Water Distribution Systems Optimization

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Invited paper

Abstract. A water distribution system is a complex assembly of hydraulic control elements connected together to convey quantities of water from sources to consumers. The common high number of constraints and decision variables, the nonlinearity, and the non-smoothness of the head flow water quality governing equations are inherent to water distribution systems planning and management problems. This paper provides a brief overview on some of the more traditional and new water distribution systems problem algorithms and solution methodologies. The manuscript concludes with challenges and a look into the future for water supply systems optimization.

Keywords: water distribution systems, optimization, review, water quality, robust optimization, genetic algorithms.

1 Introduction

A water distribution system is an interconnected collection of sources, pipes and hydraulic control elements (e.g., pumps, valves, regulators, tanks) delivering consumers prescribed water quantities at desired pressures and water qualities. Such systems are often described as a graph with the links representing the pipes and the nodes defining connections between pipes, hydraulic control elements, consumers, and sources.

The typical high number of constraints and decision variables, the nonlinearity, and the non-smoothness of the head flow water quality governing equations are inherent to water supply systems planning and management problems. An example of this is the least cost design problem of a water distribution system defined as finding the water distribution system's component characteristics (e.g., pipe diameters, pump heads and maximum power, reservoir storage volumes, etc.), which minimize the system capital and operational costs, such that the system hydraulic laws are maintained (i.e., Kirchhoffs Laws No. 1 and 2 for continuity of flow and energy, respectively), and constraints on quantities and pressures at the consumer nodes are fulfilled.

In addition, problems related to aggregation, maintenance, reliability, unsteady flow and security can be identified for gravity, and/or pumping, and/or

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storage branched/looped water distribution systems. Flow and head, or flow, head, and water quality can be considered for one or multiple loading scenarios, taking into consideration inputs/outputs as deterministic or stochastic variables. Figure 1 provides a schematic map of water distribution systems related problems.

Traditional methods for solving water distribution systems management problems used linear or nonlinear optimization schemes which were limited by the system size, the number of constraints, and the number of loading conditions. More recent methodologies employ heuristic optimization techniques, such as genetic algorithms or ant colony optimization as stand alone or hybrid data driven heuristic schemes. Other recent methods employ robust optimization methodologies for incorporating uncertainty.

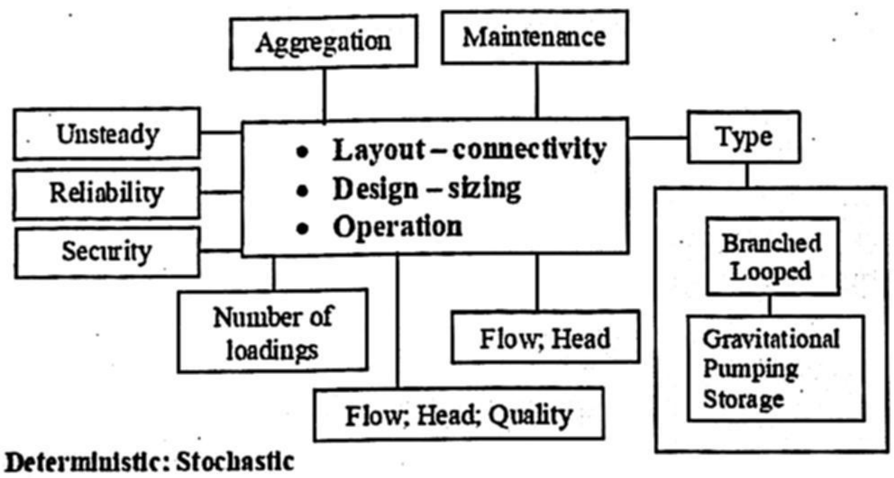

Fig. 1. A map of water distribution networks related problems $z(t)$

This paper reviews part of the topics presented in Figure 1. It includes sections on least cost optimal design of water networks, reliability incorporation in water supply systems analysis, optimal operation of water networks, water quality considerations inclusion in distribution systems, water networks security, robust optimization employment for water distribution systems management, and a look into the future.

2 Least cost design of water networks

Numerous models for least cost design of water distribution systems have been published in the research literature during the last four decades. A possible classification for those might be: (1) decomposition: methods based on decomposing the problem into an "inner" linear programming problem which is solved for a fixed set of flows (heads), while the flows (heads) are altered at an "outer" problem using a gradient or a subgradient optimization technique [1, 38, 39, 22, 13, 34]; (2) linking simulation with nonlinear programming: methods based on linking a network simulation program with a general nonlinear optimization code [29, 23, 50]; (3) nonlinear programming: methods utilizing a straightforward nonlinear programming formulation [55, 44]; (4) methods which employ evolutionary or metaheuristic techniques: genetic algorithms [46, 42, 40, 53, 56], simulated annealing [25], the shuffled frog leaping algorithm [14], ant colony optimization [27]; and (5) other methods: dynamic programming [48], integer programming [41].

