BIOSYSTEMS ENGINEERING 147 (2016) 67–80

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Optimal reservoir sizing in on-demand irrigation networks: Application to a collective drip irrigation network in Spain

*Argenis Izquiel, Rocio Ballesteros, Jose M. Tarjuelo, Miguel A. Moreno**

University of Castilla-La Mancha (UCLM), Regional Centre of Water Research (CREA), Campus Universitario s/n, 02071, Albacete, Spain

ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form
26 March 2016
Accepted 9 April 2016
Published online 28 April 2016

Keywords:
Reservoir
Holistic approach
Energy cost
Irrigation
Pumping system

Optimal reservoir sizing in on-demand irrigation networks with a minimum cost was obtained, taking into account the variability of pressure and flow rate demanded by the network during the irrigation season. With this aim, a model called DRODIN (Design of Reservoirs of regulation in On-Demand Irrigation Networks) was developed under a holistic approach. That obtain the optimal design and management (minimum total annual cost, C_T) of the water abstraction systems in an integrated manner to include the aquifer along with the pumping station, reservoir and pumping and distribution pipes in a collective irrigation network. This tool has been applied to an on-demand irrigation network located in Spain with 171 ha of drip irrigation in vineyard and olive crops. The optimal reservoir volume is approximately 5000 m^3, and the C_T for water lift (WL) = 100 m (the most common case for this aquifer) is 325 € ha^{-1} yr^{-1}. The energy cost is the primary component of C_T, both in the abstraction and the water supply to the irrigation network, representing between 57% and 80%. The operation of the pumping station determines the size of the reservoir and the annual costs of the water supply to the network for a given water supply guarantee. The C_T increases linearly with the WL, primarily because of the increase in energy costs (C_e), although there is a clear relation between the investment costs (C_a), C_e and the reservoir size, which is only possible to analyse with tools such as DRODIN.

1. Introduction

It is predicted that global energy consumption will increase by 56% over the next 30 years, including the use of fossil fuels (EIA, 2013). In Europe, the energy price has increased (2008–2012) at an average annual rate of 4% (COM, 2014). In countries such as Spain, for which the cost of electricity is increasing greatly (over 100% from 2008 to 2014), together with the high energy dependence of irrigation that is used to cover the more than 70% of the 3.4 million hectares irrigated by pressurized irrigation (48% sprinkler irrigation and 22% localized irrigation) (ESYRCE, 2013), and the decreasing availability of water for irrigation because of increasing urban and

* Corresponding author.
E-mail addresses: izquiela@agr.ucv.ve (A. Izquiel), Rocio.Ballesteros@uclm.es (R. Ballesteros), Jose.Tarjuelo@uclm.es (J.M. Tarjuelo), MiguelAngel.Moreno@uclm.es (M.A. Moreno).
http://dx.doi.org/10.1016/j.biosystemseng.2016.04.003

environmental needs, it is essential to develop tools and models to help improve the efficiency of water and energy use in irrigation (Moreno, Medina, Ortega, & Tarjuelo, 2012; Pulido-Calvo & Gutiérrez-Estrada, 2011). One of the objectives of the Energy Action Plan in Spain is to improve energy efficiency through the reduction of water consumption in irrigation in addition to the improved management and performance of pumping systems (IDAE, 2011).

The potential energy savings could be primarily achieved by the proper selection of pumps and by adapting its operation to the given electricity rates (Moradi-Jalal, Mariño, & Afshar, 2003). Pumping is the largest consumer of energy during water abstraction from aquifers and distribution for different uses, and thus, many algorithms have been developed to minimize the costs of this process (Moradi-Jalal, Rodin, & Mariño, 2004; Moreno, Carrión, Planells, Ortega, & Tarjuelo, 2007; Planells Alandi, Carrión Pérez, OrtegaÁlvarez, Moreno Hidalgo, & Tarjuelo Martín-Benito, 2005; Pulido-Calvo, Roldán, López-Luque, & Gutiérrez-Estrada, 2003). To determine the distribution of the water volumes required through space and time by on-demand irrigation networks, several statistical (Clément, 1996; Mavropoulos, 1997) and probabilistic (Lamaddalena & Sagardoy, 2000; Moreno, Planells, Ortega, & Tarjuelo, 2007) models have been developed.

