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# Optimal control of water distribution networks with storage facilities

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ABSTRACT

Optimal operation of water distribution networks (WDNs) is concerned with meeting consumer demands at desired pressures in an efficient and equitable manner while conserving resources. This can be achieved by implementing advanced control schemes such as model predictive control (MPC). If sufficient water is available, the control objective is to meet consumer demands while preventing wastage. On the other hand, if the available water is insufficient or inadequate to meet consumer demands at the required pressures, equitable distribution of the available resource is of primary importance. In this contribution, a nonlinear model predictive controller is proposed for optimal operation of WDNs that can deal with both the above situations. The proposed approach takes into account availability of storage facilities at the source and demand points. In addition, the control algorithm can account for plant-model mismatch. Performance of the proposed model based control strategy is illustrated through numerical simulations of an illustrative WDN operating under various water availability scenarios. In the water sufficient scenario, the proposed MPC strategy is able to meet the consumer requirements while minimizing the excess amount of water supplied. In the water deficient scenario, the MPC algorithm is able to exploit the available storage facilities at consumer end to reduce the daily supply deficit by about 20%. Using a longer prediction horizon in MPC results in a further reduction of about 40% in the daily supply deficit.

## 1. Introduction

A water distribution network (WDN) is an important component of civic infrastructure used for providing water for domestic as well as industrial uses. Research in the field of water distribution networks has been concerned mainly with the simulation, calibration and optimal design of networks. Since water scarcity is a major problem in many countries, utilities that operate WDNs are interested in increasing the efficiency and reliability of operation while conserving water. As a result, there has been increased focus on optimal control of WDNs for improving the operational performance of the system. Optimal operation and control of water distribution networks deals with the problem of taking appropriate operational decisions to achieve certain performance goals or objectives. The objectives that have been considered in the past include (i) minimizing the cost of energy required for pumping, (ii) regulating pressures for preventing/reducing leakages, and (iii) maximizing the quality of water supplied to the users by reducing the residence time of water in the network.

Under the assumption that the required demands of customers can be met, one of the important objectives considered in the control of a WDN is the minimization of operating costs, a significant proportion of which is the cost of pumping [1–3]. Lansey and Awumah [4] used dynamic programming in a simulation–optimization framework for determining optimal pump operations for a fixed horizon, while limiting the number of pump switches between on and off status. In the above methods, the decision variables were the status of pumps which were treated as discrete binary (0 or 1) variables. Klempous et al. [5] proposed two algorithms: one for simulation of the network and the other for determining the actual number of working pump units and regulating valve positions to minimize energy costs, taking into account the varying prices for electricity. Ertin et al. [6] determined a pump-schedule that control pumps at a booster station to meet water demands while maintaining reservoirs at acceptable levels. Yu et al. [7] considered both constant rates and variable rates for cost of electricity. They considered variable speed pumps and thus the decision variables are pump static pressure heads and water levels in tanks. Rao and Salomons [8] proposed an artificial

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## Nomenclature

| | |
|---|---|
| $A_R$ | cross-sectional area of the reservoir (m$^2$) |
| $A_t$ | cross-sectional area of the storage tank (m$^2$) |
| $a_{ij}$ | pipe-node incidence coefficients |
| $C_v$ | valve coefficient |
| $d_i$ | outflow rate at demand node $i$ (m$^3$/s) |
| $d_i^{sp}$ | desired outflow rate at demand node $i$ (m$^3$/s) |
| $D_j$ | diameter of the pipe $j$ (m) |
| $\Delta d_i$ | cumulative deviation between demand outflow rate and the requirement at demand node $i$ (m$^3$/s) |
| $E$ | number of pipes in the WDN |
| $E_v$ | number of control valves |
| $J$ | objective function of the control problem |
| $G_L$ | specific gravity of the fluid |
| $\Delta h_j$ | head loss in pipeline element $j$ (m) |
| $\Delta h_{v_j}$ | head loss across control valve $j$ (m) |
| $k_i$ | resistance offered to outflow at demand node $i$ |
| $h_i$ | pressure head at node $i$ (m) |
| $h_{i\,\min}$ | specified minimum pressure head to be maintained at demand node $i$ (m) |
| $H_r$ | water level in reservoir (m) |
| $H_{t_i}$ | water level in storage tank at demand node $i$ (m) |
| $H_{t_i\,\max}$ | maximum storage height of the storage tank at demand node $i$ (m) |
| $\hat{H}_{t_i}$ | estimate of water level in storage tank at demand node $i$ (m) |
| $\hat{H}_{t_i}^{pmm}$ | estimate of plant-model mismatch in terms of water level in storage tank at demand node $i$ (m) |
| $L_j$ | length of the pipeline $j$ (m) |
| $M$ | control horizon length |
| $N$ | number of nodes in the network |
| $N_d$ | number of demand nodes |
| $P$ | prediction horizon length |
| $Q_{\mathrm{in}_i}$ | sum of inflow rates into a reservoir/tank at node $i$ (m$^3$/s) |
| $Q_j$ | flow rate in pipeline/valve $j$ (m$^3$/s) |
| $Q_{\mathrm{out}_i}$ | sum of outflow rates from a reservoir/tank at node $i$ (m$^3$/s) |
| $\Delta t$ | sampling time period (s) |
| $u$ | vector of manipulated inputs |
| $V$ | fraction of valve open |
| $z_i$ | elevation of node $i$ (m) |
| $\lambda$ | Hazen–Williams coefficient |
| $\tau$ | valve rangeability |