The capabilities of solving water distribution systems optimization problems have improved dramatically since the employment of genetic algorithms [17]. Genetic algorithms are domain heuristic independent global search techniques that imitate the mechanics of natural selection and natural genetics of Darwins evolution principle. The premise is to simulate the natural evolution mechanisms of chromosomes, represented by string structures, involving selection, crossover, and mutation. Strings may have binary, integer, or real values. Simpson et al. [46] were the first to use genetic algorithms for water distribution systems least cost design. They applied and compared a genetic algorithm solution to the network of Gessler [16], to enumeration and to nonlinear optimization. Savic and Walters [42] used genetic algorithms to solve and compare optimal results of the oneloading gravity systems of the Two Loop Network [1], the Hanoi network [15], and the New York Tunnels system [43]. Salomons [40] used a genetic algorithm for solving the least cost design problem incorporating extended period loading conditions, tanks, and pumping stations.

3 Reliability of water supply

Reliability of water distribution systems gained considerable research attention over the last three decades. Research has concentrated on methodologies for reliability assessment and for reliability inclusion in least cost design and operation of water supply systems.

Shamir and Howard [45] were the first to propose analytical methods for water supply system reliability. Their methodology took into consideration flow capacity, water main breaks, and maintenance for quantifying the probabilities of annual shortages in water delivery volumes.

Reliability measures such as the probability of shortfall (i.e., total unmet demand), the probability of the number of failure events in a simulation period, and the probability of interfailure times and repair durations were used in various studies as reliability criteria. Bao and Mays [4] suggested stochastic simulation by imposing uncertainty in future water demands for computing the probability that the water distribution system will meet these needs at minimum pressures. Duan and Mays [12] used a continuous-time Markov process for reliability assessment of water supply pumping stations. They took into consideration both mechanical and hydraulic failure (i.e., capacity shortages) scenarios, all cast in a conditional probability frequency and duration analysis framework. Jacobs and Goulter [18] used historical pipe failure data to derive the probabilities that a particular number of simultaneous pipe failures will cause the entire system to fail.

Recently, Tanyimboh et al. [51] compared the surrogate measures of statistical entropy, network resilience, resilience index, and the modified resilience index for quantifying the reliability of water networks. Torii and Lopez [52] utilized first order reliability methods in conjunction with an adaptive response surface approach for analyzing the reliability of water distribution systems.

4 Water networks optimal operation

Following the well known least cost design problem of water distribution systems [21, 19, 1], optimal operation is the most explored topic in water distribution systems management. Since 1970 a variety of methods were developed to address this problem, including the utilizations of dynamic programming, linear programming, predictive control, mixedinteger, nonlinear programming, metamodeling, heuristics, and evolutionary computation. Ormsbee and Lansey [30] classified to that time optimal water distribution systems control models through systems type, hydraulics, and solution methods. Examples for optimal operation of water distribution systems are described below.

Dreizin [11] was the first to suggest an optimization model for water distribution systems operation through a dynamic programming (DP) scheme coupled with hydraulic simulations for optimizing pumps scheduling of a regional water supply system supplied by three pumping units. Sterling and Coulbeck [49] used a dynamic modeling approach to minimize the costs of pumps operation of a simple water supply system. Olshansky and Gal [28] developed a two level linear programming methodology in which the distribution system is partitioned into subsystems for which hydraulic simulations are run and serve further as parameters in an LP model for pumps optimal scheduling. This approach was used also by Jowitt and Germanopoulos [20] who developed a linear programming model to optimize pumps scheduling in which the LP parameters are set through offline extended period hydraulic simulation runs. Biscos et al. [7] used a predictive control framework coupled with mixed integer nonlinear programming (MINLP) for minimizing the costs of pump operation. Biscos et al. [8] extended Biscos et al. [7] to include the minimization of chlorine dosage. Pulido-Calvo and Gutiérrez-Estrada [37] presented a model for both sizing storage and optimizing pumps operation utilizing a framework based on a mixed integer non linear programming (MINLP) algorithm and a data driven (neural networks) scheme. Ostfeld and Salomons [31] minimized the total cost of pumping and water quality treatment of a water distribution system through linking a genetic algorithm with EPANET (www.epa.gov/nrmrl/wswrd/dw/epanet.html).

Van Zyl et al. [54] utilized a genetic algorithm (GA) linked to a hillclimber search algorithm for improving the local GA search once closed to an optimal solution. LópezIbáñez et al. [26] proposed an ant colony optimization (ACO) [10] framework for optimal pumps scheduling. Boulos et al. [9] developed the H2ONET tool based on genetic algorithms for scheduling pump operation to minimize operation costs.

