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An optimization model for the allocation of water resources

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ABSTRACT

Critical water shortages, triggered by increasing demands and decreasing supplies, are growing in frequency and spatial extent pausing major challenges for water resources managers around the world. This paper presents an integer linear programming decision support model for the optimal treatment and allocation of water resources. The model seeks to minimize the total water cost which includes the economic cost of treatment and distribution, as well as the associated environmental costs. The model is unique in its ability to account for spatially distributed water supply and demand nodes, as well as multiple water supply (seawater, surface, ground and wastewater) and demand (irrigation, potable, and industrial) types and qualities. It accommodates various treatment technologies, different energy recovery levels, and resource availabilities or capacities. The optimal solution yields volumes of water transported from each supply source to each treatment plant and treated by an appropriate technology in order to satisfy multiple water demands at different required water qualities with the lowest overall economic and environmental costs. The model is applied to a case study. Results showed that the distance of brackish water sources and the environmental cost, observed in terms of carbon savings only, had limited impact on the optimal solution with the demand for the base case being met through a combination of conventional water and wastewater treatment and brackish water reverse osmosis. Sensitivity analysis is performed to determine the effects of variations in demand/supply volumes as well as variable distances and environmental cost. Sensitivity analysis showed that increased demand under limited resources can be met through the introduction of seawater desalination plants, initially through multi effect distillation combined with residual thermal energy then augmented with seawater reverse osmosis plants with further increase in demand.

1. Introduction

Scarcity of fresh water resources is becoming increasingly critical in different regions around the world due to growing populations, increasing consumption patterns, rising anthropogenic activities, and climate change (Schwarzenbach et al., 2010; Oelkers et al., 2011; Bagatin et al., 2014). Water scarcity already affects every continent and more than 40% of the world population (WWAP, 2012). By 2025, 1.8 billion people will be living in regions with absolute water scarcity, and two-thirds of the people in the world could be living under water stressed conditions (WWAP, 2012).

In order to cope with increasing demands under limited supplies, degrading qualities, and increased treatment options, water resource management decisions are becoming increasingly complex (Bagatin et al., 2014). Water, depending on its quality and source, undergoes one or more treatment processes such as, but not limited to, desalination, filtration, and disinfection, to render it suitable for the intended use. Thus, decision makers need to determine the optimal amount of water from each supply source to be transported to each plant and treated by an appropriate technology in order to satisfy the demands, while meeting water quality constraints, at the lowest possible overall economic and environmental cost.

The use of decision support systems (DSS) for water resource management has received growing attention in the past few years. Several problem formulations have been devised and operations research tools such as linear programming (LP), multi criteria decision analysis (MCDA), and cost-benefit analysis have been used to solve these formulations (Al-Zaharani et al., 2016; Atilhan et al., 2012; Ghassemi and Danesh, 2013; Molinos-Senante et al., 2015;

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Ruiz-Rosa et al., 2016).

Afify (2010) used Multi-criteria Decision Analysis (MCDA) to compare all desalination alternatives for Egypt, considering the use of desalinated water, source of feed water, desalination technology, locations of the plants, and their capacities. Al-Zahrani et al. (2016) used a multi-objective goal programming approach to simulate water distribution from multiple sources to multiple users for the city of Riyadh, Saudi Arabia over a thirty five year period. Atilhan et al. (2012) developed an optimization-based approach for the design of water desalination and distribution networks to satisfy the demands of the various water-consuming sectors. Chung et al. (2008) presented a general water supply planning tool comprised of modular components including water sources, users, recharge facilities, and water and wastewater treatment plants. They concluded that these modules should be linked with optimization routines for more reliable results.

Ghassemi and Danesh (2013) developed an integrated two-step model based on the fuzzy-analytic hierarchy process (AHP) and technique of order preference by similarity to ideal solution (TOPSIS) methods for the selection of the optimum desalination technology. Joksimovic et al. (2006) developed a simulation model to be used in combination with an integrated optimization engine for the evaluation and selection of optimal treatment and distribution alternatives in water reuse projects. Molinos-Senante et al. (2012) developed an approach for implementing efficient and effective policies for wastewater treatment by integrating economic and environmental benefits from wastewater using an environmental decision support system (EDSS). More recently, Molinos-Senante et al. (2015) used a different solution approach, namely the analytic network process approach, to solve the problem formulated in their earlier research.

