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Optimal design of sustainable water systems for cities involving future projections

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ABSTRACT

Water scarcity is one of the main concerns of several countries around the world. In this context, several approaches have been proposed for resource conservation and available water augmentation through specific actions such as process intensification and the use, reclamation, reuse, and recycle of alternative water sources. Nonetheless, there are no reported methodologies optimizing the multiannual planning of water usage, discharge, reclamation, storage and distribution in a macroscopic system considering natural and alternative water sources. In this paper, a multi-period mathematical programming model for the optimal planning of water storage and distribution in a macroscopic system is presented. The model addresses important factors such as population growth, change in the time value of money and change in the precipitation patterns. The proposed model is applied to the case of a Mexican city. The results show important advantages from the economic and sustainability points of view.

1. Introduction

In the recent years the concern for the overexploitation of water bodies has stimulated research in the field of water conservation and resource augmentation. This phenomenon has been driven by human factors such as population growth, industrial development, life standard enhancement, irrational use of the resources and climate change. But also due to natural causes like uneven distribution of the water in the world and geographical limitations (for example in the case of islands and arid regions). The main focus of recent research efforts is the resource conservation and water augmentation through specific actions such as regeneration, reuse and recycle of water. These strategies have been successfully implemented in the industrial context by several authors. In this context, Foo (2009) presented an extensive review of pinch-based techniques for water network synthesis in continuous processes. Although pinch-based techniques have shown being useful, they have at least one of the following limitations: they are suited only for small or medium size problems, they are generally limited to the single contaminant case, they do not consider stream regeneration and/or cannot include multiple fresh utilities; thus several authors have proposed mathematical programming approaches to overcome these limitations. This way, Gouws et al. (2010) presented a review for water minimization techniques involving batch processes. Furthermore, Jezowski (2010) presented another review rewarding water networks using graphical and mathematical programming techniques. More recently, the synthesis of water networks has been extended for the case of industrial complexes (i.e. eco-industrial parks). This way, Chen et al. (2010) considered the problem of interplant water optimization with central and decentralized water mains; they considered two separate objective functions: reducing the water consumption and reducing the total annual cost of the network. Then, Rubio-Castro et al. (2011) also considered the synthesis of multi contaminant water networks in an eco-industrial park. Tudor and Lavric (2011) proposed an approach to minimize simultaneously the water consumption and the operating cost. These works have been successfully extended by several authors (see for example Burgara-Montero et al., 2013; Lira-Barragán et al., 2010, 2011, 2012; Martinez-Gomez et al., 2013) through mathematical programming approaches to consider the problem of water networks and its impact in the surrounding watersheds; these models are also multi-objective optimization problems and have taken into account different optimization criteria such as economic,

