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EVALUATION OF CHLORINE BOOSTER STATION PLACEMENT FOR WATER SECURITY

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Abstract

Drinking water utilities use booster stations to maintain chlorine residuals throughout water distribution systems. Booster stations could also be used as part of an emergency response plan to minimize health risks in the event of an unintentional or malicious contamination incident. The benefit of booster stations for emergency response depends on several factors, including the reaction between chlorine and an unknown contaminant, the fate and transport of the contaminant in the system, and the time delay between detection and initiation of boosted levels of chlorine. This research takes these aspects into account and proposes a mixed-integer linear programming formulation for optimizing the placement of booster stations for emergency response. A case study is used to explore the ability of optimally placed booster stations to reduce the impact of contamination in water distribution systems.

Methods

This research compares two MILP formulations that place booster stations in a water distribution system to minimize the expected population dosed given an ensemble of contamination scenarios.

- The Neutralization method, described in [1], assumes that chlorine completely and instantaneously inactivates all of the contaminant on contact.
- The Limiting Reagent method, developed as part of this research, assumes instantaneous reaction of the contaminant and chlorine according to a stoichiometric ratio, which defines the mass of chlorine removed per the mass of contaminant rendered harmless by its reaction with chlorine.

Both methods are available in WST [2]. The Neutralization and Limiting Reagent methods approximate the unknown reaction between a contaminant and chlorine, as shown below.

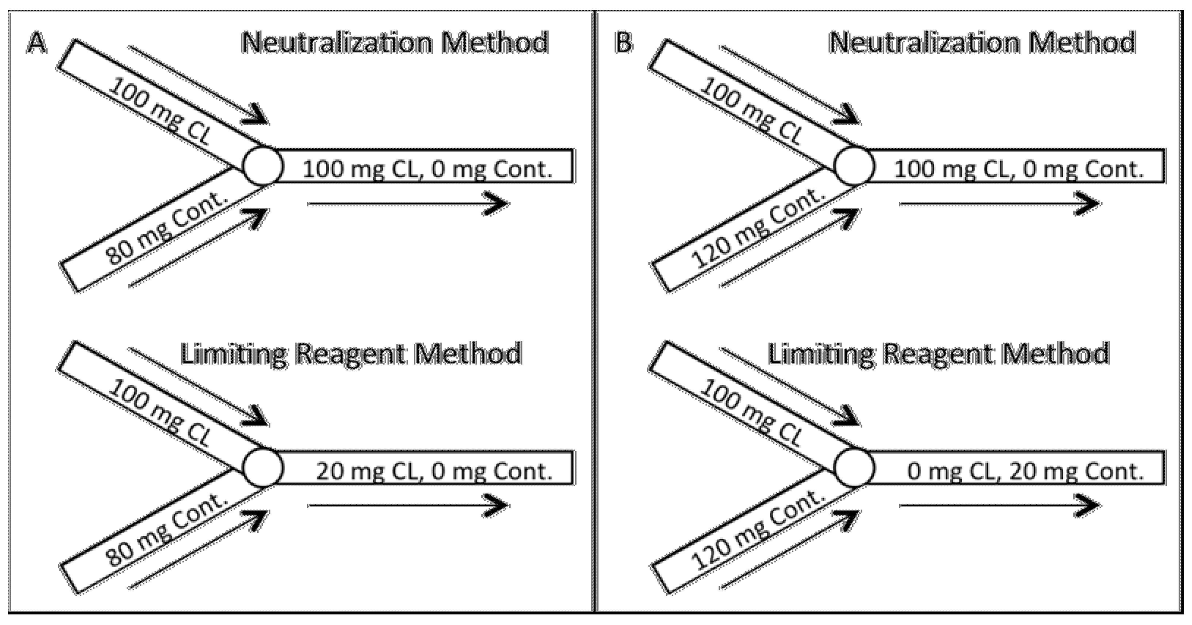

Fig 1. Neutralization and Limiting Reagent method examples. Both examples assume a stoichiometric ratio of 1 mg chlorine (CL) per mg contaminant (Cont)

Limiting Reagent method

Minimize population dosed. Binary variable z is 1 if contaminant dose is above a threshold

$$\min \sum_{s\in S} P(s) \sum_{n\in N} z_{ns} pop_n$$

Linear water quality model maps mass injection to concentration. Contaminant is removed according to a stochiometric ratio

$$s.t. \mathbf{G}\mathbf{c}_s^{con} = \mathbf{D}(\mathbf{m}_s^{con} - \mathbf{r}_s^{con}) \quad \forall s \in S$$

$$\mathbf{G}\mathbf{c}_s^{dis} = \mathbf{D}(\mathbf{m}_s^{dis} - \rho \mathbf{r}_s^{con}) \quad \forall s \in S$$

