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# Formulation of Chlorine and Decontamination Booster Station Optimization Problem

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## ABSTRACT

A commonly used indicator of water quality is the amount of residual chlorine in a water distribution system. Chlorine booster stations are often utilized to maintain acceptable levels of residual chlorine throughout the network. In addition, hyper-chlorination has been used to disinfect portions of the distribution system following a pipe break. Consequently, it is natural to use hyper-chlorination via multiple booster stations located throughout a network to mitigate consequences and decontaminate networks after a contamination event. Many researchers have explored different methodologies for optimally locating booster stations in the network for daily operations. In this research, the problem of optimally locating chlorine booster stations to decontaminate following a contamination incident will be described.

## INTRODUCTION

Drinking water distribution systems are a critical infrastructure, which are vulnerable to intentional attacks as well as accidental contamination (Murray et al. 2009). Contamination warning systems using water quality sensors are being deployed to assist water utilities in the detection of anomalous incidents. A commonly measured water quality parameter is residual chlorine, and an event detection system can analyze the residual chlorine data to identify periods of anomalous water quality.

Following successful detection of a contamination incident, water utility personnel must make decisions on how to respond and mitigate the consequences. A common method to address perceived changes to water quality is to increase the amount of the disinfectant in the water distribution system. Typically, disinfectants are applied at the water treatment plant. Unfortunately, based on residence times associated with storage and transport of water in a network, disinfectants applied at the treatment plant could take a long time to neutralize a contamination event. Additionally, the reaction dynamics of disinfectants make it difficult to maintain adequate residuals at critical locations without excessive residuals elsewhere. Booster stations address these concerns through the reapplication of disinfectant at strategic locations throughout a water distribution system.

Although booster disinfection is commonly practiced, a standardized procedure for the location and operation of booster stations has not been adopted in the water utility community. Thus, booster stations are often located near areas with low levels of disinfectant residual, and they are operated with regard to the local goals of increased residual which often ignores the system-level interactions. Booster disinfection has been shown to minimize the total disinfectant required to maintain adequate and uniform levels of residual when compared to adding disinfectant only at the source of the distribution system (Boccelli et al. 1998). The location and operation of chlorine booster stations is a problem which has been studied numerous times (Munavalli et al. 2003; Ostfeld et al. 2006; Prasad et al. 2004; Propato et al. 2004a, 2004b; Tryby et al. 2002). In addition to the normal operation of booster stations, they can be utilized when responding to a contamination incident. A limited amount of research has explored the application of booster stations to this problem (Parks et al. 2009; Propato et al. 2004c).

## LITERATURE REVIEW

A few researchers (Boccelli et al. 1998; Tryby et al. 2002) have used linear superposition and first-order reaction kinetic assumptions to avoid the computational burden of water quality simulations during optimization. Using these assumptions, the chlorine booster station operation problem can be formulated as a linear programming (LP) model, where the objective is to minimize the total chlorine mass injected into the system. Boccelli et al. (1998) formulated a linear optimization model for the scheduling of disinfectant injections into water distribution systems to minimize the total disinfectant dose required to satisfy residual constraints. Their approach used network water quality models to quantify disinfectant transport and decay as a function of the booster dose schedule. The booster scheduling model was then formulated as a finite-time linear programming model using the principle of linear superposition by assuming first-order kinetics for disinfectant decay. They analyzed multiple disinfectant injection locations and determined that the optimal injection schedule is influenced by the location of the booster station as well as the system hydraulics. They also reported that the best schedule was found when a booster station was located at a storage tank.

Sakarya and Mays (2000) developed a methodology for determining optimal pump operations for water quality improvements while satisfying hydraulic and water quality constraints. The decision variables were discrete-time pump operation schedules and the optimization problem was solved by interfacing EPANET with a nonlinear optimization code.

Tryby et al. (2002) extended the study of Boccelli et al. (1998) to incorporate booster station location as a decision variable within the optimization process. The formulation is similar to the general, mixed-integer linear programming, fixed-charge facility location problem, and is solved using a branch-and-bound solution procedure.

Munavalli and Mohan Kumar (2003) formulated a nonlinear optimization problem to determine the chlorine injection rates which reduced chlorine residuals closest to the target minimum value. They solved this problem by linking EPANET with a genetic algorithm (GA), where the objective was to minimize the squared difference between computed chlorine concentrations and the minimum specified concentration at all monitoring nodes at all times. The constraints required that concentration profile be maintained within the specified range.

Prasad et al. (2004) used a multi-objective genetic algorithm to minimize the total disinfectant dose and maximize the volumetric demand within specified chlorine limits. They showed a trade-off relationship between the disinfectant dose and the volumetric demand satisfied for a given number of booster stations.

To optimize the operation of chlorine booster stations, Propato and Uber (2004b) formulated a linear least-squares (LLS) model to minimize the sum of squared deviations of residual chlorine from a desired target. They assumed that the booster station locations were known. Propato and Uber (2004a) extended their previous work to include the location of the booster stations as decision variables. The problem was formulated as a mixed integer quadratic programming problem and solved using a brand-and-bound technique.

