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Optimisation approaches for the synthesis of water treatment plants

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ABSTRACT

Efficient water treatment design has progressively been growing in importance as the usage of water resources increases with population rise and industrial development. Their availability has been reduced with the more evident effects of climate change. Addressing this challenge necessitates more and efficient purification plants which can be realised by optimal design at conceptual stage. In this work, a mixed integer nonlinear programming (MINLP) model for the synthesis and optimisation of water treatment processes is proposed. Due to its numerous non-linearities and consequently, its non-stability, various linearisation, approximation and reformulation techniques have been implemented. Consequently, two improved formulations are derived, i.e. a partially linearised MINLP (plMINLP) and a mixed integer linear fractional programming (MILFP) models. The applicability of the mathematical formulations are investigated in case studies of seawater desalination and surface water treatment for the production of potable water. Finally, the models performance is analysed and compared against each other.

1. Introduction

World water baseline scenario for year 2050 reveals approximately 5500 km^3 of freshwater withdrawals will be required to meet the demand of water necessary for manufacturing, electricity production and domestic use. This represents an increase of 55% from current global demand where 130% more drinking water will be in demand for households than volumes nowadays (United Nations, 2015).

Water supply to end users is governed by publicly accepted practices which entail sources such as groundwater or surface water to undergo water treatment. Seawater desalination has become an alternative option for the provision of clean water. After purification, the product water is distributed to agriculture, industry and households (shown in Fig. 1).

It can be deduced from Fig. 1 that the connecting role in the water chain belongs to water treatment and desalination. Hence, with the outlook of future water demand, investments on new purification plants have been planned. By 2018, for instance, Middle East and Africa are expected to have an annual growth of water production capacity of 13.2%, followed by Asia with 10.1% and the Americas with 5.7% (Fig. 2). Desalination, on the other hand, has gained popularity in less than a century. It has evolved from an idea in 1951 into an industrial process with large clean water production capabilities today. Fig. 3 depicts the progressively installed desalination plants capacities in selected countries from the discovery of reverse osmosis to 2016. The global desalination capacity by the end of 2016 is projected to be 86.8 million m^3 which is predicted to reach 128 million m^3 by 2018 (International Desalination Association, 2016).

The water challenge has brought questions of how to most efficiently treat water resources to ensure good quality and safety of final products. A number of works published in literature have given answers to those questions. Tchobanoglous et al. (2003) and Cheremisinoff (2002) have outlined guidelines for the design of water and wastewater treatment plants. Voutchkov (2013) and Lior (2013) have provided exhaustive principles of design and cost estimation of seawater desalination plants. Process Systems Engineering, however, and process synthesis, in particular, hold the power of designing flowsheets that will lead not only to water quality up to regulatory standards but also to minimum capital and operating expenditures. Table 1 gives a summary of recent representative contributions in water treatment as stand-alone process and as a component of integrated systems. In some of those works, synthesis and optimisation of wastewater treatment with single and multiple contaminants have been proposed (Tsiakis and Papageorgiou, 2005; Skiborowski et al., 2012; Gabriel et al., 2015; Teles et al., 2012; Khor et al., 2012). Deterministic design of water, wastewater and seawater treatment processes formulated as non-linear programming (NLP) or mixed integer non-linear

