Computers and Chemical Engineering 84 (2016) 63–82

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

# Optimal design of integrated agricultural water networks

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ARTICLE INFO

*Article history:*
Received 16 November 2014
Received in revised form 7 August 2015
Accepted 11 August 2015
Available online 20 August 2015

*Keywords:*
Water integration
Fertilizer reuse
Agricultural water
Multi-period optimization

ABSTRACT

This paper presents a mathematical programming model for the optimal design of water networks in the agriculture. The proposed model is based on a new superstructure that includes all configurations in terms of use, reuse and regeneration of water in a field constituted by a number of croplands. The model also includes the allocation of pipelines, pumps and storage tanks in different irrigation periods. The objective function consists in maximizing the annual profit that is formed by the economic incomes owing to the crop sell minus the costs for fresh water, fertilizer, storage tanks, treatment units, piping and pumping. The proposed multi-period optimization problem is formulated as a mixed integer non-linear programming formulation, which was applied to a case study to demonstrate the economic, environmental and social benefits that can be obtained.



## 1. Introduction

Agriculture is the activity with the highest water demand in the world. Besides it contributes to the water pollution due to the use of nutrients (fertilizers) and pesticides that are discharged as wastewater. Agriculture helps to the ecosystems biodiversity, provides elements to the flue gas capture, contributes to enhance the landscape, is an important factor to combat the world hunger and represents great economic profits (OECD, 2013). In this sense, agriculture is vital to the human being, therefore several technologies and methodologies have been developed to improve seeds, fertilizers, pesticides, process equipment, storage and preservation feeds as well as irrigation systems. The irrigation technologies have been focused on the reduction of fresh water and the application of this resource for increasing the yield of crops. Here, water reduction can be analyzed from two perspectives: (a) *Inside the process*: It consists in finding the best irrigation technique as well as the reuse of wastewater, (b) *Outside the process*: It is related to the reuse of wastewater coming from industrial activities. While a combination of the above scenarios produces a *simultaneous scheme* to consider the reuse of treated water, the irrigation technique as well as the water reuse. Nevertheless, the simultaneous scheme could be a good strategy to optimize the water use in agriculture, the reported works have been focused on reducing the fresh water consumption. In this way, Wilson and von Broembsen (2010) studied the advantages and disadvantages to reuse wastewater in greenhouses. Anderson (2003) presented an analysis about the environmental benefits related to water reusing. Lazarova and Bahri (2004) proposed a strategy for planning water reusing.

Furthermore, the water reusing has been studied from different points of view, including removing heavy metals (Petruzzelli, 1989; Wu et al., 1998), health risks (Chang et al., 1996; Shuval et al., 1997) and irrigation costs (Schleich et al., 1996; Schwarz and Mcconnell, 1993). Hussain et al. (2002) presented a review about the characteristics and international regulations of wastewater utilized in agriculture, and the positive as well as negative impacts owing to the use of treated water. Besides, the rainwater harvesting has been the most used strategy to meet with the water demand for the agriculture in several parts of the world. In this regard, several works dealing with the hydrological impact on watersheds due to the application of domestic and agricultural rainwater harvesting have been reported (Ghimire and Johnston, 2013). Other approaches have implemented economic analysis of different rainwater harvesting structures (Goel and Kumar, 2005). Furthermore, Hatibu et al. (2006) determined the economic aspects of harvesting rainwater, He et al. (2007) analyzed the factors that affect the rainwater harvesting, and Jiang et al. (2013) presented the benefits in the consumption of fresh water and energy associated to the rainwater harvesting. In addition, some reviews about rainwater harvesting have been

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http://dx.doi.org/10.1016/j.compchemeng.2015.08.006
0098-1354/

