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Optimal design of macroscopic water networks under parametric uncertainty

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A R T I C L E I N F O

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A B S T R A C T

The efficient use of water worldwide is of overriding importance due to its vital role in life. Recently, several countries have suffered water scarcity mainly due to population increase and problems associated to climate change such as the change in the precipitation patterns in the world. In this project, a mathematical programming model for the efficient and sustainable use of water under parametric uncertainty is proposed. The model considers rainwater harvesting (which includes catchment, storage and distribution) as alternative water source; it also considers sustainability aspects from the economic and environmental points of view, maximizing the revenue from the sales of water minus the cost of production and treatment, while maintaining desirable levels of water in the natural reservoirs. The uncertainty is a result of the change in the precipitation patterns. The proposed model is applied to a case study for the city of Morelia, Michoacán in Mexico, considering a time horizon of 5 years. Results show the optimal schedule for water storage and distribution to different sectors of the society (public, agricultural and industrial users). It was found that the use of alternative water sources such as harvested rainwater, along with an appropriate planning schedule of storage and distribution might help reduce the pressure over natural reservoirs even under conditions of uncertainty in the precipitation, while satisfying the water demands in a city.

1. Introduction

Water is essential for the development of all living creatures on earth. The average per capita consumption in the United States is 340 lpcd (EPA, 2009). In Mexico, the average consumption is 264 lpcd, and in some regions it reaches up to 350 lpcd (CONAGUA, 2010), which is of great concern because the population growth and climate change reduce water availability every year. Furthermore, the available water usually contains pollutants of anthropogenic origin, which make necessary to implement treatment technologies in order to use it for human consumption. However, even with the implementation of appropriate treatments, both surface and ground water are insufficient to satisfy all the demands in some regions of the world, especially those geographically limited (such as islands), overpopulated and/or prone to long drought periods. In recent years, several strategies have been proposed to assure the water supply. In this sense, Santos-Pereira et al. (2002) discussed some of the issues related to crop irrigation management focusing on management policies under water scarcity situations, with special attention to the case when low quality water is used (reclaimed water and water with high salinity content), taking into account the impact on health and the environment. Additionally, Jhorar et al. (2009) showed a water distribution model for irrigation under low precipitation conditions and examined different scenarios for alternative management policies, showing that management policies might affect the soil salinity and groundwater availability. Agrafioti and Diamadopoulos (2012) demonstrated that adapting the existing wastewater plants to include tertiary treatment might help to satisfy up to 4.3% of the irrigation requirements in the Greek island of Crete. Due to the severe droughts in recent years, Sheng (2005) took the concept of Aquifer Storage and Recovery (ASR) and extended this concept to an integrated level in which either treated or untreated surface

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water or reclaimed wastewater is stored in an aquifer through a system of spreading basins, infiltration galleries and recharge wells; this system had a successful recharge in the Hueco Bolson aquifer in El Paso, Texas through 10 wells recharged in the last 18 years. Furthermore, several other studies have been presented in recent years for water reclamation. Hurlimann (2011) showed that the use of reclaimed water in single households has potential to satisfy some of the demands mainly of irrigation; however, it is limited manly due to the inflexibility of existing infrastructure and cost. Yi et al. (2011) presented a study on the current situation of water reclamation and the challenges associated to its use in China. Zaneti et al. (2012) showed a study of the use of reclaimed water in vehicle washes, showing payback periods lower than one year. Al Khamisi et al. (2013) recommend the use of reclaimed water in conjunction with good quality water to satisfy crop water requirements.

