

# Assessing the impact of dissolved organic carbon changes on disinfectant stability in a distribution system

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**Abstract** Maintaining disinfectant residuals throughout the entire water distribution system is considered an efficient strategy to guarantee the biological stability of drinking water as it flows from the plant to the customer tap. Dosed at the plant, the disinfectant disappears in the distribution system due to reactions with both water and pipe constituents. Among them, certain fractions of the organic matter content are directly responsible for the loss of disinfectant. This study presents an example of the impact of the organic matter UV absorbance on free chlorine decay for a surface water. In addition, this study illustrates the use of laboratory experiments together with a water quality model as a valuable tool to predict the impact of organic carbon concentration changes on chlorine residuals in interconnected distribution systems.

**Keywords** Chlorine; disinfection; dissolved organic carbon; distribution systems; organic matter; water quality models

## Introduction

Many drinking water utilities are currently considering the implementation of treatment changes aimed at minimizing the amount of the organic carbon entering the distribution system. The reduction of the organic content should result in an improvement of the microbiological quality of the distribution system due to two effects: first, it reduces the amount of organic substrate susceptible to support biological growth; and secondly, it results in higher disinfectant residuals due to the elimination of chlorine-consuming compounds. In addition, the removal of natural organic content before final disinfection prevents the formation of undesirable disinfection by-products.

Although the impact of organic matter on disinfectant stability in a given water can be characterized in laboratory experiments, little is known about the response of full scale distribution systems to treatment changes affecting organic concentration and structure. Understanding and being able to predict this response is specially important in the operation of interconnected distribution systems fed by supplies of different organic content. This is the case of a distribution system of the Southern Suburbs of Paris, which is supplied by three water treatment plants that distribute water with different dissolved organic carbon (DOC) concentrations. Since 1998, one of these treatment plants removes the DOC with a powdered activated carbon ultrafiltration system (PAC/UF), while the other two rely on more conventional polishing treatment schemes consisting of ozone and biofiltration through activated carbon.

Both extensive sampling and water quality modeling were conducted to fully characterize the impact of the PAC/UF process on the water quality of its distribution system (Campos *et al.*, 2000b; Najm *et al.*, 2000). The reduction of DOC concentrations down to less than 1 mg/L (UV/DOC less than 1 L/mg m) resulted in a better disinfectant coverage of the distribution system due to the reduction of the chlorine consumption. Based on these observations, the chlorine doses at the plant were gradually reduced in half, from 0.3 to 0.15 mg/L, while achieving measurable disinfectant residuals (>0.05 mg/L) at distant points in the distribution system. These encouraging results led the other two water treatment plants

to consider the optimization of their organic carbon removal. However, given the hydraulic complexity of the interconnected system and the different level of organic carbon removal, the impact of changes in the organic content of these two supplies on the disinfectant stability at all points of the distribution system was unknown.

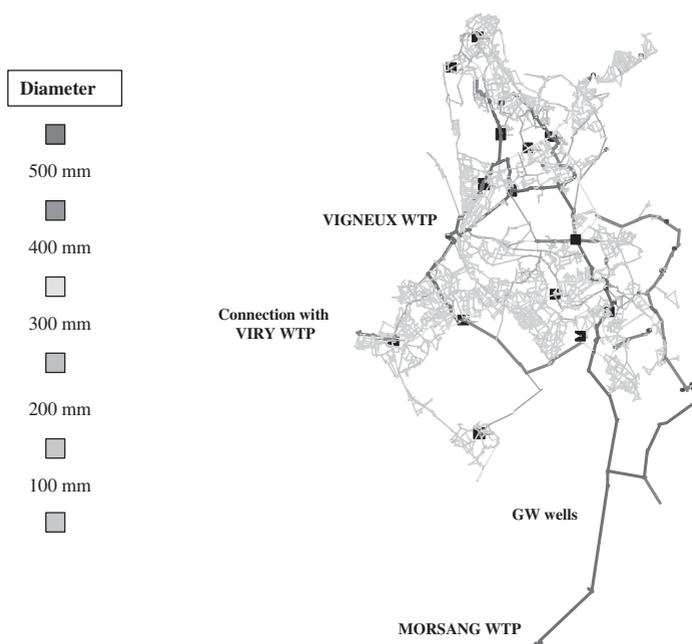
The objective of this study was to assess the impact of changes in DOC concentration on the chlorine stability in an interconnected distribution system by using water quality models that use chlorine decay constants previously determined in the laboratory. The impact of the UV or DOC concentration on the first-order decay constant obtained in batch experiments is also discussed.

## Methods

### Distribution system

The sector of the distribution system considered in this study is located in the right bank of the Seine River upstream from Paris (southern suburbs). It represents a sub-network integrated in a larger system, operated by ONDEO Services (Lyonnaise des Eaux, France). The distribution system contains roughly 105 miles of piping, with diameters ranging from 40–800 mm. Unlined cast iron, cement-lined ductile iron and high density polyethylene are the materials found in a proportion of 29, 68 and 3%, respectively.

