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Reclaimed water distribution network design under temporal and spatial growth and demand uncertainties

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ABSTRACT

A significant—but underutilized—water resource is reclaimed water, i.e., treated wastewater that is reintroduced for various purposes. Especially in water scarce regions, reclaimed water is often the only remaining source of water to meet increasing population and water demands. In this paper, we develop a new model formulation for the cost-effective branched reclaimed water network design and solve it with an exact optimization method. We consider both construction and energy costs expended over a twenty-year period. Unlike other formulations, uncertain reclaimed water demands, temporal and spatial population changes are explicitly considered in our two-staged construction and expansion model. In order for the system to meet higher demands during the peak times and to evaluate energy use, we consider two pumping conditions: one with average demands, which is used to compute the average energy consumption, and the other with peak demands, which dominates pipe size and pump station capacity selection. By introducing binary variables that indicate discrete pipe and pump sizes, we linearize the nonlinear hydraulic equations and objective function terms. We develop methods to significantly reduce the problem dimension by exploiting the problem characteristics and network structure. Our computational results indicate that these methods are very effective. Finally, we apply our model to design a reclaimed water network for a realistic municipal system under estimated demand and population scenarios, and analyze the sensitivity of the system to model parameters.

1. Introduction

Diminishing supplies and population growth are stressing the limited water resources available in many communities. The water, wastewater, and water reuse industries have recognized the need for extending the present water supplies. In many areas, the last remaining untapped water resource is reclaimed or recycled water; i.e., treated wastewater that is reintroduced for various, often non-potable, purposes. The use of reclaimed water offsets a portion of the community's demand that would otherwise be met by mining additional groundwater or developing additional surface water sources. Therefore, reclaimed water systems save precious water resources.

In this paper, we study a reclaimed water distribution system for supplying irrigation water. We consider least-cost design and operation of this system over twenty years and allow for two-staged construction under uncertain demand and community growth. The cost of building, expanding, maintaining, and operating a reclaimed water distribution system can be in the tens of millions of dollars. Least-cost design of reclaimed water systems is therefore important and even small percentage savings can be used by local governments to fund other important areas of interest such as education and security. Our solution method is exact and provides bounds on solution quality. Our numerical results are based on a representative system of a city like Tucson, AZ, but the model and methods are transferable and applicable to water scarce regions to support reclaimed water decisions.

Designing a reclaimed water distribution system involves selecting the size of various pipes and pumps that satisfy the flow demand and the pressure requirements. The hydraulic equations used for this purpose—such as the Hazen–Williams or Darcy–Weisbach equations in calculating friction loss—result in a

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challenging nonconvex optimization problem. In early work, researchers linearized the model formulation for branched networks (Gupta, 1969; Gupta et al., 1972) and for looped systems (Bhave and Sonak, 1992; Quindry et al., 1981; Alperovits and Shamir, 1977). The approach is to use the pipe length as a decision variable rather than pipe diameter and the model determines the pipe lengths of different diameters in a given link (Alperovits and Shamir, 1977). Later, conditions for the existence of an optimal solution where each link has at most two adjacent pipe diameters for this formulation were established (Fujiwara and Dey, 1987). We note that the decision variables in our formulation, in contrast, select a pipe diameter for a given link as desired by design engineers and are more realistic.

To fully account for the nonlinear set of conservation of mass and energy equations, a network solver that solves the set of hydraulic equations has been linked to an optimization model. For instance, Ormsbee (1989) and Lansey and Mays (1989) combined hydraulic network solvers with nonlinear optimization models. More recently, stochastic search algorithms such as genetic algorithms have been applied to find cost-effective designs (Dandy et al., 1996; Eusuff and Lansey, 2003; Savic and Walters, 1997; Simpson et al., 1994) but they may not be robust, they cannot guarantee global optimality, and the computation time can be problematic. In contrast, global optimization techniques can yield global optimal solutions, or solutions with bounds on their optimality gaps. The first global optimization method for water distribution network design problem was proposed by Eiger et al. (1994). Then, in a series of papers, Sherali and Smith (1997), Sherali et al. (1998, 2001) developed enhanced global optimization methods using polyhedral outer approximations and the reformulation-linearization technique embedded in a branch-and-bound methodology. As a result, they were able to solve problems that were unsolved until that point. We note that most of this work has been on designing looped potable water distribution networks whereas our focus is on reclaimed water networks. Since reliability issues are not as important in a reclaimed water network, we assume a branched network structure and thus are able to linearize the problem.

