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Optimal design of agricultural water systems with multiperiod collection, storage, and distribution

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ABSTRACT

Water is one of the most valuable resources in the world and the agriculture is one the largest fresh water consumers due to the low efficiencies in the irrigation processes. This paper proposes a mathematical programming model for the optimal planning of an integrated system which involves water collection, reuse, and distribution strategies. Because of the variability in water supplies and demands throughout the year, a multiperiod optimization approach is adopted. The multi-objective function includes the minimization of fresh water consumption and the minimization of the total annual cost, this cost is divided in capital cost which consists of the catchment areas, storages and pumps, as well as the operating cost for pumping and fresh water. A multi-objective mixed-integer nonlinear programming model is formulated and solved using the ε-constrained method. The applicability of the proposed approach was shown through a case study from the State of Michoacán in Mexico where a lot of fresh water is consumed for agricultural purposes. The results show that fresh water consumption can be significantly reduced by the implementation of the proposed approach while simultaneously addressing the economic objective.

1. Introduction

In recent years, water scarcity has become a problem of paramount importance because of worldwide increasing water demands and the drastic change in the rainwater precipitation due to the global warming (Lazarova and Bahri, 2004). Particularly, the agricultural activity is one of the highest fresh water consumers in the world. Several approaches have been implemented to intensify the use of the available water mainly focused on conservation of water in irrigation processes. In this context, Pereira (1999) proposed methods for improving the irrigation process through optimizing the irrigation scheduling. Burke et al. (1999) presented approaches for maximizing the plant productivity and minimizing the water lost during irrigation. Shangguan et al. (2002) presented an optimization model for irrigating under water scarcity conditions. Jones and Hunt (2010) incorporated approaches for rainwater harvesting for irrigation. Furthermore, several approaches have optimized the scheduling for irrigating agricultural fields (see for example Rao et al., 1988; Naadimuthu, 1999); however, these approaches are single objective problems and do not consider alternative water sources such as rainwater and reclaimed water. Songhao and Mao (2006) proposed an optimization model for irrigating under limited available water conditions. Theocharis et al. (2006) presened a simplified nonlinear programming method for selecting the best diameters for pipes used for irrigating. Moradi-Jalal et al. (2007) optimized the reservoir operation for irrigating. Bin et al. (2012) presented an optimal allocation model for reclimed water reuse. Garg and Dadhich (2014) incorporated nonlinear models for schedulling irrigation processes. Li and Guo (2014) proposed a multi-objective optimization model for irrigating under uncertainty. Belaqziz et al. (2014) presented an evolutionary strategy for designing optimal irrigation processes.

Water integration through recycle and reuse networks have been widely implemented in the process industries. Foo (2009) presented a detailed review about the methodologies reported

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Nomenclature

Sets

- i fresh source
- j field
- t time period

Parameters

- C_i^{RC} exponent for the capital cost function for storage devices associated to fresh source i
- C_j^{RC} exponent for the capital cost function for storage devices associated to reused water from field j
- C^{Rcap} exponent for capital cost for pumps
- $C_{j,j'}^{RP,P}$ unit variable cost for pipes
- $F_{i,t}^{available}$ available fresh water in source i over time period t
- FC_i^{FT} unit fixed cost for storage devices for fresh source i
- FC_j^{RT} unit fixed cost for storage device associated to used water from field j
- $FC_{j,j'}^{RP,P}$ unit fixed cost for pipes associated to used water
- $G_{j,t}$ required water in field j over time period t
- K_F factor used to annualize the inversion
- $prec_t$ precipitation over time period t
- $S_j^{R\max}$ maximum capacity for storage device for used water from field j
- UOp_i^F unit operating cost for storage device for fresh water from source i
- UOp_i^R unit operating cost for storage device for used water from field j
- $UPump_i^F$ unit operating cost for pumps for fresh water from source i
- $UPump_j^R$ unit operating cost for pumps for reused water from field j
- UFWC unit cost for fresh water
- VC_i^F unit variable cost for pipes for fresh water from source i
- VC_j^R unit variable cost for pipes associated to reused water from field j
- $\Psi_{j,t}^{recpre}$ recovery factor for used water from field j over period t
- $\Psi_{j,t}^{repre}$ recovery factor for rainwater from field j over period t

Variables

- A_j cultivation area for field j
- $TotFresh$ total fresh water consumed
- $CapTank_i^F$ capital cost for storage device for fresh source i
- $CapTank_i^R$ capital cost for storage device for reused water from field j
- $CapPump_i^F$ capital cost for the pump associated to fresh source i
- $CapPump_i^R$ capital cost for the pump associated for reused water from field j
- $CapPipes_{j,j'}^R$ capital cost associated to the pipes used for reused water from field j to field j'
- $F_{i,t}$ fresh water consumed from source i over time period t
- F_i^{Fcap} maximum flowrate for fresh source i over all periods of time
- $f_{i,j}$ flowrate from fresh source i directed to any field j
- $FresWCost$ fresh water cost
- $g_{j,t}$ recycled water from field j over time period t
- g_j^{Rcap} maximum flowrate for recycled water from field j
- $OpTank_i^F$ operating cost for storage device associated to fresh source i
- $OpTank_i^R$ operating cost for storage device associated to used water from field j
- $Pumping_i^F$ pumping cost for fresh water from source i
- $Pumping_j^R$ pumping cost associated to reused water from field j
- $S_{i,t}^F$ stored fresh water stored from source i over time period t
- S_i^{Fcap} maximum capacity for storage device associated to fresh source i
- $S_i^{F\max}$ maximum capacity available for storage device for fresh water from source i
- $S_{j,t}^R$ stored water from field j over time period t
- S_j^{Rcap} capacity for storage device for water used in field j
- TAC total annual cost
- $w_{j,j'}^{Rcap}$ capacity for pipes associated to reused water
- $w_{j,j',t}$ reused water from field j to field j' over time period t

Binary variables

- y_i^F binary variable associated to the existence of the storage tank for the fresh water from source i
- y_j^R binary variable associated to the existence of the storage tank for the used water from field j

for synthesizing water networks in industrial processes. In the industrial water networks, there are several process sources (which produce used water) and several process sinks (which require water with specific demands). Industrial water networks involve recycling, reusing and regenerating used water to satisfy the water demands and decrease the consumption of fresh water. It should be noticed that the idea of industrial water networks can be extended to the agricultural case where the fields represent sinks and the sources can be considered as the recovered used water from the fields as well as collected rainwater (see Fig. 1). Important challenges involved in the design of agricultural water networks are the decision of:

(a) Where to install the required facilities (storage devices, collecting systems, pipes and pumps)?
(b) What is the optimal size of the required facilities?
(c) How to operate the entire water network?

To address the foregoing challenges from a targeting point of view, this paper proposes an optimization approach for the preliminary design of the entire agricultural water network involving the minimization of the total annual cost and the fresh water consumption.

2. Problem statement

The addressed problem in this paper can be stated as follows: Given an agricultural field, with a specific geographical location, extension, crops, and water demands through the entire agricultural year, it is desired to design a water network for the effective usage and dispatch of collected and reused water. The problem consists of determining the optimal configuration for the agricultural water network involving the required water storage devices, pipes, pumps and distribution involving simultaneously the minimization for the total annual cost and the fresh water consumption. The total annual cost includes the