The whole distribution system (left and right bank) is primarily supplied by three water treatment plants (Vigneux, Morsang and Viry), with maximum capacities of 55,000, 220,000, and 120,000 m<sup>3</sup>/day, respectively. Additional supplies in the right bank include some groundwater pumping stations (Champigny) using direct chlorination (20,000 m<sup>3</sup>/day). During the hydraulic calibration period, the right bank was supplied by 25,000 m<sup>3</sup>/day from Vigneux, 30,000 m<sup>3</sup>/day from Morsang, and 2,300 m<sup>3</sup>/day from the connection to Viry. The extent and significance of these contributions varied with time and season. A series of reservoirs (Belle Etoile), installed east of the Vigneux plant, receive water from the Morsang plant during the night in order to supply the northern part of the system during the day in addition to the Vigneux contribution.



**Figure 1** Section of the distribution system in the Southern Paris Suburbs

Regarding the water quality of the system, recurrent taste and odors (musty and earthy) complaints had been reported upstream from the Belle Etoile reservoir, a zone under the influence of the Morsang water treatment plant. These odors were always associated with a lack of disinfectant residual.

#### Chlorine decay experiments

Batch kinetic tests were conducted to evaluate the chlorine decay kinetics of the effluent water from each water treatment plant and groundwater wells. The chlorine dose was 0.5 mg/L and the temperature 20°C. A first-order kinetic curve was fitted to the experimental data normalized to the residual concentration after 60 minutes in order to subtract the fraction of chlorine consumed in the chlorination basin. The waters considered in these tests had DOC concentrations ranging from 2.3 to 0.8 mg/L, corresponding to various degrees of organic matter removal from the same source water (Seine River).

#### Water quality model

A water quality model was coupled with a hydraulic model (Piccolo, SAFEGE, France) of the entire interconnected distribution system. The hydraulic model of the right bank consisted of 5781 nodes and 7483 arcs. The model was verified with hydraulic grade line data collected in the control reservoirs every 30 minutes for six monthly campaigns (May, June, July and September in 1998; and July and August in 1999). The verified model was then used to estimate the fraction of water contributed from each source, as well as the flow-averaged residence time from each source under both steady-state and dynamic conditions.

Based on the hydraulic model, a water quality module was used to describe the evolution of selected water quality parameters (chlorine and organic carbon) through the distribution system. While organic carbon was considered a conservative parameter, chlorine decay kinetics was mathematically described with a zero and first-order reaction with respect to the pipe wall and water demand, respectively (Vasconcelos *et al.*, 1997; Powell *et al.*, 2000b). In this study, chlorine consumption due to reactions with the pipe wall was estimated by comparing the overall consumption of chlorine to the bulk water consumption using field data from a single pipe which was long enough to provide water residence times higher than 6 hours. The chlorine consumption rate by the wall was observed to be negligible as compared to that from bulk water, consistent with the fact that this distribution system is not exposed to corrosive conditions. As proven by other authors, corrosion can be the major cause for chlorine decay (Ki  n   *et al.*, 1998).

Monthly samples were collected from ten sampling points in the distribution system, as well as from the effluent of all water treatment plants, in order to verify the model simulations for DOC and chlorine concentrations. Sampling times were consistent between monthly campaigns in order to compare water quality parameters corresponding to similar hydraulic conditions. The results of the model verification were presented elsewhere (Campos *et al.*, 2000a, 2000b).

#### Results

Figure 2 presents the experimental data from the free chlorine decay tests. The corresponding kinetic constants (after 60 minutes) were compared as a function of DOC and ultraviolet (UV) absorbance, temperature and initial disinfectant concentration. Selected results of these experiments are presented in Figure 2. In this particular water, UV absorbance values were very close to the corresponding DOC concentrations (UV/DOC of 1 L/mg m), so the UV values can be read as DOC as well. It is important to highlight that these waters were effluents from the treatment plants, so they had been treated by coagulation and carbon

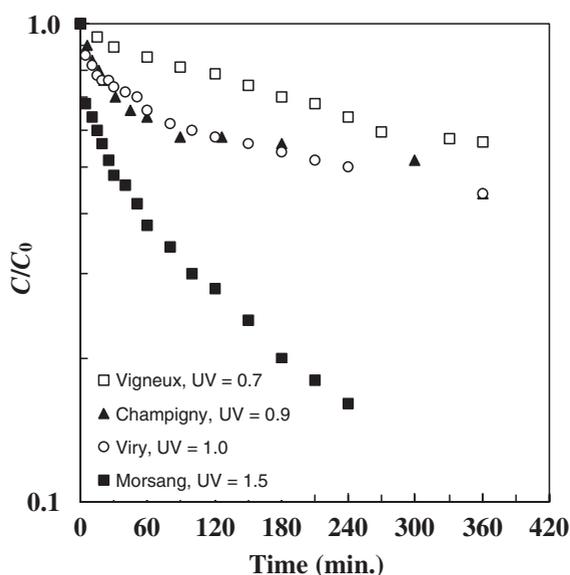
adsorption to a different degree. The UV/DOC ratio of the source water for these plants was around 2 L/mg m.

