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A mixed integer optimisation approach for integrated water resources management

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ABSTRACT

In areas lacking substantial freshwater resources, the utilisation of alternative water sources, such as desalinated seawater and reclaimed water, is a sustainable alternative option. This paper presents an optimisation approach for the integrated management of water resources, including desalinated seawater, wastewater and reclaimed water, for insular water deficient areas. The proposed mixed integer linear programming (MILP) model takes into account the subdivided regions on the island, the subsequent localised needs for water use (including water quality) and wastewater production, as well as geographical aspects. In addition, the integration of potable and non-potable water systems is considered. The optimal water management decisions, including the location of desalination, wastewater treatment, and reclamation plants, as well as the conveyance infrastructure for desalinated water, wastewater and reclaimed water, are obtained by minimising the annualised total capital and operating costs. Finally, the proposed approach is applied to two Greek islands: Syros and Paros-Antiparos, for case study and scenario analysis.

1. Introduction

With the rapid population increase and economic development, more water is needed to meet the increasing demands for irrigation, industry and food, and to satisfy the higher living standards of people (Bouwer, 2000). Lately, water shortage has become a major issue for achieving high living standards and for development, thus an integrated approach for the sustainable exploitation of all potential water sources is needed. The integrated approach for water resources management is more pronounced in arid or semi-arid water deficit areas, especially in insular areas, where there are few alternatives for water management (Lazarova et al., 2001). Groundwater is often limited and of poor quality, if it exists, thus often it is not sufficient to cover increased water demands (White et al., 2007). Fresh water importation from the mainland using tank boats is a particularly expensive and non-sustainable option (Gikas & Tchobanoglous, 2009a). Non-conventional water resources are expected to play an important role in water management (Gikas & Angelakis, 2009), as water conservation (Bakir, 2001) is usually unable to solve entirely the problem, while massive runoff collection is often expensive, time-consuming, and may also demand valuable land if artificial lagoons are to be constructed (Hellenic Ministry for Agriculture, 2002). Thus, desalinated seawater (Khawaji, Kutubkhanah, & Wie, 2008) or brackish water (Jaber & Ahmed, 2004) and reclaimed water from wastewater (Kalavrouziotis & Apostolopoulos, 2007) are the alternative options which may be considered, in conjunction with groundwater.

The existing water treatment technologies are capable of producing even potable water from wastewater (Law, 2003), but it may be expensive and often not acceptable by the public for potable use (Manners & Dowson, 2010). Desalinated and reclaimed water could rather be used in a synergic way. Desalination yields water of potable quality, at a relatively high cost, both in environmental and in money terms (Karagiannis & Soldatos, 2008), while reclaimed water can be used in non-potable urban, industrial and agricultural applications in relation to its qualitative characteristics (World Health Organization, 2006), at production cost significantly lower to that of desalinated water (Gikas & Tchobanoglous, 2009a), and is considered as a sustainable, long-term solution to the challenges presented by the growing demand for water (Miller, 2006).

Gikas and Tchobanoglous (2009a) estimated the cost of desalinated and reclaimed water for the islands of the Aegean Sea in Greece, as a function of plant capacity and reclaimed water quality. Reclaimed water storage facilities and distribution network may have a significant contribution on the cost of reclaimed water. Published work has indicated that decentralised and satellite strategies in water resources management can be particularly beneficial in achieving optimal management (Gikas & Tchobanoglous, 2009b;

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Kornelaki, Liu, Papageorgiou, & Gikas, 2010). However, if reclaimed water is to be used, a dual distribution system should be established (Okun, 1997). Reclaimed water quality is of critical importance for configuring the characteristics of water reclamation plant. Often, the design of reclaimed water systems is based on experience and existing data. However, if such data are not readily available, pilot studies may be required (Aggeli, Kalavrouziotis, & Bezergianni, 2009).

