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Optimal pumping scheduling model considering reservoir evaporation

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ABSTRACT

Reservoir evaporation losses can be high in semiarid areas with high evaporative demand. The volume of water evaporated from a reservoir is a function of the free water surface area. In agricultural reservoirs this water surface varies depending on the volume of water stored. As reservoirs are usually relatively full of water over long periods of time, evaporation water losses are consequently high. Evaporation water savings could be achieved if a pumping policy that considered evaporation losses were developed. However, optimal pumping scheduling models proposed up to now do not take these losses into account.

This paper presents a new optimal pumping scheduling model that integrates the evaporation losses from the reservoirs into the optimisation algorithm and provides the optimal pumping policy that minimises both pumping and water costs. The developed model was tested using a real irrigation water distribution system located in southeast Spain to serve as a case study. When evaporation losses were considered, water and energy savings were achieved in comparison to the optimal solution found when evaporation is not considered in the optimisation process.A sensitivity analysis of the optimal solutions to the price of water was then performed. For increasing water prices, the optimal solutions provided by the model tend to delay the pumping decisions with the aim of diminishing the evaporation losses. Although this implies a slight increase in the energy cost, it is compensated with the higher reduction in the water cost.

1. Introduction

Agriculture is the largest water consumer in the world. More than two thirds of total water use is devoted to the irrigation of agricultural lands. Sustainability, in many productive irrigated areas, is threatened by the limited availability of water resources (Khan et al., 2006; Connor et al., 2014). This is the case of many irrigation districts in the semiarid regions in the Mediterranean Basin. Nowadays, there is an increasing social demand for a more productive and responsible use of irrigation water in agricultural systems, especially taking into consideration that water resources may be even more scarce in the near future than they are today. The sustainable use of water and the water conservation is a priority for agriculture in water scarce regions (Pereira et al., 2002).

Evaporation losses from reservoirs can be very high in dry areas. Studies conducted in semiarid areas in the Mediterranean Basin have highlighted the significance of these evaporation losses. Martínez-Álvarez et al. (2008) and Martínez-Granados et al. (2011) calculated that the annual average depth of water evaporated from agricultural reservoirs in the Segura basin (southern Spain) was 1.4 m. Total annual losses in the entire basin reached 58.5×10^3 m^3, which corresponds to 8.3% of the water devoted to irrigation and 27% of the domestic water use in a region with approximately two million inhabitants. This amount is similar to the environmental demand in the basin and much higher than the industrial demand. Wurbs and Ayala (2014) estimated that the long-term mean evaporation from the reservoirs in Texas was equivalent to 61% of total agricultural water use or 126% of total municipal water use in the state during the year 2010. Other similar or even worse situations were observed in other regions of the world with similar climatic conditions (Craig et al., 2005).

Reservoirs are usually built in irrigation districts with the aim of accumulating water during wet seasons with lower irrigation water demands in order to use it in the dryer seasons with higher irrigation demands. For this reason reservoirs are usually full by the

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Nomenclature

A	reservoir water surface area
C	total cost pumping cost (€)
C_e	total energy cost (€)
c_1, c_2	parameters that define the linear area-storage relationship
D	water demand (m^3)
E_o	a-class pan evaporation
E	evaporation depth from the reservoir
ET_o	reference evapotranspiration
$F'(h)$	derivative of the Gompertz function.
H	pumping head
K_p	a-class pan coefficient that relates E_o and ET_o
K_r	a-class pan coefficient that relates E_o and E
K_h	hourly evaporation pattern multiplier
N	number of hours
n	total number of periods
p_w	price of the water (€/m^3)
p	price of the energy (€/kW h)
R	rainfall
RE	volume of water evaporated from the reservoir (m^3)
Q	discharge
S	volume stored at reservoir
S_M	maximum storage capacity
S_m	minimum storage capacity
V	volume of water pumped
W	energy consumed by the pumping system (kW h)
w	energy needed for pumping one cubic meter of water to the reservoirs
η	pumping efficiency
γ	specific weight of the water

Subscripts

d	daily period
h	hourly period
i	time period "i"
j	index of summation for periods
o	initial period

time the dryer season arrives. As a consequence, large free water surface areas are exposed to evaporation resulting in high evaporation losses and energy waste. This can be of great concern, especially when water is scarce and the cost of water and energy is high.