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Nomenclature

Parameters

A_n^a Collection area in location n for artificial ponds a
$A_n^{\max}$ Maximum capacity of artificial ponds A in location n
A_l^s Collection area in location l for storage tank s
A_k^{ROW} Collection area for natural sources k
ASC Unit water cost for agricultural use
Ce^s Runoff coefficient for storage tanks s
Ce^a Runoff coefficient for artificial ponds a
$CTND$ Unit treatment cost for natural sources with domestic use
$CTNA$ Unit treatment cost for natural sources with agricultural use
$CTNI$ Unit treatment cost for natural sources with industrial use
$CTAD$ Unit treatment cost of rainwater for domestic use
$CTAA$ Unit treatment cost of rainwater for agricultural use
$CTAI$ Unit treatment cost of rainwater for industrial use
CTP Unit treatment cost of wastewater regeneration for agricultural use
$CTPE$ Unit treatment cost of wastewater regeneration for final disposal
$D_{h,t}^{as}$ Agricultural users h demands at time period t
$D_{u,t}^{di}$ Industrial users u demands at time period t
$D_{j,t}^{ds}$ Domestic users j demands at time period t
$DPWV_{k,t}$ Water collected from direct precipitation in natural sources k at time period t
DSC Unit water sale price for domestic use
ISC Unit water sale price for industrial use
K Parameter for the type of land and used land
K_F Factor to take into account annualized investment index
P_t Precipitation over the time period t
P^{total} Annual precipitation
$PCSTD$ Unit cost of transport from storage tank l to domestic sink j
$PCASD$ Unit cost of pumping from artificial pond n to domestic sink j
$PCSTA$ Unit cost of pipeline and pumping from storage tank in location l to agricultural sink h
$PCASA$ Unit cost of piping and pumping from an artificial pond in location n to agricultural sink h
$PCSTI$ Unit cost of piping and pumping from storage tank in location l to industrial sink u
$PCASI$ Unit cost of piping and pumping from artificial pond in location n to industrial sink u
$PCND$ Unit cost of piping and pumping from natural sources k to domestic main
$PCNA$ Unit cost of piping and pumping from natural sources k to agricultural main
$PCNI$ Unit cost of piping and pumping from natural sources k to industrial main
$PCTW$ Unit cost of piping and pumping from treatment plant to agricultural sinks h
$PCTI$ Unit cost of piping and pumping from industrial treatment plant to agricultural sinks h
$p_{k,t}^g$ Water collected from direct precipitation and runoff water in sources k over time period t
$r_{m,k,t}$ Segregated flowrate from the tributaries m to natural sources k over time period t

Nomenclature

Parameters

$ROWV_{k,t}$ Runoff water collection in natural sources k over time period t
$S_l^{\max}$ Maximum capacity of storage tanks S in location l
VP Factor to consider the value of investment

Binary variables

$z_{n,t}^a$ Binary variable to select the installation of artificial ponds a in location n over the time period t
$z_{l,t}^s$ Binary variable for installing the storage tanks s in location l over time period t

Variables

$A_{n,t}$ Existing water in artificial ponds A in location n over time period t
$A_{n,t-1}$ Existing water in artificial ponds A in location n over the previous time period $t-1$
$a_{n,t}^{in}$ Water obtained from rainfall sent to artificial ponds a in location n over time period t
$a_{n,j,t}^{out,d}$ Segregated flowrate from artificial ponds a in location n sent to domestic users j over time period t
$a_{n,h,t}^{out,a}$ Segregated flowrate from artificial ponds a in location n sent to agricultural users h over time period t
$a_{n,u,t}^{out,i}$ Segregated flowrate from artificial ponds ai in location n sent to industrial users u over time period t
Ce Runoff coefficient
$Cost_{n,t}^a$ Cost of artificial pond a in location n
$Cost_{l,t}^s$ Cost of storage tank s in location l
$cw_{j,t}^d$ Water consumed and lost in domestic sinks j over time period t
$cw_{u,t}^{di}$ Water consumed and lost in industrial sink u over time period t
cw_t^{tp} Water reclaimed and sent to final disposal at time period t
cwi_t^{tpi} Water reclaimed in industrial treatment plant and sent to final disposal over time period t
$Drop_{k,t}^g$ Water that exceeds the maximum capacity of natural sources k over time period t
$f_{j,t}$ Segregated flowrate sent from the domestic main to the domestic users j over time period t
$G_{k,t}$ Existing water in natural sources k at time period t
$G_{k,t-1}$ Existing water in natural sources k in previous time period $t-1$
$g_{k,t}^a$ Segregated flowrate from the natural sources k to main agricultural a over time period t
$g_{k,t}^d$ Segregated flowrate from the natural sources k to main domestic d over time period t
$g_{k,t}^i$ Segregated flowrate from the natural sources k to main industrial i over time period t
$\mathrm{int}_{j,t}^{in}$ Wastewater produced in domestic sinks j over time period t
$\mathrm{inti}_{u,t}^{in}$ Wastewater sent to industrial treatment plant over time period t
int_t^{out} Wastewater sent to treatment plant over time period t
$\mathrm{int}_{h,t}^{out,ag}$ Water reclaimed and sent to agricultural sinks h over time period t