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Simultaneous design of water reusing and rainwater harvesting systems in a residential complex

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ABSTRACT

This paper introduces an optimization formulation to design residential water systems that satisfy the water demands in a housing complex involving rainwater harvesting, storage and distribution as well as the simultaneous design of water networks for recycling, reusing, regenerating and storing reclaimed water. The design task is considered as a multi-objective optimization problem where one objective is the minimization of the fresh water consumption and the other objective is the minimization of the total annual cost. The proposed model accounts for the variability in the water demands through the different hours of the day and for the different seasons of the year. The seasonal dependence of the rainwater has also been considered in the optimization model. A case study for the city of Morelia in Mexico is presented. The results show that significant reductions can be obtained in the total fresh water consumption and in the total cost.

1. Introduction

With the increasing population, continued urbanization, and overexploitation of water bodies, the world is facing a serious challenge to satisfy the water demands for human activities (CONAGUA, 2014). This challenge has promoted the search of new strategies for the sustainable use of water, including reclaimed greywater reusing and rainwater harvesting. First, in the case of reclaimed greywater reusing, Al-Jayyousi (2003) proposed reusing greywater in arid regions. Mandal et al. (2011) developed a strategy for greywater collection, treatment and reuse to satisfy demands of household sanitary uses and agricultural irrigation leading to freshwater savings up to 48%. Revitt et al. (2011) performed an analysis with empirical data for determining the fate of micropollutants in treatment systems for greywater recycling and obtained savings up to 43% of fresh water. Santos et al. (2012) presented a study for greywater reuse for washing basins and showers. Penn et al. (2013) presented a multi-objective optimization model for the distribution of greywater in an existing municipal sewer system for reuse in toilet flushing and garden irrigation. Chen and Chen (2014) presented an optimization model for recycling effluents from the municipal sewage for industrial use. García-Montoya et al. (2015) proposed a mathematical programming formulation for synthesizing water networks in housing complexes, where reductions of up 38% of fresh water were observed. Zhang et al. (2014) proposed a sustainable design for wastewater reusing in China. On the other hand, for the case of rainwater harvesting, Mwenge et al. (2007) proposed domestic rainwater harvesting to supply water in South Africa. Nolde (2007) implemented an approach for harvesting polluted rainwater obtained from streets and courtyard surfaces. Abdulla and Al-Shareef (2009) reported fresh water savings of up to 19.7% through the use of harvested rainwater. Helmreich and Hom (2009) proposed the use of rainwater treated with slow sand filtration and solar technology for applications in agriculture and households. Sturm et al. (2009) developed a techno-economic analysis for the use of harvested rainwater. Farreny et al. (2011) suggested a type of roof to maximize the availability and quality of harvested rainwater. Gikas and Tsihrintzis (2012) presented an evaluation for the physicochemical properties for harvested rainwater, showing that this is adequate for using in several human activities. Ward et al. (2012) carried out a socio-technical study for rainwater harvesting in UK. Chiu et al. (2009) proposed an optimization model for collecting rainwater through rooftops obtaining savings for the required fresh water and energy. Hashim et al. (2013) carried out a simulation for a large-scale rainwater harvesting system obtaining a significant reduction of fresh

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Nomenclature

Acronyms
cap capacity
capPg capital for recirculation pipes
capPW capital for outflow pipes
Capt captation rainwater
capTanks capital for storage tanks
capTU capital for treatment units
ElevStorage elevated storage device
in input
max maximum
opTU operation treatment units
out output
Stg storage
Treat treatment for water

Indexes
h hours of one day
i water using unit (sink)
j housing unit or harvesting areas
k water treatment unit
l number of storage units for harvested rainwater
m months of the year

