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A novel robust optimization approach for an integrated municipal water distribution system design under uncertainty: A case study of Mashhad

Zabih Ghelichi, Javad Tajik, Mir Saman Pishvaee*

School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran

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ABSTRACT

This paper proposes a novel robust optimization (RO) approach along with a two-stage scenario-based stochastic programming to optimize a municipal water distribution system (WDS) under demand and rainfall uncertainties. Firstly, we have proposed a new multi-period mixed-integer linear programming (MILP) formulation of a municipal WDS. The goal is to find solutions that are both cost-effective and completely fulfill potable and non-potable demand in an integrated system. Furthermore, a novel RO approach is developed which attempts to adjust protection level in a column what we call "adjustable column-wise robust optimization". The interesting point of the proposed RO approach is its linear structure and being computationally tractable. The efficiency of the proposed models are evaluated through a real case study of Mashhad. The acquired results reveal the proposed WDS model have dramatically reduced the total costs. Simultaneously, the RO approach has risen robustness besides realization demonstrates its better performance than deterministic one.

1. Introduction

Water is the most critical resource issue of our lifetime and posterity's lifetime. Population growth, economic development, environmental concerns and reduction in freshwater supply in the urban areas pose serious problems to water resources planning and management. Demand for water consumption has been ever-increasing in many municipal areas, and climate change around the world simultaneously causes drought periods in some areas like the Middle East which exacerbate water supply management concerns. High costs of water supplement and distribution have motivated water decision making practitioners to design urban water distribution networks which cope with financial concerns while supplying demand. Water has been consuming for daily usage without any attention on "what way is this precious and dearth potable water consumed?". Therefore, it would be a good idea to separate different types of water consumption (potable and non-potable), while the greatest proportion of the water consumption in total is consumed via the non-potable applications over the world. Potable water supply needs to be refined and treated more than the non-potable water, which indicates that water treatment for drinking would pose more costs than non-potable one. Thus, the present paper proposed a water distribution network (WDS), which consists of a proposed WDS for distinguishing potable from the non-potable water supply through an integrated network with the aim of minimizing total costs. Accordingly, the planning and management of the water distribution system and its resources are the exigent problems for policymaking practitioners. Hence, an integrated mathematical model can be useful for the cost-effective and efficient design of the municipal water distribution network in this respect.

Uncertainty is an inherent part of the real world and the water distribution networks are not exempt from this concern. In WDS models, there is a large number of stochastic parameters, e.g. amount of rainfall, demand, facility failure, head pressure and pipe roughness. Although uncertainty will impose a great deal of expenditure to a WDS network, it can provide more realistic models and reliable results for making strategic and tactical decisions in real world. Hereby, it is necessary for decision-makers and planners to consider different uncertainty sets in their decisions. In other words, the uncertainty cost pales in comparison with future problems and costs of uncertain events. The precipitation plays a vital role in charging the main resources of water supply chain (dams and wells). Furthermore, the

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* Corresponding author at: School of Industrial Engineering, Iran University of Science and Technology, Narmak, Tehran, 16846-13114, Iran.
E-mail addresses: zabih_ghelichi@ind.iust.ac.ir (Z. Ghelichi), j_tajik@ind.iust.ac.ir (J. Tajik), pishvaee@iust.ac.ir (M.S. Pishvaee).

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demand is seen as one of the most important uncertain parameters in every supply chain network. Hence, this paper has considered a two-stage scenario-based stochastic programming framework to address the precipitation uncertainty problem besides developing a robust approach to tackle the demand uncertainty.

In the last decades, several studies have been undertaken in the field of the multi-level water distribution system design and planning including with a variety of mathematical optimization models for WDSs in order to optimize the total costs by the use of linear programming methods (Gupta, 1969; Gupta et al., 1972). Alperovits and Shamir (1977) applied the Linear Programming Gradient (LPG) approach to optimize the pipeline systems through a WDS in order to meet the demand and decrease the total costs. Goulter and Morgan (1985) considered a closed-loop WDS, including two linked linear programming methods, where one of them determined the least cost layout of the initial pressure and the other one determined the least cost of the initial pipe layout. Samani and Mottaghi (2006) and Samani and Zanganeh (2010) presented a branch & bound linear programming technique and a MILP model to optimize the total cost of a municipal WDS. A remarkable multi-objective linear programming model was proposed by Fattahi and Fayyaz (2010) which aims to minimize water distribution costs and water leakage while maximizing social satisfaction level. Verleye and Aghezzaf (2011) and Burgschweiger et al. (2009) presented a mixed-integer non-linear programming (MINLP) model to minimize the total cost of the drinking water supply.

According to Table E.1 provided at Electronic Supplementary Material, it can be inferred from the literature that water distribution models chiefly considered a few levels for their networks, which are not adaptable to real world practices. Furthermore, the significant point of this table is the type of water in a network. In some cases, researchers did not specify the type of water in their networks. However, the rest of researches in this table have been only undertaken to consider drinking water supply. Obviously, there is a conspicuous lack of researches on potable and non-potable water supply in an integrated distribution network. Indeed, a municipal water distribution network can be designed for separating potable and non-potable water supplement and distribution through an integrated system.