A reduction of UV from 1.6 to 0.8  $\text{m}^{-1}$  resulted in a reduction of the chlorine decay constant by a factor of five. These results illustrate the benefit of targeting UV reduction for disinfectant stability. The impact of organic matter (measured as DOC) on chlorine decay kinetics has been previously reported (Jadas-Hécart *et al.*, 1992; Powell *et al.*, 2000a). This reduction in the bulk water decay constant has tremendous implications on the water quality of the distant sites in the distribution system. Thus, reducing the decay constant by a factor of five, from 0.005 to 0.001 translates into disinfectant residuals that last five times longer in the distribution system, as illustrated in Figure 3. In this respect, while a residual of 0.3 mg/L free chlorine in a water with a UV of 1.6  $\text{m}^{-1}$  was not able to last for longer than 6 hours ( $>0.05$  mg/L), the same residual can last up to 35 hours in the distribution system.

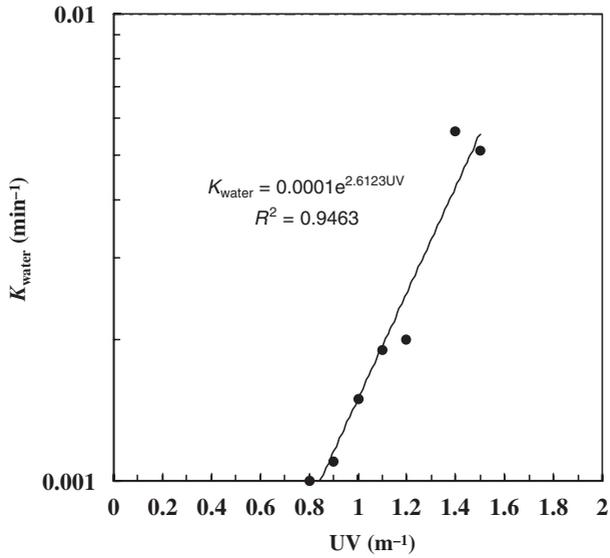
According to the results from the routine monitoring of this distribution system, chlorine residuals higher than 0.1 mg/L should result in heterothrophic plate counts (HPC) below 100 CFU/mL. In addition, this chlorine level should also minimize the chlorine-type taste and odors, so a residual of 0.1 mg/L was targeted for all points in the distribution system. Furthermore, these low levels of organic content together with reduced chlorine doses (0.15 mg/L) should result in total trihalomethanes (THMs) concentration lower than 20  $\mu\text{g/L}$ .

Using the kinetic constants obtained in the laboratory, the water quality model was used to simulate the chlorine concentration throughout the distribution system under various organic matter removal scenarios. The use of the water quality model allowed us to determine both the borders or zones of influence and how they evolve versus time.

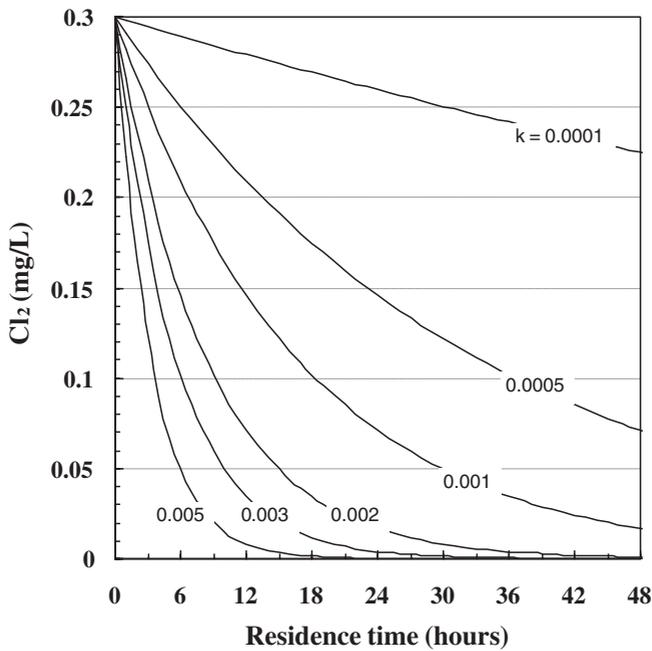
Figure 5 shows the simulated chlorine residuals corresponding to the existing values of UV (or DOC in this case), from 1.6 and 0.8  $\text{m}^{-1}$ , and for chlorine residuals at both the plants and reservoirs of 0.3 mg/L. In this situation, the northern part of the distribution system was found to be primarily supplied by the Morsang plant (higher UV values), and therefore explained the low chlorine residuals usually observed. Similarly, the border zone between the Vigneux plant and the Belle Etoile reservoirs presented very long water residence times