A way of reducing these high evaporation losses is to cover the reservoirs. Some researchers have proposed and evaluated different types of covers (Martínez-Álvarez et al., 2009; Martínez-Álvarez et al., 2010; Gallego-Elvira et al., 2010). However, these methods are expensive for large agricultural reservoirs.

Recently, various research works on evaporation losses in reservoirs in semiarid regions have been conducted (Martínez-Álvarez et al., 2007, 2008; Gallego-Elvira et al., 2010). Other researchers performed some studies to measure and analyse the evaporation in several types of waterbodies with different sizes (Assouline et al., 2008) and water depths (Assouline et al., 2013). In these studies, significant advances have been made into understanding the evaporation process and the measurement and modelling of water losses. Unfortunately, in spite of these noteworthy findings, it is currently not common for them to be put into practice with respect to the optimal management and operation of agricultural reservoirs.

Several models have been proposed for optimizing pumping scheduling and agricultural reservoir operation and for reducing the pumping energy costs in irrigation districts (López et al., 1993; Moradi-Jalal et al., 2003, 2004; Planells et al., 2005; Pulido et al., 2006; Pulido and Gutiérrez, 2011, Reca et al., 2014). However, none of these models take into consideration the effect of evaporation.

The main objective of this paper is to present an optimal pumping scheduling and reservoir management model that considers evaporation losses from the reservoir and provides the optimal pumping policy that minimises both pumping and water costs. This proposed model computes evaporation losses as a function of the area of the free water surface which is related to the volume of water stored in the reservoir.

2. Methodology

2.1. Characterisation of the agricultural reservoirs

Storage reservoirs commonly used in agricultural irrigation systems are enclosed by earth embankments. They are usually lined with a high-density poliethilene (HDPE) geomembrane to avoid seepage water losses. Due to their usually low depths, they are also characterised by a large area-to-volume ratio which implies high evaporation losses, especially in dry climates. Their layout varies among reservoirs and is irregular-shaped as it usually adapts to the terrain.

Evaporation losses in this kind of reservoirs are a function of the volume of water stored as the area of the free water surface increases with the depth of the water. In order to assess the evaporation water losses from a reservoir, its surface-volume relationship is required. This relationship approximates fairly well to a linear function (see Eq. (1)).

$$A = c_1 \times S + c_2 \quad (1)$$

where A is the area of the free water surface, S is the volume of water stored in the reservoir and c_1 and c_2 are the parameters that define the linear area-volume relationship.

The methodology developed in this work can be applied to any kind of reservoir in which this relationship is linear.

2.2. Modelling evaporation from reservoirs

A widely used and accurate method to estimate the depth of water evaporated from a reservoir (E) is to relate it to the depth of water evaporated from an A-Class pan (E_o). Martínez-Álvarez et al. (2007) applied this methodology in a study to assess evaporation losses at a regional scale in the Mediterranean basin.

Pan evaporation is usually greater than evaporation from reservoirs due to extra energy gain through the walls and bottom of the pan, and the higher advective effect in smaller water surfaces (Molina-Martínez et al., 2006; Linacre, 1994). In order to derive more accurate reservoir evaporation values from pan evaporation measurements, an empirical coefficient, K_r, should be applied (Linsley et al., 1992; Kohler, 1954). An annual K_r coefficient can be used to relate both variables. However, more accurate estimations can be achieved if monthly K_r values are used. On a monthly scale, K_r values were found to be dependent on water depth and slightly influenced by the area of the water surface (Martínez-Álvarez et al., 2007).

Finally, the daily reservoir evaporation for a specific day d (E_d) can be computed by applying the following equation:

$$E_d = K_{r,d} \times E_{o,d} \quad (2)$$

where $K_{r,d}$ is the reservoir coefficient for day d and $E_{o,d}$ is the pan evaporation for the same day d.

The proposed model requires disaggregating the daily reservoir evaporation estimations into an hourly basis. Short-term evaporation rates modelling is an issue of contention as some researchers