Water Science and Technology: Water Supply Vol 2 No 3 pp 205–211 © IWA Publishing 2002

A risk assessment case study in the suburbs of Paris: balancing health effects of *Cryptosporidium parvum* and bromate

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Abstract To meet newly proposed bromate standards, ozone doses should be decreased, thus also decreasing the risk of renal cell cancer, but the risk of infection with *Cryptosporidium parvum* will increase at the same time. The present study was designed to evaluate and balance these two risks, using a probabilistic risk assessment, which involves calculating the disease burden, expressed in the number of disability adjusted life-years (DALY) as developed by Havelaar *et al*. In the case of Neuilly-sur-Marne ozone contactors, four ozone doses were studied at 5°C and at 22°C. Results showed a sharp decrease of the disease burden with the application of ozone, and then a slight increase as the ozone dose was increased. Minimal DALYs were obtained with ozone doses of 1.5 mg/L at 22°C and 2.5 mg/L at 5°C. Nevertheless, these two ozone doses do not comply with the 10 µg/L bromate standard, as an average of 12 at 5°C and 11 at 22°C are produced.

Keywords Bromate; *Cryptosporidium parvum*; DALY; ozone; risk assessment

Introduction

Water treatment professionals are faced with the challenge of balancing disinfection by-products with microbiological risks, such as *Cryptosporidium parvum*. This situation is becoming an increasing concern because of the new bromate maximum concentration limit for the Neuilly surface water treatment plant, which delivers water to 1,260,000 consumers of Syndicat des Eaux d'Ile de France (SEDIF). Treatment steps are as follows: coagulation, flocculation, settling, rapid sand filtration, ozonation, biological filtration through granular activated carbon, and chlorination. Ozonation is the only step responsible for bromate formation. There is a seasonal fluctuation caused in the summer by higher temperatures, bromide concentrations and applied ozone doses. Current practice for ozonation allows good disinfection but does not always meet the coming standard of 10 µg/L for bromate (EU.C, 1998). Intensive studies have been carried out to minimise bromate formation, but the easiest way to meet this new standard is obviously to decrease ozone doses.

Before deciding on whether or not to make any changes in treatment practices, it was decided to study the impact of different ozone doses, and compare the positive and negative heath effects of drinking water disinfection. In fact, if the ozone dose is decreased, the risk of renal cell cancer arising from the consumption of bromate will decrease, but the risk of infection from *C. parvum* will increase at the same time. The study was designed to evaluate and balance these two risks, using the approach developed earlier by Havelaar *et al*. (2000). The study uses a probabilistic risk assessment, which consists of calculating the net health benefit, expressed as the number of disability adjusted life-years (DALY).

Material and methods

Disability adjusted life-years (DALY)

The DALY concept was introduced by Murray (1994). DALYs integrate number of life-years lost (LYL) due to mortality and number of years lived with a disability (YLD), weighed with a factor between 0 and 1 for the severity of the disability. Thus:

$$DALY = LYL + YLD$$

The DALY approach was used to assess different treatment scenarios in the Neuilly treatment plant. Data from the clinical, epidemiological, and toxicological literature on morbidity and mortality were used to calculate DALYs. This study takes into account: *C. parvum*, leading to diarrhoea disease in the immuno-competent and the AIDS population; and bromate, leading to renal cancer.

Methodology

Teunis and Havelaar (1999) and Havelaar *et al*. (2000) conducted a study evaluating the applicability of DALYs as a measure to compare positive and negative health effects of drinking water disinfection. The authors have adapted Havelaar's model to a drinking water supply in France: the Neuilly-sur-Marne treatment plant.

All the parameters characterising the treatment plant were redefined from available data or from the authors' studies. When possible, the authors identified variability and uncertainty for model parameters. Possible values of each variable were determined by probability distributions. The principal modified parameters are:

- concentration of *C. parvum* in raw water (Marne River);
- decimal reduction of *C. parvum* by the Neuilly-sur-Marne pre-treatment step;
- ozonation (ozone contactors, model of disinfection, model of formation of bromate);
- population size and structure.

C. parvum in the raw water

The Marne River drains a highly developed watershed that includes agricultural, industrial and municipal regions. As a consequence the river has a very variable water quality. Regular campaigns of analyses (Rouquet *et al*., 2000) from January 1999 to August 2000 permitted the fitting of two log-normal distribution laws: one for winter and one for summer.

