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A management and optimisation model for water supply planning in water deficit areas

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SUMMARY

The integrated water resources management approach has proven to be a suitable option for efficient, equitable and sustainable water management. In water-poor regions experiencing acute and/or chronic shortages, optimisation techniques are a useful tool for supporting the decision process of water allocation. In order to maximise the value of water use, an optimisation model was developed which involves multiple supply sources (conventional and non-conventional) and multiple users. Penalties, representing monetary losses in the event of an unfulfilled water demand, have been incorporated into the objective function. This model represents a novel approach which considers water distribution efficiency and the physical connections between water supply and demand points. Subsequent empirical testing using data from a Spanish Mediterranean river basin demonstrated the usefulness of the global optimisation model to solve existing water imbalances at the river basin level.

1. Introduction

Many regions of the world are currently facing moderate to severe water crises due to population growth, industrialisation, food production practices, improved living standards and poor water management strategies (UNEP, 2011). More than 25% of the world's population lives in arid or semi-arid areas where a shortage of water is a critical, chronic problem that requires resolution (Kondili et al., 2010).

Traditional water supply planning is based on fixed water requirements and the necessary mechanisms to deliver the water to meet those requirements (Medellín-Azuara et al., 2007). The rising costs to achieve 100% water supply reliability and the need for more sustainable management of scarce water resources have led to the well-known concept of Integrated Water Resources Management (IWRM). The concept of IWRM has been recently recognised as a functional strategy for achieving efficient, equitable and sustainable development and management of the worlds limited water resources (UNDP, 2012). Moreover, taking into account the uncertainty of global climate change, a sustainable option to the water situation can only be achieved by an integrated approach (Grundmann et al., 2012).

The goal of the IWRM is to balance water supply and demand, taking into account the availability of conventional and non-conventional water resources both from a quantity and quality point of view. Conventional resources include surface water and groundwater while non-conventional water sources are mainly desalinated water and reclaimed water. For example, although it is technically feasible to generate potable water from wastewater, other issues such as the regeneration costs, the potential damage from the use of recycled water and, the social acceptance of the reclaimed water should be taken into account. Therefore, in areas where freshwater is particularly scarce, an IWRM approach could include the diversion of high quality groundwater from agriculture to urban and industrial uses, and the distribution of reclaimed water to agricultural demand. This change would more appropriately distribute available water resources in accordance with the quality required for each use, resulting in a positive environmental impact. This simple example shows the important role that non-conventional water resources are expected to play in water management. It has been made clear through recent structured research that one of the most important challenges in regions of water scarcity is efficient and fair allocation in the face of mounting competition between agricultural, urban, industrial and environmental demands (FAO, 2010).

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In this context, optimisation is appealing in cases where problems (i) are clearly defined with quantifiable objectives, (ii) are describable using one or more mathematical models, (iii) have been analysed through the generation of a sufficient amount of available data to characterise the effects of alternative solutions and (iv) are without an obvious best alternative practice (Haith, 1982). Therefore, if these conditions are met, optimisation techniques are a useful tool for water management policy analysis and strategic decision support (Cetinkaya et al., 2008).

In spite of increasing interest in optimisation models, there remains a substantive need for further model development and refinement based on the IWRM concept. To best of our knowledge, only CALVIN (California Value Integrated Network) model by Jenkins et al. (2001), Draper et al. (2003) and Medellín-Azuara et al. (2007) and the model proposed by Kondili et al. (2010) include multiple supply sources and multiple users, i.e., follow an IWRM approach. CALVIN is an economic-engineering optimisation model that jointly considers water management and economic performance, including water sources, storage and agricultural and urban uses. The aim of the model is to minimise the total costs of operation in a system. It has been used in California to explore water market behaviour and to facilitate economically driven managerial decisions (Draper et al., 2003). The aim of the model proposed by Kondili et al. (2010) is to optimise water supply and distribution under conditions of water shortage. The optimisation criterion is the maximisation of the total water value, taking into account all the benefits from water use and costs. A drawback of both models is they assume that all water sources can accommodate all types of demand, i.e., they do not have considered quality issues. On the one hand, the main limitation of the model developed by Kondili et al. (2010) is lack of consideration of a water distribution cost as an objective function, since the model assumes that users will take water directly from a storage tank. On the other hand, the CALVIN model, which considers distribution costs, does not take into account water losses or efficiency of the distribution network. Moreover, since it is an economic-engineering model, data requirements are high and therefore, complex calibration processes are often necessary.