Given computational difficulties, applications of stochastic optimization for water distribution network design have been limited. An exception is a chance constrained optimization model to account for parameter uncertainty (Lansey et al., 1989). Some researchers looked at the reliability of the system under uncertainties such as pipe breaks, demands and pipe roughness (Babayan et al., 2007; Sherali et al., 1996; Tolson et al., 2004). We note that in a reclaimed system, reliability concerns due to pipe breaks are not of primary interest as reclaimed water demands can be met via potable water resources but not vice versa. However, expansion of the system in the future is worth considering in a long-term design.

As water resources become scarcer and the value of water increases, expansion of the reclaimed water system is important for sustainable growth of cities. In our model the expansion is formulated using a two-stage stochastic program with recourse, where the expansion decisions are considered in the second stage. Most stochastic programming applications in water resources have been focused on managing water reservoirs (see, e.g., Dupačová et al., 1991; Edirisinghe et al., 2000). These water reservoirs are usually used for hydroelectric power generation and irrigation of agriculture. There is also considerable work on water quality (Lence and Ruszczyński, 2002; King et al., 1988; Somlyódy and Wets, 1988; Takyi and Lence, 1999; Wagner et al., 1992; Watkins et al., 2005; Peña-Haro et al., 2011), and some on water allocation (Kracman et al., 2006; Watkins et al., 2000) and sensor placement in water networks (Berry et al., 2005; Rico-Ramirez et al., 2007).

To the best of our knowledge, no two- or multi-stage stochastic optimization models have been developed for pipe and pump sizes selection problem in municipal reclaimed water distribution system models. This paper and its earlier version that appeared in a WDSA conference proceedings (Zhang et al., 2010) are the first works for such a model. Compared to the WDSA conference proceedings paper, we have improved the reclaimed water network design model to be more realistic by taking into account the velocity constraints. More importantly, we have developed methods to reduce the problem dimension that enabled us to solve problems that we were unable to solve earlier. As a result, computations and analysis have been conducted on larger problems with more scenarios for a better representation of future demand uncertainties. In addition, we have significantly improved the sensitivity analysis by examining the sensitivity of the value of stochastic solutions and system cost breakdowns under different problem parameters and gained deeper insight into the system. This yielded more detailed and constructive recommendations for decision makers.

Our approach can be summarized like this: 1. Model development → 2. Separate into sub-networks → 3. For each sub-network: → 3.1. Pipe size reduction → 3.2. Pump size reduction → 4. Solve the problem → 5. Sensitivity analysis. Our model explicitly considers hydraulic equations as model constraints; so there is no need to use network simulators such as EPA-NET. Our new reclaimed network design model is more realistic compared to earlier models in the literature in several ways: it (i) explicitly considers future uncertainties and expansion of the system as in real-world systems, (ii) uses discrete pipe/pump sizes and velocity constraints as desired by engineers, and (iii) considers energy costs expended when operating the system in addition to construction costs. Our solution method is an exact/global optimization method, which, unlike genetic algorithms, yields global optimal solutions or solutions within known bounds to global optimality regardless of the starting point. Separating the network and the preprocessing methods developed in this paper significantly reduce the number of pipe and pump decisions and thus considerably improved the solution time, which has the potential benefit to improve of the performance of other solution methods as well. Note that the removed pipe and pump decisions need not be considered in an optimal solution.

The remainder of this paper is organized as follows. In §2, we present the reclaimed water distribution network design problem and describe the model formulation. In §3, we discuss how to reduce the problem dimension via separability and preprocessing engineering constraints. In §4, we test the effectiveness of dimension reduction and present an application of this model to a realistic system. In §5, we examine the sensitivity of the system to varying model parameters. Finally, we conclude the paper in §6, by providing a summary and discussion. The appendices to the paper provide additional information on the network data (Appendix A) and detailed component cost breakdowns (Appendix B).

2. Problem description and mathematical formulation

2.1. Model overview and characteristics

We develop a cost-effective reclaimed water distribution system over twenty years, which includes a sequence of decisions, such as pipe sizes, pump station locations, and pump capacities. Pipe paths are assumed to follow existing or planned road networks, which is typical in practice. For newly developing areas, road networks are planned ahead of any construction. Within the twenty-year time horizon, we consider construction decisions today (now), and also expansion decisions in ten years. We define the first stage from now to the beginning of the tenth year, and the second stage as the next