Along the same lines, a large body of researches have been undertaken to apply the meta-heuristic approaches (in particular the genetic algorithm (GA)) in the field of water supply and distribution network design literature. Indeed, meta-heuristic approaches are implemented to deal with intractability of large-scale and NP-hard problems. For example, Gupta et al. (1999) applied the genetic algorithm to a WDS problem. Prasad and Park (2003) presented a multi-objective programming model, in which the least costs and reliability was simultaneously optimized, and a new reliability measure, called "network resilience", developed. Hemker et al. (2008) presented a mixed-integer simulation-based approach for surrogate functions as an efficient and powerful method for a water resources design and management problem. Furthermore, a simple GA was linked to an integer linear programming (ILP) method over an hybrid optimization model by Haghighi et al. (2011). Kougias and Theodossiou (2013) exploited the Harmony Search Algorithm (HSA) so as to solve an application of a classic dam scheduling problem as a large-scale problem. A noteworthy environmental friendly WDS has been developed by Blinco et al. (2014). They optimized the operational greenhouse gas (GHG) emissions through combining the operational economic costs of different possible future energy scenarios by employing GA algorithm. Matrosov et al. (2015) linked a WDS simulator to an evolutionary multi-objective model (by reducing principal budget, operational costs and energy consumption and thus improving the resilience, engineering and environmental metrics) in order to depict the trade-offs between the best portfolio schemes to fulfill water demand.

Many researchers have developed supply chain management problems under uncertainties and applied different robust optimization and stochastic programming approaches to a myriad industries and areas which range from petroleum (e.g. Fernandes et al., 2016; Fernandes et al., 2015; Oliveira et al., 2014), transportation (e.g. Daghigh et al., 2016) and biomasses (e.g. Andersen et al., 2012; Babazadeh et al., 2017) to blood (e.g. Jabbarzadeh et al., 2014) and food industries (e.g. Behzadi et al., 2017). Similarly, some researchers have employed a wide variety of stochastic programming and robust optimization techniques which range from scenario-based techniques to Bertsimas and Sim approach so as to address uncertainty in WDS literature. Watkins and McKinney (1997) proposed a scenario-based water resources planning problem to make decisions under the demand and supply uncertainties, as an application to evaluate the trade-offs and control the impacts of these uncertainties in the water resources. Kang and Lansey (2012) presented a scenario-based multi-objective optimization model in order to deal with the demand changes due to the population growth. In the same way, Alhassan et al. (2016) and Zhang et al. (2013) modeled linearization of the nonlinear hydraulic equations and the objective function terms of the water network supply. Moreover, Pérez et al. (2015) applied a scenario-based approach that described how the pressure measurements used to derive the uncertainty model of the demand. A scenario-based MINLP model is presented by Mortazavi-Naeini et al. (2015) in order to fulfill portable water under climate change condition. A municipal WDS is employed to deal with the uncertainty of the extreme drought and climate changes through applying some scenario-based multi-objective functions (minimizing the expected total investment costs of infrastructures and the operational costs besides minimizing the difference between present value costs imposed by the future climate change scenarios). Mo et al. (2015) analyzed a number of scenarios related to the river inflow levers by developing the interval parameters of two-stage stochastic integer programming models (ITSIP). A mathematical model with the aim of maximizing the income from the sales of water by subtracting the expenditure of treatment and distribution of different public, agricultural and industrial sectors under precipitation uncertainty was examined by Nápoles-Rivera et al. (2015) and Zhu et al. (2015). Lan et al. (2015) developed both cost-effectiveness and robustness of a WDS system by defining the specific scenarios via the facility failure risk monitoring.Housh et al. (2012) designed a WDS model, which includes the aquifers and the desalination plants with exploiting the mean-variance approach in the stochastic replenishment of the aquifers.

Chung et al. (2009) implemented an RO approach on the water demand in the municipal WDS. Bertsimas and Sim presented this salient approach, which allows the examination of the trade-off between the system reliability and the economic costs, to control the protection levels. Furthermore, Ben-Tal and Nemirovski developed another remarkable RO approach, which is employed by many researchers. For instance, Housh et al. (2011) have developed a water supply system by resourcing with the aquifer and desalination plants to minimize the net present value of costs by applying Ben-Tal and Nemirovski ellipsoidal robust counterpart (RC) approach. Similarly, Perelman et al. (2013) and Schwartz et al. (2016) applied this approach to determine the least cost design of a WDS problem under demand uncertainty based on the fluctuation of the hydraulic heads. Recently, Naderi and Pishvaee (2017a) have presented a bi-objective municipal WDS redesign and rehabilitation with the aim of minimizing total costs and leakage simultaneously under a number of uncertain parameters such as demand, precipitation surface stream discharge, evaporation and dams' inflow and outflow.

Recently, a few researchers have tried to apply the fuzzy theory methods for the water distribution problems under uncertainty. Shibu and Reddy (2014) handled the uncertainty of the future water demand by exploiting the theory of the Fuzzy Random Variable (FRV). The water demand is defined as a triangular fuzzy number with a random demand, as its kernel has two scenarios. Another research was con-