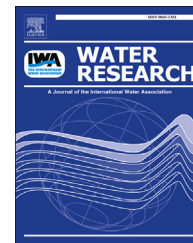




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# Optimal design and operation of booster chlorination stations layout in water distribution systems

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## ABSTRACT

This study describes a new methodology for the disinfection booster design, placement, and operation problem in water distribution systems. Disinfectant residuals, which are in most cases chlorine residuals, are assumed to be sufficient to prevent growth of pathogenic bacteria, yet low enough to avoid taste and odor problems. Commonly, large quantities of disinfectants are released at the sources outlets for preserving minimum residual disinfectant concentrations throughout the network. Such an approach can cause taste and odor problems near the disinfectant injection locations, but more important hazardous excessive disinfectant by-product formations (DBPs) at the far network ends, of which some may be carcinogenic. To cope with these deficiencies booster chlorination stations were suggested to be placed at the distribution system itself and not just at the sources, motivating considerable research in recent years on placement, design, and operation of booster chlorination stations in water distribution systems. The model formulated and solved herein is aimed at setting the required chlorination dose of the boosters for delivering water at acceptable residual chlorine and TTHM concentrations for minimizing the overall cost of booster placement, construction, and operation under extended period hydraulic simulation conditions through utilizing a multi-species approach. The developed methodology links a genetic algorithm with EPANET-MSX, and is demonstrated through base runs and sensitivity analyses on a network example application. Two approaches are suggested for dealing with water quality initial conditions and species periodicity: (1) repetitive cyclical simulation (RCS), and (2) cyclical constrained species (CCS). RCS was found to be more robust but with longer computational time.

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## 1. Introduction

Disinfection has been routinely carried out since the early 1900s as a major mean for preventing water born diseases. Disinfectants, in addition to removing pathogens from drinking water, can prevent biological re-growth if a

minimum disinfectant residual is maintained throughout the water distribution system (WDS).

Chlorine and their compounds are the most popular disinfectants for water. This is due to the chlorine low cost and necessity to preserve a residual level. On the other hand high level of chlorine can cause complaints and be poisonous, thus the chlorine residual is kept within proper bounds.

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**Table 1 – Summary of trihalomethanes (TTHMs) predictive models.**

Source	Output	Units	Predictive model
Amy et al. (1987)	TTHM	μmol/l	$0.0031(\text{UV TOC})^{0.44}(\text{D})^{0.409}(\text{t})^{0.265}(\text{T})^{1.06}(\text{pH}-2.6)^{0.715}(\text{Br}+1)^{0.036}$
Adin et al. (1991)	TTHM	μg/l	$(K_1)(K_2)(\text{TOC}) \left[ \frac{1}{1 + ((K_1 + K_3)(K_2 + 0.19))} + \frac{1}{1 + (K_1 + K_3 - K_2 - 0.19)} \times \left( \frac{((1/(K_1 + K_3)) \exp^{-(K_1 + K_3)(\text{tc})})}{-(1/(K_2 - 0.19)) \exp^{-(K_2 - 0.19)(\text{tc})}} \right) \right]$ where $K_1 = 4.38 \times 10^8 (\text{D}); K_2 = 11.36 \times 10^{-7} (\text{D}); K_3 = 7.14 \times 10^{-13} (\text{D})^2$
Watson (1993)	CHCl <sub>3</sub> BDCM BDCM DBCM DBCM CHBr <sub>3</sub>	μg/l	$0.0064(\text{TOC})^{0.329}(\text{UV})^{0.874}(\text{Br} + 0.01)^{0.404}(\text{pH})^{1.161}(\text{D})^{0.561}(\text{t})^{0.269}(\text{T})^{1.018}$ $0.0098(\text{Br})^{0.181}(\text{pH})^{2.55}(\text{D})^{0.497}(\text{t})^{0.256}(\text{T})^{0.519}$ (for D/Br < 75) $1.325(\text{TOC})^{-0.725}(\text{Br})^{0.794}(\text{D})^{0.632}(\text{t})^{0.204}(\text{T})^{1.441}$ (for D/Br > 75) $14.998(\text{TOC})^{-1.665}(\text{Br})^{1.241}(\text{D})^{0.729}(\text{t})^{0.261}(\text{T})^{0.989}$ (for D/Br < 50) $0.028(\text{UV})^{-1.175}(\text{TOC})^{-1.078}(\text{Br})^{1.573}(\text{pH})^{1.956}(\text{D})^{1.072}(\text{t})^{0.2}(\text{T})^{0.596}$ (for D/Br > 50) $6.533(\text{TOC})^{-2.031}(\text{Br})^{1.388}(\text{pH})^{1.603}(\text{D})^{1.057}(\text{t})^{0.136}$
Clark (1998)	TTHM	μg/l	$A \left( \text{Cl}_0 - \frac{\text{Cl}_0(1 - K)}{1 - \text{Ke}^{-ut}} \right)$ where $u = M(1 - K)$ $A = 4.44\text{Cl}_0^{-0.44}\text{TOC}^{0.63}\text{pH}^{-0.29}\text{T}^{0.14}$ $K = 1.38\text{Cl}_0^{-0.48}\text{TOC}^{0.18}\text{pH}^{-0.96}\text{T}^{0.28}$ $M = e^{(-2.46 - 0.19\text{TOC} - 0.14\text{pH} - 0.07\text{T} + 0.01\text{T pH})}$
Gang et al. (2002)	TTHM		$\alpha D \{ 1 - fe^{-k_R t} - (1 - f)e^{-k_S t} \}$