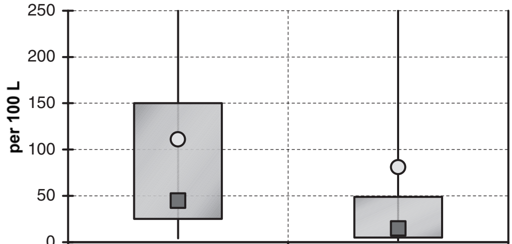
Figure 1 shows there is less *C. parvum* in the Marne River in summer than in winter. The authors have used box plots graphics: the box represent the range between the 25th and 75th percentile, and the whiskers represent the range between the 1st and the 99th percentile.

Decimal reduction of *C. parvum* by pre-treatment

Decimal reduction of *C. parvum* were estimated from decimal reduction of sulfite reducing clostridia (SRC), as indicated earlier by Payment and Franco (1993). The average reduction of *C. parvum* as well as SRC is 2.5 log units.

Ozonation step

The step of ozonation is composed of five ozone tanks with two different reactor designs. Each tank is divided into three compartments: one for the injection of ozone, and two for the contact with the ozone. Tracer tests have been performed on the ozone contactors (Peltier *et al*., 2001). This study permitted the definition of residence time distribution in ozone contactor by an inverse Gaussian distribution.



	Winter	Summer
25P	25	5
99P	563	1 075
1P	4	2
75P	150	49
■ Median	45	15
○ Mean	111	81

Figure 1 *C. parvum* concentration in Marne River in winter and summer (from Rouquet *et al.*, 2000)

Disinfection model

The authors chose the Incomplete Gamma Hom (IgH) with coefficients of Finch and Gyürek (1997). The IgH model can describe deviations from exponential die-off kinetics as well as account for first-order disinfectant decay.

$$\log\left(\frac{N}{N_0}\right) = \frac{-mkC_0^n}{(nk')^m}\gamma(m,nk'\,t)\ m > 0,\ nkk'\,t \geq 0$$

where N is the number of infectious oocysts at contact time t; N_0 is the initial number of infectious oocyts prior to ozonation; k is the inactivation rate constant; m and n are empirical constants; C_0 is the measured ozone residual at time zero (mg/L); k' is the first-order ozone disappearance rate constant (min^{-1}); and $\gamma(m,nk't)$ is the incomplete gamma function. At 22°C, $k = 0.83$, $m = 0.63$ and $n = 0.66$. At 5°C, $k = 0.4$, $m = 0.8$ and $n = 0.8$.

Bromate model

To understand the formation of bromate at the Neuilly-sur-Marne treatment plant, several experimental designs were realised on a pilot unit, allowing the construction of a model for the Neuilly plant (Dilé *et al.*, 2000; Galey *et al.*, 2001). Bromate formation reads:

$$[\text{BrO}_3] = \frac{1.6\times\left[\text{Br}_0^-\right]}{100}\times\begin{pmatrix}\alpha + \beta_1\,\text{O}_3 + \beta_2\text{pH} + \beta_3\text{temp} + \beta_4\ \text{time} \\ +(\beta_5\ \text{O}_3\times\text{pH}) + (\beta_6\ \text{O}_3\times\text{temp}) + (\beta_7\ \text{O}_3\times\text{time}) \\ +(\beta_8\ \text{pH}\times\text{Time})\end{pmatrix}^2$$

where Br is the concentration of bromide in µg/L, temp is the temperature in °C, "time" is the contact time in ozone contactors in minutes, and O_3 is the applied ozone dose in mg/L.

Population

The study was done on the population supplied with drinking water produced at the Neuilly-sur-Marne treatment plant. It concerns 37 municipalities, which constitute a total population of 1,260,000 inhabitants. Individuals do not react in the same way, according to their immune status. In the case of *C. parvum* ingestion, the probability of infection is different for the immuno-competent and for the immuno-compromised (AIDS patients, old persons, etc). For the Ile-de-France population in 1999, the Observatoire Régional de Santé d'Ile-de-France recorded 22,691 AIDS cases for a total population of 10,952,000 inhabitants. The proportion of persons affected by AIDS is thus 2.07×10^{-3}. This value was retained as an evaluation of the immuno-compromised ratio.

Simulation

Monte Carlo simulations were realised on @Risk of Palisade Corporation and add-in to Microsoft Excel. Two models were created, to distinguish the results obtained at two different water temperatures, 22°C and for 5°C. Table 1 gives the different scenarios tested at each temperature. The objectives of simulations were to try all the possible combinations of variables of entry to simulate all possible exits. For every model, a simulation of 10,000 repetitions was realised. These 10,000 repetitions are the results for each output parameter.