Ostfeld and Salomons (2006) formulated two different optimization objectives for optimal pump operation and booster disinfection. The proposed objectives were (1) minimization of the cost of pumping and the booster stations operation and (2) maximization of the chlorine injected in order to maximize the system protection. The problem was solved using a GA linked with EPANET.

By assuming first-order reaction kinetics, Lansey et al. (2007) formulated an integer linear programming optimization problem to determine the optimal location of booster stations as well as their injection rates. The objective function minimized the total mass of chlorine injected into the system. Their constraints required the chlorine concentrations at the beginning and end of the design period to be the same. The problem was solved using a GA.

In the study to evaluate the effectiveness of a booster response system, Parks and Van Briesen (2009) used EPANET and a database to determine the booster station locations in order to reduce the volume of contaminated water consumed. They noted that to maintain water quality, booster stations should be placed in areas of the network that have low residual. To mitigate the consequence of a contaminant incident or to decontaminate a network, booster stations should be placed in locations with wide network coverage.

Kang and Lansey (2010) formulated a real-time optimal valve operation and booster disinfection problem as a single objective optimization model. Two objectives were proposed: (1) minimize the total mass of chlorine injected at the sources and/or booster stations or (2) minimize excessive chlorine residuals at consumer nodes.

Constraints on the objective function included the upper and lower bounds on the chlorine residual, nodal pressures, and tank levels in the system. The optimization model was formulated and solved using a GA linked with EPANET.

## PROBLEM FORMULATION

In this study, the problem of locating booster stations to support booster disinfection in the context of a contamination incident is considered. The objective is to locate a given number of booster stations to support the activation of a booster disinfection protocol that hyper-chlorinates water in the distribution system in order to neutralize a contaminant that has been introduced into a system.

In this approach, several general assumptions must be made. First, it is assumed that water quality sensors are used to support the automatic detection of contaminants in the distribution system. This ensures that the booster stations can be activated quickly to minimize the impact of the contamination incident that triggered them. Second, it is assumed that the booster stations are being located to minimize the expected impact over an ensemble of contamination incidents. Although several different impact statistics can be considered, for each impact this statistic can be directly computed given the set of sensors and booster stations. The sensors determine the time of detection, and the booster stations reflect where chlorinated water enters the distribution system. In this approach, it is assumed that sensors detect without errors (i.e., no false-positive or false-negative errors), and that booster stations begin chlorinating immediately, or after a suitable delay. Finally, it is assumed that all booster stations are started simultaneously, and that they are on throughout the duration of the contamination incident (i.e., until the end of the time-horizon for modeling the contamination incident).

In this study two different ways of formulating a booster station optimization are proposed, with the principal difference being in how the contaminant-chlorine reactions are computed. The first optimization formulation is a black-box approach where the multi-species EPANET-MSX software is used to evaluate the effects of chlorine utilization and contaminant reactions. Given a candidate set of booster stations, EPANET-MSX can be used to predict contaminant and chlorine travel in a distribution system, and how they react. This computation can be used to determine the amount of contaminant that exits the distribution system, which can be used to evaluate a variety of impact measures (e.g., population health impacts and extent of contamination in the distribution system).

These impact calculations can be easily used to perform booster station optimization using general purpose optimization heuristics like genetic algorithms and TABU search. These types of optimizers iteratively search through a space of booster station locations, generating candidate solutions that are evaluated with an external routine. In this application, this routine involves the evaluation of the candidate solution over an ensemble of contamination incident. Each incident requires the execution of an EPANET-MSX computation, along with an impact calculation. Although this is likely to be an expensive computation, note that the costly hydraulic computations can be pre-computed if it is assumed that the booster stations do not change the hydraulic dynamics in the network. Additionally, these computations can be easily parallelized on a compute cluster.

The second proposed optimization formulation uses an algebraic model to model the flow of contaminants and chlorine in the network. This model leverages the previous formulations for booster station placement that have used linear programming and integer programming formulations (Boccelli et al. 1998; Tryby et al. 2002). Thus, the common assumption of linear superposition and first-order reaction kinetic assumptions are required. The reaction between the contaminant and chlorine is also modeled with a first-order reaction.

This algebraic model can be used to formulation a mixed-integer program model for booster station optimization. The integer decision variables are the locations of the booster stations. Note that this is a particularly large integer program because the algebraic model is replicated for each contamination scenario. The integer program computes the impact for each scenario and minimizes the sum of these impacts. Note that the sensor locations do not need to be explicitly represented. Instead, the time of first detection given the sensor locations are pre-computed, and this value is used to determine the time at which booster stations are started.

Integer programming models like this can be solved with a generic branch-and-bound algorithm that reliably finds the best sensor location. A variety of commercial and open-source solvers can be practically applied for integer programming models. However, this optimization formulation may become extremely large for realistic distribution systems. Consequently, advanced algorithmic strategies may be needed to optimally locate booster stations. For example, optimization heuristics like progressive hedging (Watson et al. 2010) can be used to decompose large problems like this into sub-problems, where each sub-problem involves the analysis of a single contamination scenario.

## DISCLAIMER

This project has been subjected to the U.S. Environmental Protection Agency's review and has been approved for publication. The scientific views expressed are solely those of the authors and do not necessarily reflect those of the U.S. EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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