In countries with arid and semiarid climates, groundwater is widely used for irrigation. Approximately one-third of the irrigated landmass in the world is irrigated by groundwater (Zektser & Everett, 2004). Many countries rely heavily on this water source for agriculture, with 45% of irrigated land pulling groundwater from within the United States of America, 58% from within Iran, and 67% from within Algeria. In the Castilla-La Mancha region of Spain, 78% of water used for irrigation comes from aquifers at a water lift between 50 and 200 m, with an irrigated area of 507,200 ha. This area is served by 55% drip irrigation, 40% sprinkler irrigation and 5% surface irrigation (ESYRCE, 2013), which requires the use of tools to aid in the decision-making process for the correct management of water and energy.

The storage and regulation reservoir between the source of water and the irrigation system is an option for controlling the pump flow rate and timing of energy consumption, with the goal of reducing energy costs (Hirose, 1997). An additional advantage is that they make it possible to receive water from different sources and feed irrigation systems at different flow rates and pressure requirements. Mehta and Goto (1992) proposed a model for calculating the optimal size of a reservoir, and they managed to reduce water losses by 20% and ensure a water supply in an area irrigated by different water sources. Pulido-Calvo, Gutierrez-Estrada, López-Luque, and Roldán (2006) developed software that integrates the reservoir design into the management and planning of the pumping system based on the crop distribution in the irrigated area and the flow rate data recorded during several irrigation seasons, reducing the total annual costs by 12%. Moreno, Córcoles, Moraleda, Martinez, and Tarjuelo (2010) developed software for the optimal design of boreholes (DOS), which considers hydraulic, hydrologic and energy variables. The best option for pumping to minimize the cost of water abstraction is to avoid working during high-energy cost periods, although this choice could drive higher investment costs. Reca, García-Manzano, and Martínez (2015) adapted a model to optimize the pumping system by considering the evaporation losses from the reservoir. No decision support system tool was found in the literature that could help in the design and management of the water abstraction systems in an integrated manner to include the aquifer along with the pumping station, reservoir and pumping and distribution pipes in a collective irrigation network. The interrelation between the different systems requires this integrated approach to optimize the design and management of the whole system.

The objective of this work is to obtain the optimal reservoir sizing in on-demand irrigation networks with a minimum cost over the process as a whole, taking into account the variability in the pressure and flow rate demanded of the network during the irrigation season, and the water lift (WL) of the aquifer. To reach this objective an optimization model called DRODIN (Design of Reservoirs of regulation in On-Demand Irrigation Networks) was developed, which implements a holistic approach by considering the primary factors that affect the water abstraction and supply to an on-demand irrigation network in an integrated manner, with respect to the optimization of the regulation reservoir sizing and the operating strategy of the pumping station (the power, flow rate and operating time).

It is also analysed the effect of the water lift (WL) on the C_T by applying the method to an on-demand irrigation network of 171 ha that are irrigated with drip irrigation using water from the Eastern Mancha aquifer, in the province of Cuenca (Spain). WL was analysed because is the main variable affecting the energy demand of the system.

2. Methodology

The DRODIN model implements an optimization process at different phases as described in the methodology. The primary objective of the optimization process is to minimize the total cost (investment + operation costs) by optimally sizing the reservoir and the pumping from the borehole and the pumping station that supplies the pressure and flow rate to the irrigation network. In addition, the pumping pipe from the borehole to the reservoir and the distribution pipe from the pumping station to the irrigation network were optimized, under a holistic approach. To provide a general overview of the methodology, a general description of the model is presented here, although it is accurately described in the methodology.

The different phases of the optimization process are as follows:

1. Determination of the daily operation time (OT) of both pumping systems (water abstraction (OT_P) and pumping station (OT_R)). The DRODIN model uses the average irrigation water requirements for each month to estimate the optimal OT_R of the pumping systems in this first step, which is primarily affected by the energy rates and investment cost.
2. Once the OT of the pumping systems are determined, a more accurate water balance is performed in the reservoir by using a probabilistic methodology (Random Daily