## Notation

*Parameters*

$\alpha$ exponent to consider the economies of scale
*Ac* crops area, ha
*Cf* fixed cost of equipment and accessories, US$
*Cr* irrigation criteria
$\mathrm{Cu}_c^{sl}$ unitary sell price of crops, US$/ton
$\mathrm{Cu}_w^{op}$ unitary cost of fresh water, US$/m$^3$
$\mathrm{Cu}_l^{op}$ unitary cost of fresh fertilizer, US$/kg
$\mathrm{Cu}_e^{op}$ unitary cost of electricity, US$/kWh
$\mathrm{Cu}_p^{op}$ unitary cost for pipe lines maintenance, US$/kg
$\mathrm{Cu}_s^{op}$ unitary cost for storage tanks maintenance, US$/kg
$\mathrm{Cu}_u^{op}$ unitary cost for treatment units maintenance, US$/kg
$\mathrm{Cv}^{pip}$ variable cost of pipelines, US$/m$^3$/h
$\mathrm{Cv}^{pu}$ variable cost of pumps, US$/kg
$\mathrm{Cv}^{sw}$ variable cost of storage tanks, US$/m$^3$
$\mathrm{Cv}^{tu}$ variable cost of treatment units, US$/m$^3$
*D* distance between units, m
*Dr* root depth, cm
*Fwpc* precipitated water in the crops, m$^3$
*Fwpst* precipitated water in the storage tanks, m$^3$
*Fwrc* capillary rise of water table, m$^3$
*g* acceleration due the gravity, m$^2$ s$^{-1}$
*gc* conversion factor for the acceleration due the gravity, kg m N$^{-1}$ s$^{-2}$
*He* height between process components, m
$\eta$ efficiency
$K_F$ factor used to annualize the inversion, year$^{-1}$
*m* fractional interest rate per year, %
*n* number of years of operation, year
$v$ velocity, m/s
$\rho$ density, kg/m$^3$
$\theta_{fc}$ field capacity, cm$^3$ of water/cm$^3$ of soil
$\theta_{pwp}$ permanent wilting point, cm$^3$ of water/cm$^3$ of soil
$Qwc^{in}$ volumetric flowrate, m$^3$/h
$\Omega_{\mathrm{Fcc}}^{\max,\mathrm{pu}}$ upper limit of the pump capacity to handle the flowrate between crops, kg/h
$\Omega_{\mathrm{Fcc}}^{\max,\mathrm{pip}}$ upper limit of the pipeline capacity to handle the flowrate between crops, m$^3$/h
$\Omega_{\mathrm{Fstc}}^{\max,\mathrm{pu}}$ upper limit of the pump capacity to handle the flowrate from storage tanks to crops, kg/h
$\Omega_{\mathrm{Fstc}}^{\max,\mathrm{pip}}$ upper limit of the pipeline capacity to handle the flowrate from storage tanks to crops, m$^3$/h
$\Omega_{\mathrm{Fcst}}^{\max,\mathrm{pu}}$ upper limit of the pump capacity to handle the flowrate from the crops to storage tanks, kg/h
$\Omega_{\mathrm{Fcst}}^{\max,\mathrm{pip}}$ upper limit of the pipeline capacity to handle the flowrate from the crops to storage tanks, m$^3$/h
$\Omega_{\mathrm{Fctu}}^{\max,\mathrm{pu}}$ upper limit of the pump capacity to handle the flowrate from the crops to treatment units, kg/h
$\Omega_{\mathrm{Fctu}}^{\max,\mathrm{pip}}$ upper limit of the pipeline capacity to handle the flowrate from the crops to treatment units, m$^3$/h
$\Omega_{\mathrm{Cfe}_{l,t}}^{\max}$ upper limit for the concentration of each fertilizer in the environmental discharge, kg of fertilizer/total kg
$\Omega_{\mathrm{Fst}}^{\max}$ upper limit for the capacity of storage tanks, m$^3$
$\Omega_{\mathrm{Ftu}}^{\max}$ upper limit for the capacity of treatment units, m$^3$
$\Omega_{\mathrm{w,t}}^{\max}$ limit for each type of fresh water in the periods, m$^3$

*Variables*

Capc capital cost, US$/year
*Cfc* fertilizer concentration in the crops, kg of fertilizer/total kg
*Cfe* fertilizer concentration in the environment discharge, kg of fertilizer/total kg
*Cfs* fertilizer concentration in the storage tanks, kg of fertilizer/total kg
*Cft* fertilizer concentration in treatment unit, kg of fertilizer/total kg
Copc operating cost, US$/year
$Fc^{tot}$ total flowrate in the crops, kg/h
*Fcc* flowrate between crops, kg/h
$Fcc^{capc,pu}$ pump capacity to handle the flowrate between crops, kg/h
$Fcc^{capc,pip}$ pipeline capacity to handle the flowrate between crops, m$^3$/h
*Fce* flowrate from crops to environment discharge, kg/h
*Fcst* flowrate from crops to the storage tanks, kg/h
$Fcst^{capc,pu}$ pump capacity to handle the flowrate from crops to the storage tanks, m$^3$
$Fcst^{capc,pip}$ pipeline capacity to handle the flowrate from crops to the storage tanks, m$^3$/h
*Fctu* flowrate from crops to treatment units, kg/h
$Fctu^{capc,pu}$ pump capacity to handle the flowrate from crops to treatment units, m$^3$
$Fctu^{capc,pip}$ pipeline capacity to handle the flowrate from crops to treatment units, m$^3$/h
*Fe* flowrate in the environment discharge, kg/h
*Ffc* flowrate fertilizer in the crops, kg/h
*Ffcc* fertilizer flowrate between crops, kg/h
*Ffctu* fertilizer flowrate from crops to treatment units, kg/h
*Fff* fresh fertilizer flowrate, kg/h
*Ffrc* reused fertilizer flowrate, kg/h
*Ffrt* fertilizer flowrate from the storage tanks to crops, kg/h
*Ffst* fertilizer flowrate from the storage tanks to crops, kg/h
*Fftue* fertilizer flowrate from treatment units to environment discharge, kg/h
Flc fertilizers cost, US$/year
$Fst^{capc}$ storage tanks capacity, m$^3$
$Fst^{tot}$ total flowrate in the storage tanks, kg/h
*Fstc* flowrate from storage tanks to crops, kg/h
$Fstc^{capc,pu}$ pump capacity to handle the flowrate from storage tanks and crops, kg/h
$Fstc^{capc,pip}$ pipeline capacity to handle the flowrate from storage tanks and crops, m$^3$/h
$Ftu^{capc}$ treatment units capacity, m$^3$
$Ftu^{tot}$ treatment units flowrate, kg/h
*Ftue* flowrate from treatment units to the environment discharge, kg/h
Fwc fresh water cost, US$/year
$Fwc^{abs}$ absorbed water flowrate by the crops (soil and plants), m$^3$/h
$Fwc_{c,t}^{ev}$ lost water flowrate by evapotranspiration in the crops, m$^3$/h
*Fwc* water flowrate on each crop, m$^3$/h
*Fwcc* water flowrate between crops, m$^3$/h
*Fwct* water flowrate from the storage tanks to crops, m$^3$/h
*Fwctu* water flowrate from crops to treatment units, m$^3$/h
*Fwf* flowrate available fresh water, m$^3$/h
*Fwfs* fresh water flowrate on each crop, m$^3$/h
*Fwrt* reused water flowrate, m$^3$/h
*Fwst* water flowrate from to crops to storage tanks, m$^3$/h