**Figure 2** Chlorine decay kinetics of Seine River water treated to various extent



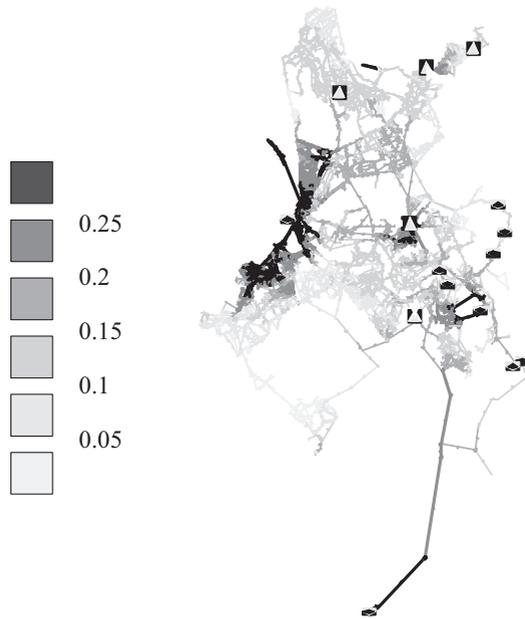
**Figure 3** Chlorine decay constant as a function of UV absorbance



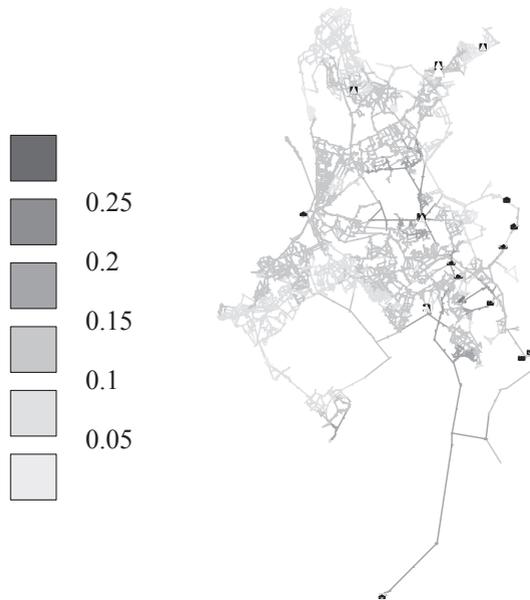
**Figure 4** Impact of the decay constant from bulk water on the disinfectant residuals

(30 hours), which is consistent with the musty and earthy odors complaints reported in this area. Both DOC and chlorine residuals measured in this area were in agreement with our model simulations, which validated our approach.

Figure 6 shows the simulated chlorine residuals that would result from lowering both the organic content to UV values of  $0.8 \text{ m}^{-1}$  and the chlorine residual at the plants ( $0.15 \text{ mg/L}$ ). According to these results, the entire system should present chlorine residuals from  $0.1\text{--}0.15 \text{ mg/L}$ , with the exception of isolated sections in the northern part ( $<1\%$  of water consumed).



**Figure 5** Free chlorine residual corresponding to the existing DOC concentrations (from 0.8 mg/L up to 1.6 mg/L) and 0.3 mg/L chlorine leaving the plants



**Figure 6** Free chlorine residual corresponding to the target DOC concentration (0.8 mg/L all over) and a chlorine residual of 0.15 mg/L leaving the plants

### Conclusions

The results of this study showed a significant impact of the reduction of organic content of the distributed water on chlorine disappearance. Thus, a reduction of UV absorbance from 1.6 to 0.8  $m^{-1}$  resulted in a reduction of the chlorine decay constant by a factor of five, confirming the interest of targeting UV reduction for disinfectant stability. This reduction in

the chlorine decay constant would allow the reduction of the chlorine doses at both the plants and the prechlorination stations down to 0.15 mg/L while maintaining the target residuals between 0.05 and 0.1 mg/L throughout the entire interconnected network.

This study also illustrated the use of a water quality model in predicting the impact of DOC changes on chlorine residuals in an interconnected water distribution system supplied by sources of different organic content. The approach included:

- hydraulic model development;
- model verification
- laboratory experiments to determine decay constants;
- model simulations;
- verification with field data;
- predictions for various treatment scenarios.

This paper presented selected results, specially focusing on chlorine residuals under different water treatment scenarios. The use of water quality models was shown to be a valuable tool in assisting the involved water utilities to decide on both the treatment level and the location of the boosting chlorination stations.

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