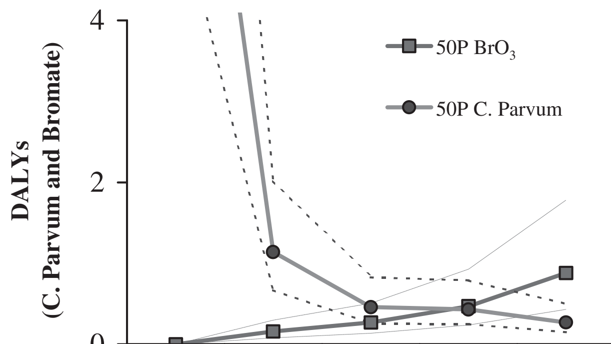
Results and discussion

The results are plotted in the following figures, which present the descriptive statistics of the earlier mentioned 10,000 iterations.

Figure 2 permits the comparison of the evolution of the disease burden due to bromate or *C. parvum*. The disease burden for bromate appears to be lower than that for *C. parvum*, for ozone doses inferior or equal to 3 mg/L. For an ozone dose of 4 mg/L, the bromate disease burden appears to be higher than that of *C. parvum*. However, one must note that the

Table 1 Scenarios used in the study

Simulation	Temperature (°C)	Ozone dose (mg/L)	Outlet residual (mg/L)	Bromide (μg/L)
Winter	5	1.5	0.6	30
	5	2.5	1.2	30
	5	3	1.4	30
	5	4	1.9	30
Summer	22	1	0.2	45
	22	1.5	0.4	45
	22	2	0.55	45
	22	3	0.85	45



	O_3 =0	O_3=1.5	O_3=2.5	O_3=3	O_3=4
50P BrO_3	0	0,16	0,27	0,47	0,88
25P BrO_3	0	0,08	0,14	0,24	0,43
75P BrO_3	0	0,3	0,51	0,93	1,78
50P C. Parvum	9,53	1,14	0,46	0,43	0,27
25P C. Parvum	5,61	0,67	0,26	0,25	0,15
75P C. Parvum	16,67	2,02	0,83	0,79	0,5

Figure 2 Disease burden of *C. parvum* and bromate at 5°C and different ozone doses. Solid lines are median and dashed lines are 25th and 75th percentiles

bromate disease burden is always much lower than *C. parvum* disease burden without ozonation.

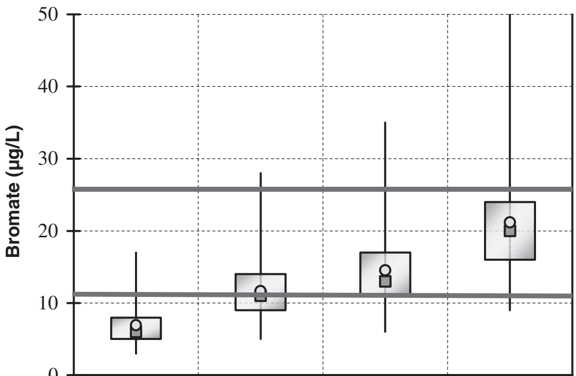
One must note that even without ozonation, the DALYs appear to be much lower than coronary artery disease (21,000 DALYs) and anxiety disorder (18,000 DALYs) for the same population size (Meles, 2000). For a rare disease such as tuberculosis, the ratio is still 1:6 when compared with the DALYs without ozonation.

Bromate concentration formed in the different scenarios are reported in Figure 3. When the ozone dose is increased, bromate concentration in drinking water also is increased, with a nearly linear relationship according to the conditions simulated here. It must be pointed out that with an ozone dose of 1.5 mg/L, the intermediate standards of 25 μg/L and final standard of 10 μg/L could be met at 5°C, whereas at 22°C the new standards could be met with ozone doses ≤ 1 mg/L (results not shown).

Figure 4 presents the total disease burden, for *C. parvum* and bromate, at 5°C. This other presentation allows direct comparison of the net health benefit of the scenarios under consideration. Simulations at 5°C (Figure 4) and 22°C (results not presented here) both show that ozonation is always preferable to absence of ozonation. The ratio is 1:10 with different medians. One can observe that the ozone significantly decreases the disease burden but if the ozone dose is too high, i.e. > to 3 mg/L, the disease burden increases as a consequence of higher bromate concentration, leading to a greater risk of renal cell cancer.