Recently, optimisation techniques have become a valuable tool in the water resources management. Reca, Roldán, Alcaide, López, & Camacho (2001) proposed an optimisation model for water optimal allocation planning in complex deficit agricultural water resources systems to maximise overall economic benefits obtained. Georgopoulou et al. (2001) considered brackish water desalination, wastewater treatment and aquifer recharge by treated wastewater as an alternative water supply strategy, and developed a decision aid tool for the investigation of the feasibility and applicability of the alternative strategy and used for economic evaluation of the overall scheme. Wang and Jamieson (2002) presented an objective approach to regional wastewater treatment planning based on the combined use of Genetic Algorithm (GA) and Artificial Neural Networks (ANN) to minimise the total cost of wastewater treatment with a fixed-emission standard or in-stream water quality requirements. Voivontas, Arampatzis, Manoli, Karavitis, & Assimacopoulos (2003) proposed a mathematical model to identify the economically optimal water supply enhancement to the existing infrastructure of Paros island in Greece. Draper, Jenkins, Kirby, Lund, & Howitt (2003) presented an economic-engineering optimisation model of California's major water supply system. The model was used to suggest water facility operations and allocations so as to maximise the economic value of agricultural and urban water use in California's main intertied water supply system. Later, Medellín-Azuara, Mendoza-Espinosa, Lund, & Ramírez-Acosta (2007) applied the same economic model to explore and integrate water management alternatives, such as water markets, reuse and seawater desalination, in Ensenada, Mexico. Leitão, Matos, Gonçalves, & Matos (2005) developed a decision support model to trace and locate regional wastewater systems, in terms of number, capacities and locations of wastewater treatment plants and the length of main sewers, based on Geographic Information Systems (GIS) and location models. Zechman and Ranjithan (2007) applied an extended evolutionary algorithm to generate alternatives (EAGA) to a regional wastewater treatment network design problem. Joksimovic et al. (2008) developed decision support software (DSS) for water treatment for reuse with network distribution, in which a GA approach is used for the best selection of customers. Han, Xu, & Xu (2008) presented a multi-objective linear programming model to allocate various water resources, including groundwater, surface water, reclaimed water, rainwater, seawater, among multiusers and applied it for the water supply and demand in Dalian, China. Cunha, Pinheiro, Zeferino, Antunes, & Afonso (2009) presented a mixed integer nonlinear programming (MINLP) model for regional wastewater systems planning, as well as the simulated annealing (SA) algorithm developed for solving the model to optimise layout of sewer networks, location of treatment plants, etc., for the wastewater system of a region. Ray, Kirshen, & Vogel (2010) proposed a static and deterministic linear programming (LP) model to optimise the minimum cost configuration of future water supply, wastewater disposal, and reuse options for a semiarid coastal city, where reclaimed water was included as one viable option for water supply. The integrated optimisation model was applied to Beirut, Lebanon, and the optimal water and wastewater systems were obtained for different scenarios. Kondili, Kaldellis, & Papapostolou (2010) proposed a systemic approach for the optimal planning of water systems with multiple supply sources and multiple users. The benefit from water users and cost from water sources are considered in the objective function, but the cost for water distribution was not included.

To the best of our knowledge, no literature work so far has considered the management of the production, distribution and storage of desalinated and reclaimed water, as well as the collection and treatment of wastewater, simultaneously, with the integration between potable and non-potable water systems. In this paper, we propose an optimisation approach using mixed integer linear programming (MILP) techniques to manage water resources, including desalinated seawater, wastewater and reclaimed water. The locations and capacities of the desalination, wastewater treatment and water reclamation plants, the pipeline main networks, and number and types the pumps and storage tanks for all desalinated seawater, wastewater and reclaimed water are to be optimised.

The structure of this paper is organised as follows: the problem statement is presented in Section 2. Section 3 proposes an MILP optimisation model for the problem. In Section 4, the proposed model is applied to two islands in Greece: Syros and Paros. Finally, some concluding remarks are made in Section 5.

2. Problem statement

In this problem, we consider an insular and geographically isolated area which is water deficient. The demands can only be satisfied by desalinated seawater, reclaimed water from wastewater and limited groundwater. All other options including freshwater importation and runoff collection are not taken into account.

Based on the population distribution and land terrain, the whole area is divided into several sub-regions. We consider that all the population in each region is located at the relative population centre, with given seasonal needs for potable and non-potable water. In addition, we consider several potential water/wastewater plant locations. The population centres and potential plant locations are called as "nodes" in this paper. The optimal locations and capacities of desalination, wastewater treatment and water reclamation plants need to be determined in the problem.

The whole water system in the area is divided into non-potable water and potable water systems. In the non-potable water system, wastewater is collected from all possible regions. The collected wastewater undergoes primary and secondary treatment in wastewater treatment plants according to specific quality requirements. Then, part of treated wastewater may need further treatment, at an extra cost, for reclamation, while the rest is disposed into the sea. The reclaimed water could be distributed to other regions to satisfy only non-portable water demands for irrigation, industry, agriculture, etc. In the potable water system, the desalinated water from desalination plants can be distributed to satisfy both potable and non-potable water demands, Groundwater may be used to satisfy, both, potable and non-potable demands, if available. We assume that there is no water loss in the processes.

The water demands (potable and non-potable) and wastewater productions vary throughout a year. Based on the demand volumes, the whole year can be divided into a number of time periods. In our case studies, two such time periods have been used: high-demand and low-demand seasons. The daily water demands and wastewater productions are assumed to be the same within each time period.

It is assumed that both qualities of water, and wastewater, are allowed to be distributed to most regions, in order to satisfy all the water demands at minimum cost. Thus, the infrastructure needs for water distribution and storage, including the pipeline main network between nodes, pumping stations, and storage tanks, are also optimised in the problem. The pipeline for groundwater conveyance is assumed as existing. However, the fraction of the groundwater pipeline, which could be utilised for desalinated