neural network (ANN) model as a surrogate for hydraulic simulation model, and used a genetic algorithm (GA) as the optimization technique to minimize energy consumption.

The other aspect that has been considered in the operation and control of a WDN is the quality of water supplied. Cembrano et al. [9] considered cost of water supply and treatment, and costs related to pressure and flow regulation in their objective function. The decision variables are optimal number of pumps to operate, and control valve positions. Ostfeld and Shamir [10,11] developed models for optimal operation of a multi-quality water supply system under steady and unsteady state conditions. The objective was to minimize the total cost of water treatment and pumping, while delivering water to all consumers at acceptable qualities and pressure. Constans et al. [12] developed a new control-oriented computational model for chlorine concentration in distribution networks operating under varying demand conditions. They solved a constrained linear programming optimization problem which minimizes the difference between the permissible and actual chlorine concentration levels.

All the above studies on optimal operation and control of WDNs only solve the “open loop problem”, viz the offline optimization problem of determining the optimal operating policy for pumps and valves so as to satisfy the chosen objectives. Active online control of the WDN based on feedback from measured variables of the network is not incorporated in these formulations. The feedback information from the system is important for dealing with uncertainties in the model and in the operation. Only the methods proposed by [13] and [9] mention the use of incorporating feedback from the measurements in their formulation and the method for achieving this is clearly explained only by [13], under the assumption that the controlled variables are all measured.

Miyaoka and Funabashi [13] developed a two-level control scheme for the optimal control of WDNs such that the pressures at all nodes and inflows at the supply nodes are close to the specified values. This is to minimize the wastage of water due to excess withdrawal at the consumption nodes. In the first level, the optimal operating point which minimizes the above objective function is determined. A linear quadratic regulator (LQR), based on observed flows and pressures, is designed at the second level to determine the optimal valve settings that regulate the WDN operation at the optimal state determined in the first level. Jowitt and Xu [14] proposed a method for reducing the leakage from the network by optimally controlling the pressures at the outflow nodes by manipulation of flow control valves. A pressure dependent outflow model of WDN was used in their formulation.

Biscos et al. [15] proposed a method for generating control strategies ahead of time, using predictive techniques, to achieve certain objectives such as maximization of the use of low cost power (overnight pumping) and the maintenance of target chlorine concentration. Constraints of the problem are defined on valve openings, reservoir levels, and chlorine concentration. A model predictive control (MPC) technique is used to solve the problem. Tu et al. [16] developed a multi-commodity flow model to optimize water distribution and water quality in a water supply system with blending requirements, perfect mixing and two way flow conditions.

The above-described MPC techniques use a single, monolithic controller for network control. Alternatively, Trnka et al. [17] have demonstrated different types of distributed control schemes. Javalera et al. [18] showed that the solution of multi-agent control based on negotiations are within acceptable degree of accuracy as compared to a centralized controller. Given the large, complex and heterogeneous nature of WDNs, distributed MPC (DMPC) is an attractive alternative to centralized MPC. For control of large WDNs, Leirens et al. [19] proposed the use of DMPC based on linearized models of the system. Ocampo-Martinez et al. [20] derived a suboptimal DMPC that allowed hierarchical controllers to control each sub-network.

In all the above methods for optimal operation/control, the objectives chosen are applicable to situations in which sufficient water is available to meet the demand requirements at all the nodes. However, with the alarming depletion of water resources and increasing population, it may not always be possible to meet customer demands at all times and in all places. In certain situations, even if adequate quantity of water is available, the pressure in the balancing reservoirs may not be sufficient to deliver the required flow rate of water to customers. These situations are collectively referred to in this work as water deficient. In water deficient situations, it is important that the control strategy allocates water so as to minimize the shortfall in supply, and supplies the available water in as equitable a manner as possible. Even if sufficient water is available, it is necessary to conserve this precious resource by preventing wastage through excess withdrawal. This