5 Inclusion of water queality

Research in modeling water quality in distribution systems started in the context of agricultural usage [24, 47] primarily in arid regions where good water quality is limited. In 1990 the United States Environmental Protection Agency (USEPA) promulgated rules requiring that water quality standards must be satisfied at the consumer taps rather than at the treatment plants. This initiated the need for water quality modeling, the development of the USEPA simulation water quantity and quality model EPANET (EPANET 2.0@2002), and raised other problems and research needs that commenced considerable research in this area to assist utilities.

Optimization models of water distribution systems can be classified according to their consideration of time and of the physical laws which are included explicitly [32, 33]. In time the distinction is between policy and real time models. Policy models are run off line, in advance, and generate the operating plans for several typical and/or critical operating conditions. Real time (online) models are run continuously in real time, and generate an operating plan for the immediate coming period. The classification with respect to the physical laws which are considered explicitly as constraints are: (1) QH (discharge - head) models: quality is not considered, and the network is described only by its hydraulic behavior; (2) QC (discharge quality) models: the physics of the system are included only as continuity of water and of pollutant mass at nodes. Quality is described essentially as a transportation problem in which pollutants are carried in the pipes, and mass conservation is maintained at nodes. Such a model can account for decay of pollutants within the pipes and even chemical reactions, but does not satisfy the continuity of energy law (i.e., Kirchoffs Law no. 2), and thus there is no guarantee of hydraulic feasibility and of maintaining head constraints at nodes; and (3) QCH (discharge - quality - head) models: quality constraints, and the hydraulic laws, which govern the system behavior, are all considered. The QH and QC problems are relatively easier to solve than the full QCH.

Since the events of 9/11 in the US the security of water distribution systems became a foremost concern. Threats on a water distribution system can be partitioned into three major groups according to their resulted enhanced security: (1) a direct attack on the main infrastructure: dams, treatment plants, storage reservoirs, pipelines, etc.; (2) a cyber attack disabling the functionality of the water supervisory control and data acquisition (SCADA) system, taking over control of key components which might result water outages or insufficiently treated water, changing or overriding protocol codes, etc.; and (3) a deliberate chemical or biological contaminant injection at one of the system's nodes.

The threat of a direct attack can be minimized by improving the system's physical security (e.g., additional alarms, locks, fencing, surveillance cameras, guarding, etc.), while a cyber attack by implementing computerized hardware and software (e.g., an optical isolator between communication networks, routers to restrict data transfer, etc.).

Of the above threats, a deliberate chemical or biological contaminant injection is the most difficult to address. This is because of the uncertainty of the type of the injected contaminant and its effects, and the uncertainty of the location and injection time. Principally a contaminant can be injected at any water distribution system connection (node) using a pump or a mobile pressurized tank. Although backflow preventers provide an obstacle, they do not exist at all connections, and at some might not be functional.

The main course to enhance the security of a water distribution system against a deliberated contamination intrusion is through a sensor system [2, 3].

6 Robust Optimization

The approach presented in most previous studies is to treat the problem as deterministic assuming perfectly known parameters. Consequently, deterministic models are likely to perform poorly when implemented in reality when the actual problem parameters are revealed, hence the need to find more "robust" solution approaches. Perelman et al. [35, 36] proposed formulating a deterministic equivalent of the stochastic problem of optimal design/rehabilitation of water distribution systems using the non probabilistic robust counterpart (RC) approach [5, 6] for uncertainty inclusion into optimization modeling. The uncertainty of the information is quantified through a deterministic userdefined ellipsoidal uncertainty set, which can be probabilistically justified, with the decision maker seeking a solution that is optimal for all possible realizations in the uncertainty set. The robust counterpart makes no assumptions about the probability density function of the uncertain variables and their dependencies, does not require the construction of a representative sample of scenarios, and has the same size as the original deterministic model.

7 Conclusions

Traditionally, water distribution networks were designed, operated, and maintained through utilizing offline small discrete datasets. Those were the governing and limiting constraints imposed on modeling challenges and capabilities. This situation is dramatically changing: from a distinct framework of data collection to a continuous transparent structure. With multiple types of sensor data at multiple scales, from embedded real time hydraulic and water quality sensors to airborne and satellite based remote sensing, how can those be efficiently integrated into new tools for decision support for water distribution networks is a major challenge.

This new reality is expected to limit all current modeling efforts capabilities and require new thinking on approaches for managing water distribution networks: from a state of lack of data to a situation of overflowing big data information. New tools for data screening, algorithms and data driven modeling constructions, as well as computational efficiency are anticipated to govern all future developments for water distribution networks analysis and optimization.

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