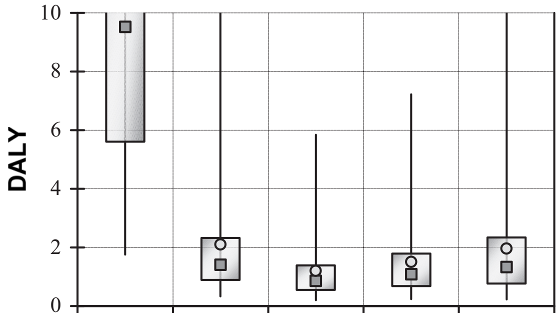
Optimum ozone doses at 5°C and 22°C are 2.5 mg/L and 1.5 mg/L, respectively. These doses are currently applied on the treament plant under consideration, the impact of temperature on *C. parvum* inactivation being of utmost importance. It can be observed that the disease burden is fairly similar under optimum ozone doses at both temperatures.

Figure 5 and 6 allows more appreciation of the variability of results. At 22°C, in 62% of cases, an ozone dose of 1.5 mg/L appears to be optimal (Figure 5). In 25% of cases, the ozone dose has, however, to be higher to minimise the total disease burden, in order to account for high *C. parvum* counts in raw water. At 5°C, similar conclusions can be drawn: in 70% of cases, an ozone dose of 2.5 mg/L seems to be the optimal solution, but for 23% of cases, the ozone dose has to be increased (Figure 6).



	O_3=1.5	O_3=2.5	O_3=3	O_3=4
25P	5	9	11	16
99P	17	28	35	50
1P	3	5	6	9
75P	8	14	17	24
■ Median	6	11	13	20
○ Mean	6.9	11.66	14.52	21.16

Figure 3 Bromate ions formed at different ozone doses (T = 5°C)



	O_3=0	O_3=1.5	O_3=2.5	O_3=3	O_3=4
25th Q	6	1	1	1	1
99th Q	94	12	6	7	10
1th Q	2	0	0	0	0
75th Q	17	2	1	2	2
Median	10	1	1	1	1
Mean	15	2	1	2	2

Figure 4 Total disease burden of *C. parvum* and bromate at 5°C and different ozone doses

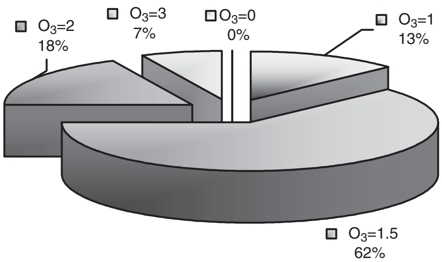


Figure 5 Percentage of cases for which an ozone dose gives the minimum total disease burden at 22°C

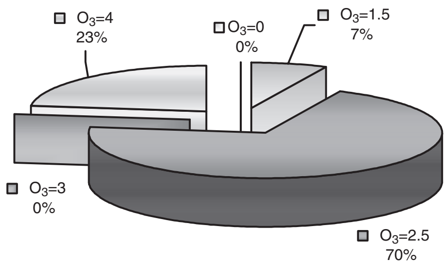


Figure 6 Percentage of cases for which an ozone dose gives the minimum total disease burden at 5°C

Conclusion and perspectives

The European Directive 98/93 sets the maximum bromate concentration levels to 25 µg/L in 2003 and 10 µg/L in 2008. SEDIF surface water treatment plants do not meet these standards, and ozonation practices will have to change. An alternative is to decrease ozone doses, however, leading to an increased risk of infection due to pathogens. In order to document the impact of such a change, a risk assessment study comparing the effects of viable *C. parvum* and bromate ingestion was carried out.

Results show that the number of gastro-enteritis cases increases as the ozone dose is decreased, whereas the number of renal cancer cases decrease with ozone doses. Minimal total disease burden can be obtained when the ozone dose equals 1.5 mg/L at 22°C and 2.5 mg/L at 5°C.

The study also shows that these optimal ozone doses are given for average situations. Detailed observation of results shows that in 23–25% of cases, ozone doses should be higher to minimise the disease burden. This is mainly explained by *C. parvum* peaks in raw water; under these circumstances, the ozone dose should be increased to 2 or 3 mg/L to minimise the total disease burden.

The suitable ozone doses of 1.5 mg/L and 2.5 mg/L allows the standard of 25 µg/L of bromates to be met, but 10 µg/L is often exceeded. Hence, the standard of 25 µg/L appears to be compatible with current plant design. Since this study illustrates the potential problems associated with the 10 µg/L bromate standard, consideration is now given to other disinfection solutions, such as membranes and/or ultraviolet disinfection.

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