Chlorine mass injection is included if a booster station is placed at a node, otherwise chlorine mass injection is 0

$$m_{bts}^{dis} = y_b L_{bts} \quad \forall b \in B, t \in T, s \in S$$

$$m_{nts}^{dis} = 0 \quad \forall n \in N \backslash B, t \in T, s \in S$$

Total dose is based on concentration and consumption. Big-M constraint is used to switch the binary variable z to 1 when the contaminant dose is above a threshold

$$d_{ns} = \sum_{t\in T} c_{nst}^{con} v_{nst} \quad \forall n \in N, s \in S$$

$$d_{ns} \le z_{ns}(M - \tau) + \tau \quad \forall n \in N, s \in S$$

Limit the number of booster stations that can be placed

$$\sum_{b\in B} y_b \le B_{max}$$

Binary variables for booster placement and tracking dose above a threshold

$$y_b \in \{0,1\} \quad \forall b \in B$$

$$z_{ns} \in \{0,1\} \quad \forall n \in N, s \in S$$

Concentration and mass is greater than or equal to 0

$$c_{nts}^{con}, c_{nts}^{dis}, r_{nts}^{con} \ge 0 \quad \forall n \in N, t \in T, s \in S$$

Notation

- *S, N, T and B represent the sets of contamination scenarios, network nodes, time steps, and potential booster station locations*
- *z indicates whether the total dose is above a threshold*
- *pop is the population*
- *P(s) is the scenario probability*
- *ρ is the stoichiometric ratio*
- *m, c, and r are the mass of contaminant and chlorine, concentration of contaminant and chlorine, and mass of contaminant that has been removed*
- *G and D map the contaminant and chlorine mass injected to contaminant and chlorine concentration*
- *y is a binary variable that is 1 if a node is selected as a*
- *booster station location and 0 otherwise*
- *L is the chlorine mass injection*
- *v is the volume of water ingested by the population*
- *d is the total dose*
- *M is part of the* Big-M constraint
- *τ is the mass threshold*
- *B_{max} is maximum number of booster stations that can be placed*

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Case Study

Two water distribution network models are used to evaluate the effectiveness of chlorine injection at booster stations as a response to water contamination scenarios.

- Contamination scenarios are simulated from each non-zero demand node.
- Booster stations are activated after contaminant is detection by a network of 5 sensors. Other sensor layouts and delay times can be used.
- Booster stations inject chlorine at a concentration of 4 mg/L (the MCL for chlorine) and continue for 8 hours.
- To calculate population dosed, it is assumed that each person ingested 2 liters of water uniformly throughout the day. Two dosage thresholds are used to evaluate the population dosed: $\tau = 0.0001$ mg (high toxicity) and 0.1 mg (low toxicity).
- Four stoichiometric ratios are used to approximate chlorine reaction with the contaminant: ρ = 0, 1, 10, and 100 mg CL/mg contaminant. When ρ = 0, the Limiting Reagent method is equivalent to the Neutralization method.