The use of alternative water sources such as water desalination and rainwater harvesting has also been considered. In this context, Appan (2000) proposed the installation of a rainwater collection system in the Nanyang Technological University in Singapore, reporting potential savings of 12.4% of the water expenditure. Chilton et al. (1999) did an analysis of a collection system installed in a mall and found that the return period was 12 years for the system, which could be reduced by optimizing the size of the storage tanks. Abdulla and Al-Shareef (2006), presented an analysis for the use of roofs for rainwater harvesting. Cheng et al. (2006) presented a quantitative evaluation method for rainwater harvesting. Farreny et al. (2011) proposed the use of linear functions to calculate the potential water collection depending on type and building materials of roofs used as collectors, collection area and a runoff coefficient. Furthermore, Abdulla and Al-Shareef (2009) have showed that these systems can save up to 5.6% of the total water demand in Jordan. Additional examples regarding rainwater harvesting have been reported in the literature Li et al. (2010) found that alternative water sources (reclaimed water and harvested rainwater) have the potential to satisfy up to 94% of the water demands in Irish households. Morales-Pinzón et al. (2012) implemented an analysis to assess the potential of rainwater harvesting for its use in urban housing projects, and found that it is viable for locations with high precipitation. Although several efforts have been made in the field of water preservation and management, there are just a few dealing with macroscopic systems. In this context, Liu et al. (2011) presented a deterministic approach for the integration of desalinated water and reclaimed water in a macroscopic system under water scarcity conditions. Atilhan et al. (2012) proposed a mathematical model for the optimal use of desalinated water and reclaimed water in a macroscopic system and applied it to a case study in Qatar for the optimal planning of water distribution during one year. Nápoles-Rivera et al. (2013) introduced a deterministic mathematical model in which the water storage and distribution scheduling during a time span of one year in a macroscopic system was performed, in this work harvested rainwater and reclaimed water were considered as alternative sources. However, all previous works have at least one of the following limitations: they do not consider multiannual planning, thus neglecting important factors such as population growth, increasing demands, and time value of money; they do not consider water storage; they do not consider all the different users in a macroscopic system (agricultural, domestic and industrial); they do not consider natural resources availability and/or they are deterministic approaches. Furthermore, Zhang et al. (2013) presented a first approach for the solution of a macroscopic system under uncertainty using reclaimed water as alternative water source. However, they did not consider different users, water storage and natural resources availability. Therefore, in this paper it is proposed a mathematical programming model for the optimal multi annual water storage and distribution scheduling considering alternative water sources (harvested rainwater) under parametric uncertainty. The planning schedules obtained will meet the user demands during the time span of the project, while satisfying sustainability constraints.

2. Problem definition

The problem is based on the source-sink representation shown in Fig. 1, which depicts a macroscopic system and the interaction between all the considered components. There are three different types of users, domestic, agricultural and industrial. Each one of these users has different water demands, which have seasonal variations. The demands increase during the hottest months while decrease during the coldest months for domestic users. For agricultural users, the variation depends on the precipitation periods of the year; it decreases during rainy periods while it increases the rest of the year, and finally the industrial demands, which remain almost constant during the year. In normal conditions, these demands are satisfied using exclusively natural water sources (superficial and underground water). The availability of water in the natural sources depends of several factors such as available tributary sources and precipitation. Before being used, the natural sources require a treatment, usually performed in centralized facilities (mains) accordingly to their final use. In order to reduce natural sources depletion, it is considered that different types of storage devices can be constructed in different locations in the city, these units can be used to collect, treat and distribute harvested rainwater, in order to complement the natural sources. Four types of storage devices are considered, storage tanks for general purposes (domestic and agricultural), storage tanks for industrial activities, artificial ponds for general purposes and artificial ponds for industrial uses. The main difference between the considered devices is the size and available collection area. It should be noticed that the precipitation affects directly the demand (in agricultural users), the availability of natural resources and the amount of harvested rainwater that can be recovered for a given collection area. However, climate change has driven changes in the precipitation patterns which cannot be accurately predicted, thus it is important to consider the uncertainty in the precipitation to assess the effect of this factor in the design of water networks, especially when using harvested rainwater as alternative water source.

Given previous information, the problem consists in determining the optimal water storage and distribution schedule in a macroscopic system, considering the seasonal increasing demands, population growth, time value of money and the uncertainty in the precipitation patterns. In order to determine the effect of the uncertainty of the precipitation, the rest of the parameters are considered as deterministic and obtained with a projection based on the present values.

3. Mathematical model

The subscripts, sets and variables used in the model are defined in the nomenclature section. It is considered that only total mass balances are required, this assumption implies that the quality of the water at the exit of each of the splitting points of the network satisfies the quality constraints imposed by the final users. The model consists of a set of mass balances in the mixing and splitting points of the network. It also includes a set of equations required to select the location and time of installation of storage devices when they are required and finally it includes additional constraints used to meet other requirements such sustainability criteria.