guarantee suitable pressure heads at the nodes. Furthermore, the replacement of old pumps with new high efficiency pumps, which also increases the installation cost, has evident beneficial effects in terms of energy consumption.

2. Methodology

The methodology described in this work aims to support decisions for rehabilitation of irrigation networks. In the initial first step, the optimal redesigns of the network considering the simultaneous operation of all hydrants, i.e., the peak demand, are determined using two alternative optimization algorithms. Once the possible redesigns of the network in the most unfavorable condition have been obtained, the on-demand operation of the network, i.e., the usual performance, is analyzed for every month of the irrigation season in the second step of the methodology. Thus, hourly Flow-Head characterization is carried out on each redesign obtained in step 1, followed by the determination of the suitable pumping station operation: relative rotary speed for variable speed pumps and number of working fixed pumps, according to each hourly pair of

Notation

γ [N m^{-3}]	Water specific weight
η_i	Efficiency of pump i
c	Configuration index
d	Day index
h	Hour index
hy	Hydrant index
i	Pump index
j	Pipe index
k	Pump replacement index
m	Individual index
nc	Number of demand configurations generated during hour h
nd	Number of different days according to the electricity tariff
nj	Number of pipes
nh	Number of hours of network operation during day d
nhy	Number of hydrants
n_{pumps}	Number of operating pumps
nv	Number of reservoirs
np	Number of electricity tariff periods
p	Period index
r	Total recovery factor
s	Pump life span
tr_{d} [h]	Daily required irrigation time
ts_{hychd}	Irrigation start time for hydrant hy in configuration c during hour h and day d
tf_{hychd}	Irrigation end time for hydrant hy in configuration c during hour h and day d
v	Reservoir index
y	Year index
D_j [mm]	Diameter of pipe j
EC [€ year^{-1}]	Energy cost
F [m^{-3} s^{-1}]	Required flow (F); flow supplied by the pump i (F_i); flow supplied by hydrant hy (F_{hy}); flow supplied by reservoir v (F_v); base demand at a certain operating hydrant (Fb_{hy})
$\text{Fhy}_{\max}$[m^{-3} s^{-1} ha^{-1}]	Maximum flow allowed per hydrant
H [m]	Required head (H); pressure head provided by the pumps (H_i); pressure head provided by the reservoir (H_v)
IR	Resilience index
Is	Individual selected
K	Number of pump replacements determined by T/s
L_j [m]	Length of pipe j
OpC [€ year^{-1}]	Operational costs
OvC [€]	Overall cost
Pa_{hy} [m]	Pressure available at hydrant hy
Pcrit [m]	Pressure in the critical hydrant
$\text{Penergy}_{\text{hd}}$ [€ kW h^{-1}]	Energy price according to hour h and day d
Po [W]	Power introduced by pump i (Po_i); contracted power according to the maximum demanded value in period p (Po_{maxp})
Ppower_p [€ kW^{-1}]	Power term price in period p
Pser [m]	Minimum acceptable service pressure
PoC [€ year^{-1}]	Power cost
PumpC [€]	Pump replacement cost
RC [€]	Rehabilitation cost
S_{hy} [ha]	Irrigated area associated to hydrant hy
T	Useful life
UC_j [€ m^{-1}]	Unit cost associated with j pipe diameter