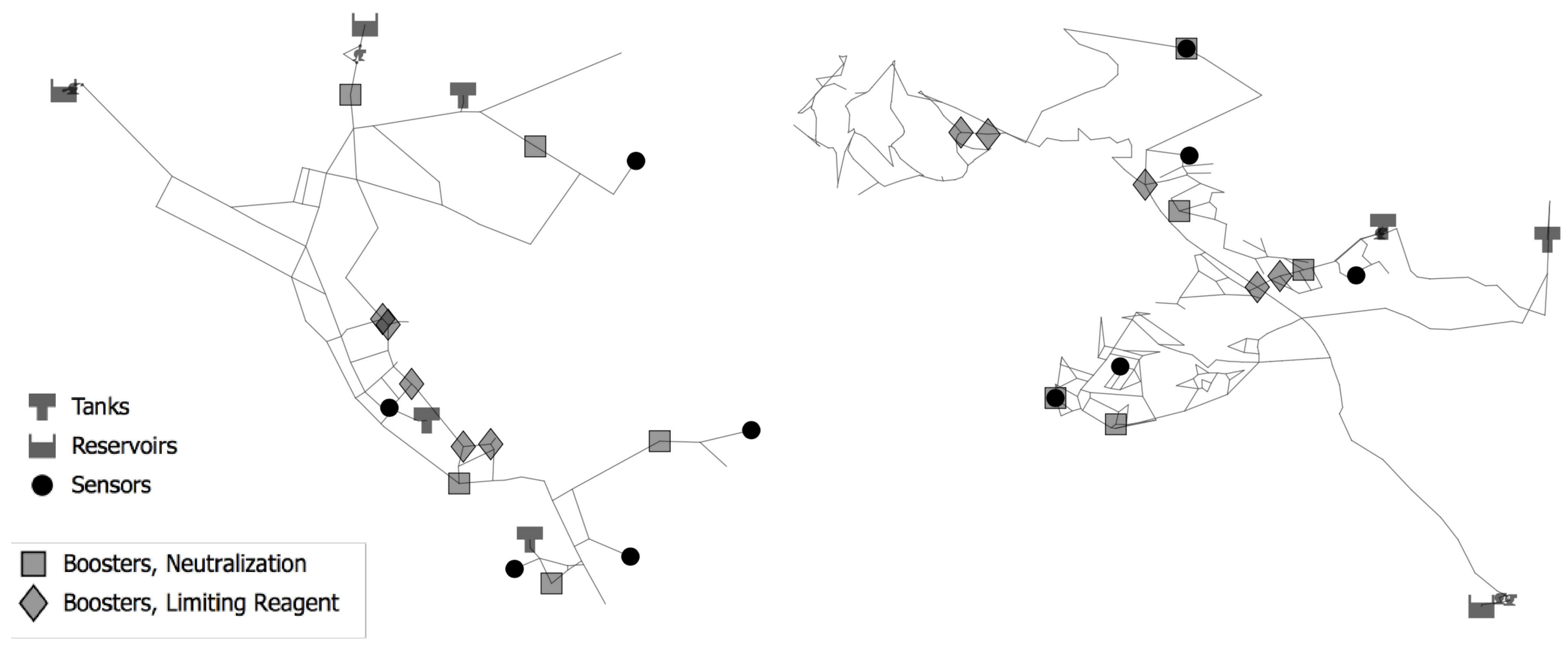

Fig 2. Booster station placements with a high contaminant toxicity using the Neutralization and Limiting Reagent methods.

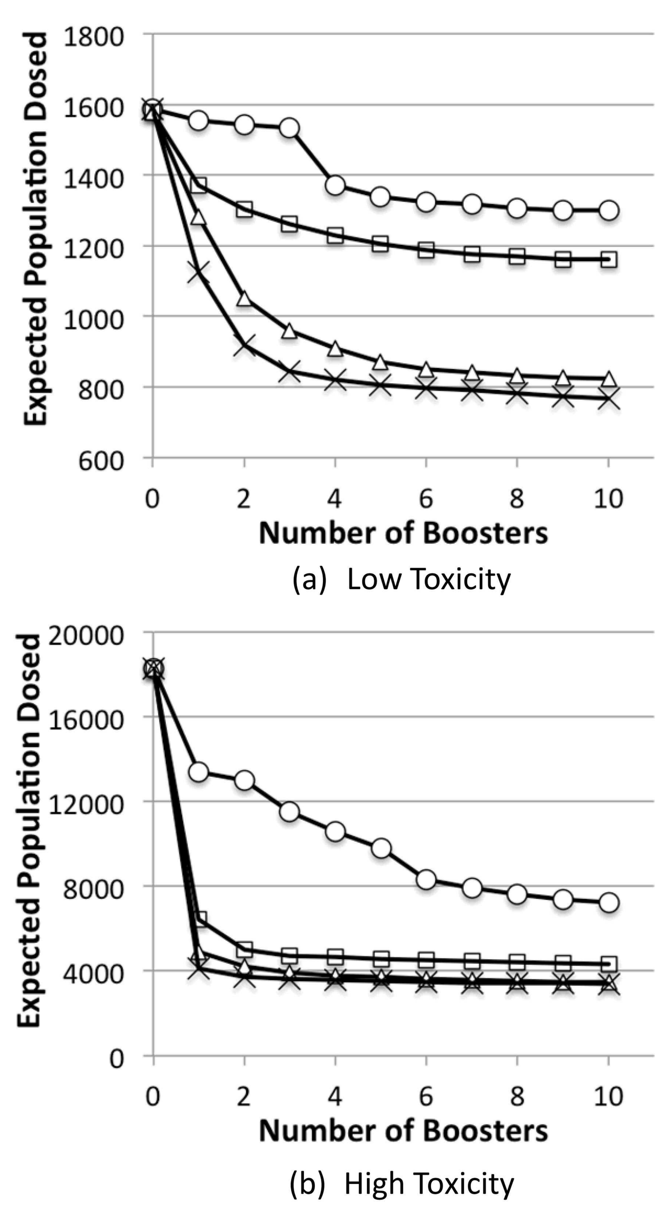

Fig 3. Reduction in expected population dosed on Network 1.

