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Lost in optimisation of water distribution systems? A literature review of system operation

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ABSTRACT

Optimisation of the operation of water distribution systems has been an active research field for almost half a century. It has focused mainly on optimal pump operation to minimise pumping costs and optimal water quality management to ensure that standards at customer nodes are met. This paper provides a systematic review by bringing together over two hundred publications from the past three decades, which are relevant to operational optimisation of water distribution systems, particularly optimal pump operation, valve control and system operation for water quality purposes of both urban drinking and regional multiquality water distribution systems. Uniquely, it also contains substantial and thorough information for over one hundred publications in a tabular form, which lists optimisation models inclusive of objectives, constraints, decision variables, solution methodologies used and other details. Research challenges in terms of simulation models, optimisation model formulation, selection of optimisation method and postprocessing needs have also been identified.

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1. Introduction

Water distribution systems (WDSs) represent a vast infrastructure worldwide, which is critical for contemporary human existence from all social, industrial and environmental aspects. As a consequence, there is pressure on water organisations to provide customers with a continual water supply of the required quantity and quality, at a required time, subject to a number of delivery requirements and operational constraints. A level of flexibility exists in the WDSs, which enables the supply of required water under different operational schedules, more or less economically. This flexibility gives opportunity for optimisation of WDS operation.

Since the 1970s, substantial research has addressed the operational optimisation of WDSs (Ormsbee and Lansey, 1994) with two main areas of focus. The first area includes pump operation, as pump operating costs constitute the largest expenditure for water organisations worldwide (Van Zyl et al., 2004). Optimal operation of pumps is often formulated as a cost optimisation problem (Savic et al., 1997). The second area includes optimisation of water quality across the water distribution network. This research area emerged in the 1990s following the U.S. Environmental Protection Agency (EPA) promulgating "rules requiring that water quality standards must be satisfied at consumer taps rather than at treatment plants" (Ostfeld, 2005).

Development in the use of various methods to optimise operation of WDSs is not only an interesting subject for research, but is also very complex. Initially, these techniques included deterministic methods, such as dynamic programming (DP) (Dreizin, 1970; Sterling and Coulbeck, 1975a; Zessler and Shamir, 1989), hierarchical control methods (Coulbeck et al., 1988a, 1988b; Fallside and Perry, 1975; Sterling and Coulbeck, 1975b), linear programming (LP) (Alperovits and Shamir, 1977; Schwarz et al., 1985) and nonlinear programming (NLP) (Chase and Ormsbee, 1989). Since the 1990s, metaheuristic algorithms, such as genetic algorithms (GAs), simulated annealing (SA), to name a few, have been applied to the optimal operation of WDSs with increased popularity. Their attractiveness for this type of optimisation is due to their potential to solve nonlinear, nonconvex, discrete problems for which deterministic methods incur difficulty (Maier et al., 2014; Nicklow et al., 2010). In recent years however, deterministic methods have started to reappear, because they are more computationally efficient, thus more suitable for real-time control, as well as other applications (Creaco and Pezzinga, 2015). An example of the former is Derceto Aquadapt, a commercial software used for real-time optimisation of valve and pump schedules (Derceto, 2016), which uses LP as the base algorithm.

2. Aim, scope and structure of the paper

The aim of this paper is to provide a comprehensive and systematic review of publications for operational optimisation of WDSs since the end of the 1980s to nowadays to contribute to the existing review literature (Lansey, 2006; Ormsbee and Lansey, 1994; Walski, 1985). Publications included in this review are relevant to optimal pump operation, valve control and optimal system operation for water quality purposes of both urban drinking and regional multiquality WDSs.

The paper consists of two parts: (i) the main review and (ii) an appendix in a tabular form (further referred to as the table), each having different structure and purpose. The main review is structured according to publications' application areas (pump, water quality and valve control) and general classification. This classification is used because it captures all the main aspects of an operational optimisation problem answering the questions: what is optimised (Section 4.1), how is the problem defined (Section 4.2), how is the problem solved (Section 4.3) and what is the application (Section 4.4)? The purpose of this part of the paper is to provide the current status, analysis and synthesis of the current literature, and to suggest future research directions.

The table forms a significant part of the paper referring to over a hundred publications and is structured chronologically. It contains a detailed classification of each paper, including optimisation models (i.e. objective functions, constraints, decision variables), water quality parameters, network analyses and optimisation methods used, as well as other relevant information. The purpose of the table is to provide an exhaustive list of publications on the topic (as much as feasible) detailing comprehensive and thorough information, so it could be used as a single reference point to identify one's papers of interest in a timely manner. Therefore, it represents a unique and important contribution of this paper.

The structure of the paper is as follows:

- The main review: Application areas (Section 3), General classification of reviewed publications (Section 4), Future research (Section 5), Summary and conclusion (Section 6), List of terms (Section 7), List of abbreviations.
- The table: Appendix.

3. Application areas

3.1. Pump operation

Typically, electricity consumption is one of the largest marginal costs for water utilities. The price of electricity has been rising globally, making it a dominant cost in operating WDSs. Pump operation is optimised in order to achieve a minimal amount of energy consumed by pumps. Pumps are controlled either explicitly by times when pumps operate (so called pump scheduling), or implicitly by pump flows (Bene et al., 2013; Nitivattananon et al., 1996; Pasha and Lansey, 2009; Zessler and Shamir, 1989), pump pressures, tank water trigger levels (Broad et al., 2010; Van Zyl et al., 2004) or pump speeds for variable speed pumps (for example Hashemi et al. (2014), Ulanicki and Kennedy (1994), Wegley et al. (2000)). These controls are specified as decision variables and their formulations are reviewed in Ormsbee et al. (2009). The most frequently used is *explicit pump scheduling*, which can be specified by (i) on/off pump statuses during predefined equal time intervals (for example Baran et al. (2005), Ibarra and Arnal (2014), Mackle et al. (1995), Salomons et al. (2007)), (ii) length of the time (in hours) of pump operation (Brion and Mays, 1991; Lopez-Ibanez et al., 2008), (iii) start/end run times of the pumps (Bagirov et al.,

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