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Residual Chlorine Modeling Sensitivity to Different Decay Models in Optimized and Non-Optimized Water Distribution Networks †

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Abstract: Water distribution networks (WDNs) are designed to comply with hydraulic and water quality parameters for appropriate operation. Methodologies for WDN optimization have been developed to achieve minimum cost designs, adhering to hydraulic conditions. The purpose of this study is to evaluate chlorine decay in 17 networks, comparing optimal and non-optimal designs, with the aim of defining if optimized designs lead to lower chlorine consumption in the networks. Chlorine consumption is modeled with different scenarios, coefficients, and decay models. Results indicate that consumption generally decreases in optimized networks, with few exceptions. Lastly, results of different bulk decay models are similar; however, wall decay results vary significantly depending on the model.

Keywords: chlorine decay; optimization; modeling; WDN; water quality

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1. Introduction

Optimizing WDN design is necessary due to increasing population density. A methodology developed for this goal is optimal power use surface (OPUS), which aims to systematically assess and optimize energy flow within the network [1]. Water quality can differ in optimal and non-optimal designs. Specifically, chlorine modeling is often used in WDN planning and management, given the importance of maintaining adequate free chlorine concentrations across WDNs. Thus, comparing optimal and non-optimal networks can define whether there is a relationship between network topology and chlorine consumption. This document presents three sections, starting with the methodology, where the prototypes of each network and the chlorine decay models are indicated. The results show that 2 of the 17 networks evaluated in the full study. Finally, the conclusions present the main differences between the optimal and non-optimal designs for chlorine concentrations.

2. Methodology

In order to make an objective comparison of the networks and their water quality, the OPUS methodology was used to obtain an optimal prototype, and the genetic algorithm methodology was used to obtain 4 non-optimal prototypes of each study network. The latter were chosen randomly from the last generations to make them appropriate networks where the hydraulics would work according to the regulations, and the prices would be close to the optimal design. These designs were generated with the REDES (Version 1.2) software, and water quality was modeled with EPANET-MSX (Version 2.2, for which chlorine was used as a tracer fluid. Chlorine consumption was modeled with an initial chlorine dose of 2 mg/L and in three different scenarios: wall and bulk decay, only wall decay, and only bulk decay. For this purpose, first-order chlorine decay coefficients reported in the literature for various WDNs were investigated, of which those mainly calibrated for WDNs, including PVC, were used for the analysis; these can be found in Table 1. Considering the fact that several authors have pointed to the limitations of the first-order model, such as, but not limited to, its incapacity to model the fast decay that chlorine exhibits at the start of the WDN [2], the inability to represent the change in decay rate that chlorine exhibits across the distribution network [3], and its general inadequacy to model rechlorination [2], two additional and more robust models were used to predict chlorine decay. The additional decay models were the 2R model [4] for bulk decay and the EXPBIO model [5] for wall decay.

With the aim of comparing the results of the first-order and more robust models, a network whose decay was calibrated with all three models was investigated [6,7]. These network's coefficients, expected to predict similar levels of chlorine consumption, were also used in the modeling. The first-order decay coefficients can be found in Table 1 and include the EXPBIO coefficients, where $A = 1.0$ [dm/h] and $B = 6.2$ [L/mg], and the 2R coefficients are $C_{f0} = 0.03$ [mg Cl − equiv/L], $C_{s0} = 1.85$ [mg Cl − equiv/L], $k_f = 6.74$ [L/mg/day], and $k_s = 0.17$ [L/mg/day].

Table 1. Literature first-order chlorine decay coefficients used in the studio.

k_b [d^{-1}]	k_w [m·d^{-1}]	Source
0.55	0.45	[8]
0.70	0.28	[9]
0.45	1.16	[10]
0.27	0.025	[6,7] [1]

[1] These coefficients were used for the comparison of the first-order, 2R, and EXPBIO models.

3. Results

Results indicate that chlorine consumption varies depending on the cost of the network; as network cost increases, consumption can either increase or decrease depending on the coefficients used, the scenario, and the network being analyzed. Chlorine decay can also behave differently depending on the model used. In addition, with the coefficients used, wall decay dominates total chlorine decay in the networks, accounting for 64% to 98% of chlorine consumption.

3.1. First-Order Model Chlorine Consumption

For the first-order model, the scenario of only bulk decay was the most conclusive. In this scenario, chlorine consumption increased with network cost, making the optimized designs the ones with higher chlorine concentrations, regardless of coefficient used or network analyzed. Average chlorine consumption increased up to 40% in the most expensive designs, taking the optimized network consumption as the base value. Wall decay results were varied; generally, optimized networks presented the least consumption, with average consumption increasing to a maximum of 20% as a network's cost increased. However, when analyzing networks with high water ages, using the largest wall decay coefficient of the study (k_w = 1.16 m/d), consumption would start to decrease as the cost of the networks increased.

Lastly, overall chlorine consumption behaved similar to wall consumption. Optimized designs generally presented lesser consumption when compared to higher cost designs. However, although the optimized design presented the least consumption, there were cases where consumption would not necessarily increase with network cost; such results can be seen in Figure 1 for the coefficients represented by the yellow series. Nevertheless, in certain networks, the optimized design could present higher consumption than higher const designs.