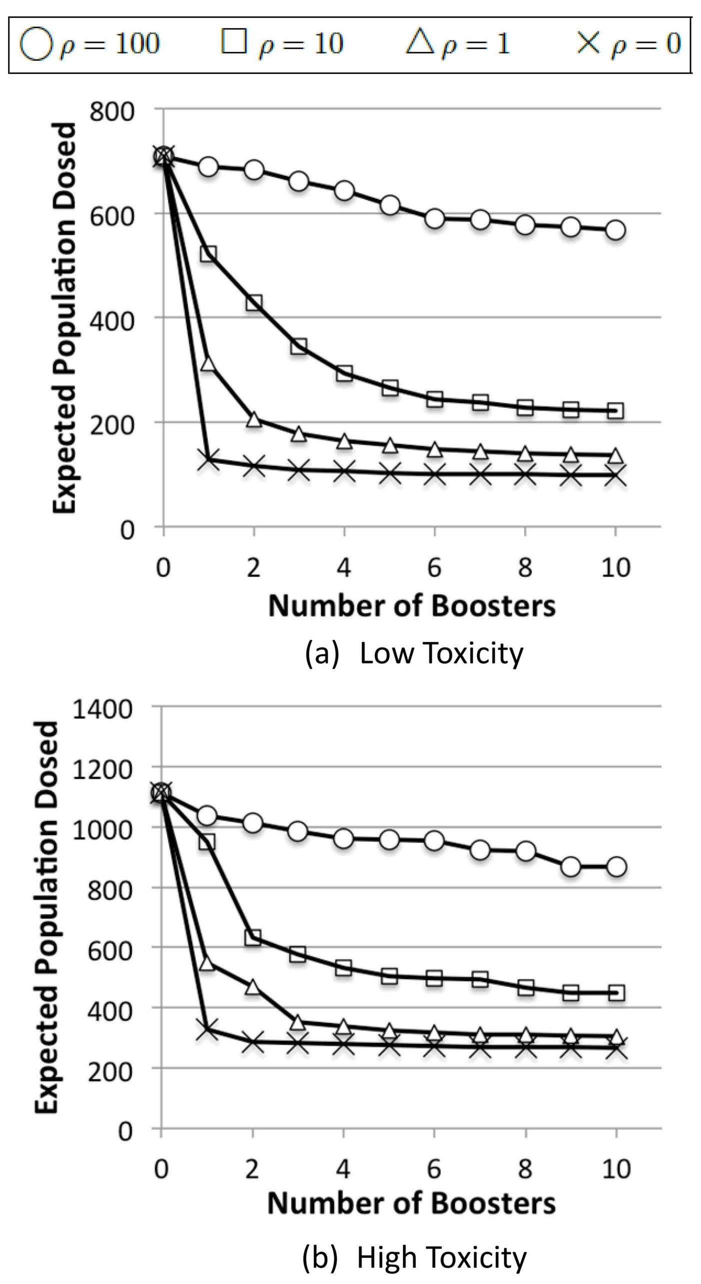

Fig 4. Reduction in expected population dosed on Network 2.

Conclusion

- Given that the contaminant and injection location are likely unknown at the time of detection, fixed booster stations would have to be effective for a wide range of scenarios.
- The effect of contaminant toxicity on the performance of booster stations can be very significant for some networks.
- Further evaluation shows that the optimal booster station placement obtained assuming the worst case scenario (high contaminant toxicity and high chlorine to contaminant stoichiometric ratio) resulted in the lowest overall expected population dosed across all scenarios.

References

[1] Seth et al. Efficient reduction of optimal disinfectant booster station placement formulations for security of large-scale water distribution networks. Engineering Optimization, 49:1281, 1298, 2017.

[2] United States Environmental Protection Agency. (2015). Water Security Toolkit User Manual, U. S. Environmental Protection Agency Technical Report, EPA/600/R-14/338, 187p.