Parameters
$\alpha, \beta, \delta, \gamma$ exponents for the capital cost functions
$\alpha_{k,i}$ coefficient for the water lost in the treatment units
$\beta_{j,i}$ loss coefficient by the water using units
$A_j^{\max}$ maximum available rainwater harvesting area (m^2)
c^{fw} fresh water cost for each use (US$)
c^{pfw} pumping cost for fresh water for each use (US$)
$C_{k,i}^{op}$ operating cost for treatment units (US$)
$CF_j^{captation}$ unit fixed cost for rainwater harvesting area (US$)
$CF^{ElevStorage}$ unit fixed cost for the elevated tank (US$)
$CF_{j,l}^{pipe}$ unit fixed cost for pipe network from the harvesting area to the storage tank (US$)
CF_l^{pipe} unit fixed cost for pipe network from the storage tanks to the elevated reservoir (US$)
$CF_l^{Storage}$ unit fixed cost for storage tanks (US$)
$Cost_{j,l}^{pump}$ unit pumping cost from the rainwater harvesting area to the storages tanks (US$)
$Cost_l^{pump}$ unit pumping cost from the storage tanks to the elevated reservoir (US$)
$Cost^{treat}$ unit cost for treating rainwater (US$)
$CV_j^{captation}$ unit variable cost for the rainwater harvesting area (US$)
$CV^{ElevStorage}$ unit variable cost for the elevated reservoir (US$)
$CV_{j,l}^{pipe}$ unit variable cost for pipes from the rainwater harvesting area to the storage tank (US$)
CV_l^{pipe} unit variable cost for pipes from the storage tanks to the elevated reservoir (US$)
D_m days per month
$E^{\max}$ maximum allowed flowrate in a pipe (m^3)
$FC_{k,i',j,i}^{capPg}$ unit fixed cost for recirculating pipes (US$)
$FC_{k,i',j,i}^{cappump}$ unit fixed cost for pumps for recirculating flowrates (US$)
$FC_{j,i}^{capPW}$ unit fixed cost for pipes for different uses (US$)
$FC_{k,i}^{Tanks}$ unit fixed cost for tanks (US$)
$FC_{k,i}^{capTU}$ unit fixed cost for treatment units (US$)
Hy annual operation time
K_F factor used to annualize the capital costs
$L_i^{\max}$ maximum limit for treatment units (m^3)
$m_{j,i,h,m}$ demanded water for each using unit (m^3/day)
$O^{\max}$ maximum allowed flowrate in pipe (m^3)
P_m rainwater precipitation per month (m)
$S^{\max}$ upper limit for storage tanks (m^3)
$STG_l^{\max}$ maximum storage capacity for tanks (m^3)
$VC_{k,i',j,i}^{capPg}$ unit variable cost for recirculating pipes (US$)
$VC_{k,i',j,i}^{cappump}$ unit variable cost for recirculating pumps (US$)
$VC_{j\cdot i}^{capPW}$ unit variable cost for outflow pipes (US$)
$VC_{k,i}^{capTU}$ unit variable cost for treatment units (US$)
$VC_{k,i}^{Tanks}$ unit variable cost for tanks (US$)

Variables
A_j used rainwater harvesting area (m^2)
$C_{k,i',j,i}^{capPg}$ capital cost for recirculating pipes (US$)
$C_{k,i',j,i}^{cappump}$ capital cost for recirculating pumps (US$)
$C_{j,i}^{capPW}$ capital cost for output pipes (US$)
$C_{k,i}^{capTanks}$ capital cost for storage tanks (US$)
$C_{k,i}^{capTU}$ capital cost for treatment units (US$)
C^{FW} fresh water cost (US$)
$C_{k,i}^{opTreat}$ operating cost for treatment units (US$)
C^{PFW} pumping cost for fresh water (US$)
$C_{k,i',j,i}^{pumpg}$ pumping cost for recirculating flowrates (US$)
CapCost capital cost for harvesting area (US$)
$E_{l,m}$ distributed flowrate of rainwater for each storage (m^3/month)
E_l^{cap} maximum flowrate from storage devices to the elevated reservoir (m^3)
ElevStorageCost capital cost for the elevated tank (US$)
$F_{h,m}$ fresh water consumed during each time period (m^3/day)
$f_{j,i,h,m}$ inlet water flowrate for each use (m^3/day)
$g_{k,i,j,i',h,m}$ recycled water flowrate (m^3/day)
$g_{k,i',i,j}^{cap}$ capacity for recycling pipes (m^3/day)
$h_{k,i,h+hh,m}^{in}$ inlet water flowrate to the treatment units (m^3/day)
$h_{k,i,h,m}^{out}$ outlet water flowrate from the treatment units (m^3/day)
$ll_{k,i,h,m}$ water flowrate after mixing for each treatment unit (m^3/day)
$L_{k\cdot i}^{cap}$ upper limit for the capacity of the wastewater treatment units (m^3/day)
$o_{j,l,m}$ feed flowrate to each storage (m^3/month)
$o_{j,m}$ harvested rainwater for each location (m^3/month)
$o_{j,l}^{cap}$ maximum flowrate for the pipes from the harvesting area to the storages (m^3)
PipeCost capital cost for pipes (US$)
PumpingCost pumping cost (US$)
$S_{k,i,h,m}$ accumulated water in the storage tanks (m^3)
$S_{k,i}^{cap}$ capacity for the storage tanks (m^3)
$ST_{l,m}$ accumulation for each tank per month (m^3/month)
$ST_l^{\max}$ maximum capacity for storage devices (m^3)
StorageCost capital cost for storage devices (US$)
T_m accumulation for the elevated tank per month (m^3/month)
$T^{\max}$ maximum capacity for the elevated tank (m^3)
TreatCost treatment cost for collected water (US$)