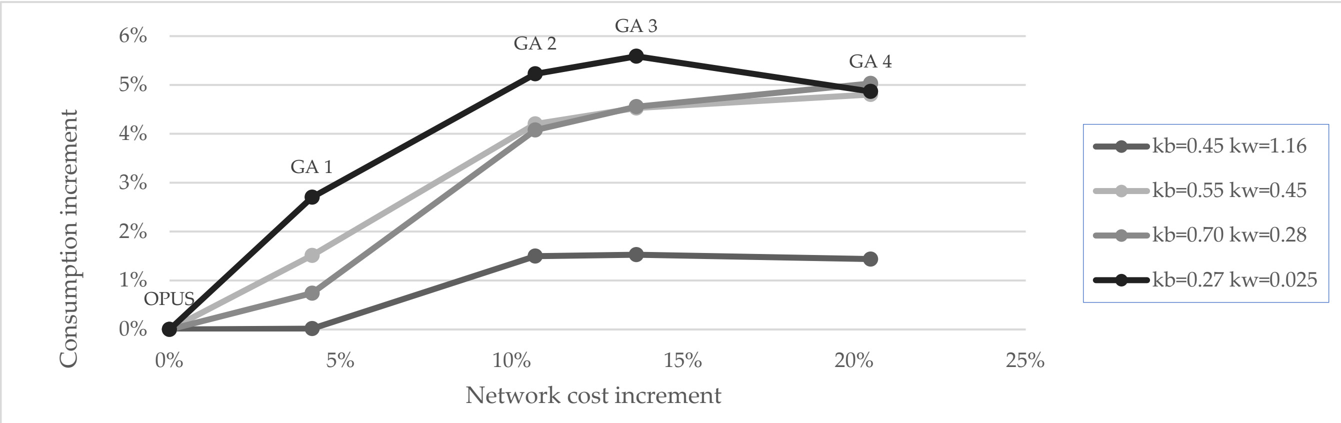

Figure 1. Average chlorine consumption increments vs. network cost; Fossolo network per set of coefficients.

3.2. Model Results Comparison

For bulk decay, the results of the first-order model and the 2R model were similar. Chlorine concentration predicted by both models varied to a maximum of 0.3 mg/L in an individual node, and, typically, variations between both models in individual nodes were between 0.01 mg/L and 0.05 mg/L, thus making these variations not significant. Average concentrations were similar, as well, between both models, with the highest difference being 0.05 mg/L. On the other hand, wall decay results were vastly different; the EXPBIO model did not predict chlorine consumption in all but one of the networks analyzed. Since the first-order model's main source of decay was wall consumption, differences in individual node concentration reached a maximum of 1.74 mg/L between both models, and average network concentration differences were up to 0.55 mg/L. Considering the above, overall decay differed significantly between the first-order model (Figure 2a) and the more robust models implemented (Figure 2b).

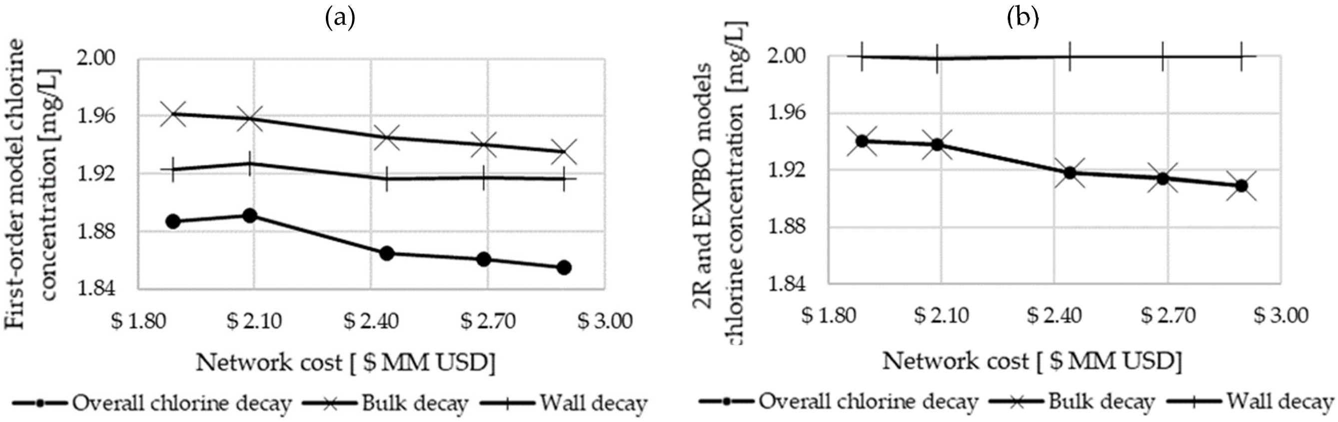

Figure 2. Pescara average chlorine concentration vs. network for first-order model (**a**) and the more robust models (**b**).

4. Conclusions

In this study, chlorine decay was modeled in 17 networks, with different decay models and scenarios. Networks were modeled with five different designs, one corresponding to an optimized design, and four non-optimal configurations. Results were then compared on every network individually to evaluate whether, using equivalent coefficients, different models estimated similar levels of decay not only on different networks but also on different configurations of the same network. Bulk chlorine consumption was similar when predicted by the 2R and first-order models; however, this was on networks that did not consider rechlorination. Otherwise, wall decay varied significantly depending on the model used, regardless of the network topology or cost. Lastly, results indicate that, in most cases, optimized networks lead to lower chlorine consumption, although this is not guaranteed in all networks, and it can vary depending on the magnitude of chlorine wall consumption.

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