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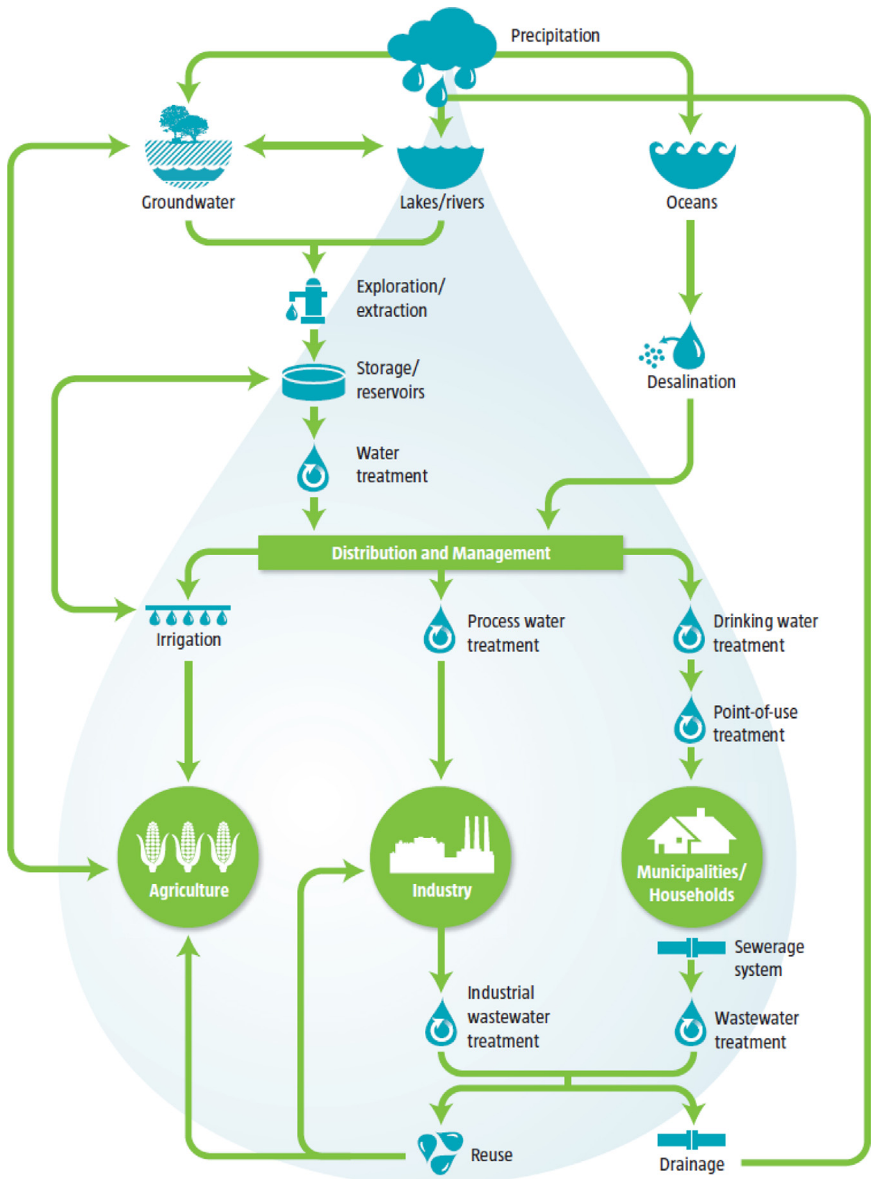

Fig. 1. Water path from precipitation to usage.
Source: RobecoSam (2015).

programming (MINLP) models has been studied in various works (Khor et al., 2012; Teles et al., 2012; Sueviriyapan et al., 2016; Koleva et al., 2016). An MINLP model specialised on reverse osmosis (RO) systems and cost estimations such as pumping, membrane cleaning and replacement has been proposed by Lu et al. (2006, 2012). Multi-objective optimisation for minimising operating costs, greenhouse gas emissions and effluent contaminants has been presented by Sweetapple et al. (2014).

Water network systems (WNS) together with wastewater treatment have been the focus of copious articles (Dong et al., 2008; Ahmetović and Grossmann, 2011; Galán and Grossmann, 2011; Rojas-Torres et al., 2013; Ibrić et al., 2014; Yang and Grossmann, 2013). A recent comprehensive review analysed and classified the various contributions made to WNS (Ahmetović et al., 2015). Integrated water resources management studies have taken into account different water and wastewater treatment options formulated as single and multi-objective optimisation problems (Liu et al., 2010, 2011; Liu and Papageorgiou, 2013). Guerra et al. (2016) have presented a novel method for the design of shale gas supply chain with wastewater management where total dissolved solids are considered.

The intricacy of the design is, normally, due to bilinearities arising from mixing of streams of different qualities, which immensely

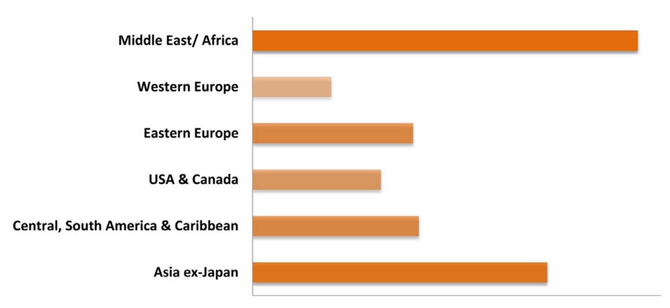

Fig. 2. Projected percentage of increase of water utilities by area by 2018.
Source: RobecoSam (2015).