Morais and Almeida (2007) dealt with the allocation of resources for water supply in order to choose the city in which a water supply system project will be implemented. They applied the elimination and choice expressing reality (ELECTRE) method, a multi-criteria decision-aid support tool. They compared their model results to decisions based on intuitive judgments and concluded that the use of their method improved the quality of the decision making process. Ruiz-Rosa et al. (2016), on the other hand, used a cost management model to determine the most suitable water source/supply option, amongst the available sources of wastewater reuse, surface water, ground water and desalination. Sadr et al. (2015) developed a fuzzy logic based multi-criteria group decision making tool for the selection of membrane assisted treatment technologies in four different water reuse scenarios.

Sudhakaran et al. (2013) created a decision support system (DSS) based on MCDA to compare processes for organic micropollutant removal using the following criteria: treatability, costs, technical considerations, sustainability and time. Their proposed DSS can be used as a screening tool for experimental planning or a feasibility study preceding the main treatment system selection and design. Zoltay et al. (2010) developed a generic decision support system to screen a range of technical, economic and policy management options for watershed management; the model was applied to the Ipswich River basin, USA, and was solved using linear programming to yield optimal water allocation and management solutions.

It is clear from the above literature that several DSSs have been developed in order to select optimal water allocation or treatment strategies under given sets of criteria. However, the vast majority of these studies have not included all the water supply, treatment and demand options that are considered in this work, nor have they considered environmental impacts (such as carbon footprint, amongst others).

In this paper, a mixed integer non-linear program (MINLP), reduced to a mixed integer linear program, is proposed for selecting the optimum water treatment technologies and water resource allocation. The objective of the linear program is to minimize the overall economic and environmental cost of the water treatment and distribution system, subject to technical, economic and environmental constraints. The model is sufficiently flexible to consider any number of supply and demand nodes, water quality types, economic and environmental cost structures, as well as treatment options, simultaneously. To achieve this formulation, data on economic and environmental costs of different water and wastewater treatment options are collected from a variety of sources, and are correlated into appropriate cost functions. The result is a decision support system (DSS) that can aid decision makers in the optimal selection of water treatment and distribution systems while keeping the economic cost and environmental damage under control.

2. Material and methods

Achieving model objective requires an abstraction of a generalized system of interest as a fundamental step prior to establishing the mathematical formulation of the model. This includes the different types of water demands, supplies, and treatments. Furthermore, the development of the objective function and constraints in the DSS requires definition of the underlying criteria and cost structure.

2.1. Water demand, supply and treatment processes

Water demand is affected by the size of the population, type of the community, potential and actual use of water (agricultural, industrial, residential, recreational), level of economic development, and local climate conditions (Miller, 2003). In this work, the water demand options are classified into three main categories: (1) domestic, (2) agricultural, and (3) industrial. With respect to supply, a wide range of possible water supply sources are considered in this work, including conventional fresh water sources such as surface water (rivers and lakes) and groundwater (aquifers and wells) as well as non-traditional supply sources such as seawater and wastewater (Leverenz et al., 2011).

Processes and technologies employed for water treatment vary depending on the quality of available supply and desired water output which is often dictated by demand and the type of end use (Miller, 2003). Conventional water treatment of low salinity surface water includes processes such as acid addition, coagulant/flocculant addition, filtration and disinfection (Viessman et al., 2008). Desalination, on the other hand is a process that removes dissolved minerals from seawater, high salinity surface/ground water, or treated wastewater (Shatat and Riffat, 2014; Wenten and Khoiruddin, 2016). All desalination processes involve three liquid streams: the feed water, the low-salinity product water, and a very saline concentrate (known as brine or reject water) which requires disposal (Perez-Gonzalezet al., 2012; Wenten and Khoiruddin, 2016). The amount of product water generated from the original feed stream (termed recovery) will depend on the type of water and technology used and varies between 45 and 90% (Saavedra et al., 2013; Wenten and Khoiruddin, 2016). Desalination technologies are often divided into two main categories: thermal and membrane processes (Elimelech and Phillip, 2011). Thermal processes employ distillation, where saline water is heated to produce water vapor, which is then condensed to produce freshwater (Khawaji et al., 2008). The most widespread distillation processes used to produce potable water include Multi-stage Flash (MSF) distillation, Multiple-effect Distillation (MED), and mechanical vapor compression (MVC) (Miller, 2003; Khawaji et al., 2008). In