TTHM = total trihalomethanes; CHCl<sub>3</sub> = chloroform; BDCM = bromodichloromethane; DBCM = dibromochloromethane; CHBr<sub>3</sub> = bromoform; UV = UV absorbance at 254 nm (cm<sup>-1</sup>); TOC = total organic carbon (mg/l); T = water temperature (°C); D = chlorine dose (mg/l); f = fraction of the chlorine demand attributed to rapid reactions; Cl<sub>0</sub> = initial residual chlorine (mg/l); α = TTHM yield coefficient; k<sub>R</sub> and k<sub>S</sub> = the first order rate constants for rapid and slow reactions, respectively; Br = bromide ion (mg/l); and t = reaction time (hr).

Disinfection by-products (DBPs) were first reported by Rook (1974) leading the US EPA in 1979 to establish a maximum contaminant level (MCL) regulation for total trihalomethanes (TTHMs), as trihalomethanes are suspected to be carcinogenic (Sadiq and Rodriguez, 2004).

The common practice of sustaining a residual disinfectant level throughout a water distribution system is to inject large quantities of disinfectant at the outlet of the sources water treatment plants (WTPs). Such doses enable sufficient residuals at far- end locations of the network, but will likely result in extremely high disinfectant levels at consumers' taps with short residence times near the WTPs, and excessive DBPs formations at the water network far ends (Amy et al., 1987; Clark, 1998; Boccelli et al., 2003).

A possible way to cope with these deficiencies is to place booster chlorination stations throughout the network. Such boosters design and operation at key network locations will improve the uniformity of the disinfectant residuals spread, and lower DBPs formations. Another benefit from using booster chlorination can come in a contamination event. Detection by sensors and treatment by activating intensified chlorine injection in adjacent boosters can provide enhanced water quality control during contamination event (Parks et al., 2009).

The objective of this study, based on Ohar (2011) and Ohar and Ostfeld (2009, 2010), is to develop a design tool which can address both chlorine and trihalomethanes regulations and can aid in deciding on where and how to inject chlorine to the WDS. An objective function is formulated considering both boosters' operational and construction costs, and the species concentrations as constraints. The optimization model is solved through a genetic algorithm linked with EPANET multi-

species extension (MSX) (Shang et al., 2008) model. An example application demonstrates the model performances through base runs and sensitivity analyses.

## 2. Literature review

The literature review herein is partitioned into three parts: (1) trihalomethanes formation models, (2) booster chlorination optimization, and (3) comparison of this study to previous work.

### 2.1. Trihalomethanes formation models

Since the detection of chloroform in disinfected water by Rook (1974), more than 500 disinfection by-products (DBPs) have been identified (Clark et al., 1996). The formation of trihalomethanes has been shown to be a function of the total organic carbon content (TOC), chlorination dose, pH, temperature, bromide ion concentration, reaction time, and UV-254 absorbance (Amy et al., 1987). In addition THM levels and chlorine consumption in drinking water, originating in temperate environments, are significantly affected by seasonal variations (Singer et al., 1995). Research showed that higher THM concentrations will be observed at increased levels of the above mentioned parameters. This can enlighten, as reaction time is one of the above parameters, the generally higher THM concentrations observed in the extremities of a water distribution system, compared to the finished water at the treatment plants (Amy et al., 1987; Clark, 1998; Boccelli et al., 2003).

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