Against this background and based on the concept network flow (Yung-Hsim et al., 1995; Hsu et al., 2008), an optimisation model for water allocation has been developed which involves multiple supply sources (conventional and non-conventional) and multiple users (urban, agricultural, industrial and environmental). The main motivation to follow a network flow approach is that optimal solution is guaranteed. The model's aim is to maximise the value of the water considering all the revenues and costs associated with its use.

There are three main novel aspects that differentiate the proposed model from previous ones, those being the integration of the following issues:

- Quality of the water from the supply and demand perspective meaning that not all types of demand can be supplied from all water sources. For example, in many countries reclaimed water cannot be used for urban purposes. Moreover, the integration of water quality issues involves positive environmental impacts since it allows a more suitable allocation of available water resources in accordance with quality requirements.
- Existence of physical connections between supply and demand. The existence of water distribution networks between origins and destinations is necessary for water supply. In addition, both minimum and maximum connections capacities were incorporated as constraints. This aspect is particularly important for reclaimed, desalinated and surface water since in addition to treating the water it should be distributed.
- Water losses or efficiency in the water distribution, i.e., the volume of water supplied is different from the water received. Because water losses are not associated with the source of the water but with the distribution system maintenance, the volume of water leaving from the origin is always larger than the volume of water arriving to destination. Based on this consideration, the solution of the model can be viewed from a supply (water leaving a point of origin) or demand (water arriving at the destination) perspective.

The proposed model is a useful tool for supporting the decision process of water allocation in water scarcity areas contributing to improve the management of available water sources at watershed level.

2. Methodology

2.1. Elements of the model

The proposed mathematical model takes into account various elements from both the demand and supply perspective. To make the model functional, each water source is characterised by a given quality, associating it with certain uses and some specific supply costs. It should be noted that the revenue generated for a specific water use is highly variable.

From the supply side, conventional and non-conventional water sources have been considered. Conventional resources include surface water (S) and groundwater (B). Non-conventional water sources include desalinated water (D) and reclaimed water (R). In recent years, desalinated water has become an essential water resource in water-stressed areas. In fact, approximately 130 countries use some form of desalination, with West Asia and North Africa possessing half of the global desalination capacity (Vedachalam and Riha, 2012). Not all of the final effluent discharged from wastewater treatment plants (WWTPs) is available for direct reuse. Whether it is available depends to a large degree on whether it is meeting the appropriate water quality standards. The costs associated with water regeneration depend on the level of treatment required to achieve specific water quality limits. For example, Iglesias et al. (2010) have defined six treatment trains to achieve reclaimed water standards according to the Spanish Royal Decree 1620/2007 which establishes the legal guidelines for the reuse of treated wastewater in Spain. Structured guidelines for water reuse are lacking in some countries, and where guidelines do exist, they are not consistent from nation to nation or even within a single country. A third potential source of water comes from inter-basin water transfers (T). Although inter-basin water transfers have generated some of the greatest controversies and conflicts in water resources management (Pena de Andrade et al., 2011), the worldwide water transfer data base[1] shows that many international projects have been successfully developed.

From the demand side, four users have been considered for this model: (i) environmental (E), (ii) urban (U), (iii) industrial (I) and (iv) agricultural (A). Because water quality has been integrated into the model, not all water sources can accommodate all types of demand. In general, water users might be supplied with surface water, groundwater, desalinated water and water from transfers. However, because water quality is highly variable, for each case study it is necessary to consider the specific quality of each source. The Spanish Royal Decree 1620/2007 does not allow the use of reclaimed water for urban needs. Although either agricultural or industrial uses are allowed, the water quality standards that must be met are different.

[1] Information can be consulted at the web page: http://www.transboundarywaters.orst.edu/publications/.