Microbiological water quality management in the Paris suburbs distribution system

D. Gatel, P. Servais, J. C. Block, P. Bonne and J. Cavard

ABSTRACT

Water quality in distribution systems can deteriorate due to regrowth, contamination passing though the treatment works, or possible water intrusion within the distribution system. In order to prevent and control biofilm development, most water utilities chlorinate the treated water. It is also necessary to decrease the dissolved organic carbon as this increases chlorine stability during distribution while also reducing the formation of trihalomethanes (THM). This dual approach, based on pilot results, modelling and full-scale studies, is used by Syndicat des Eaux d'Ile de France (SEDIF) for the Paris suburbs. In order to define its management strategy, several studies were carried out by SEDIF concerning microbiological water quality, and these are summarised in the first part of this paper. Pilot and modelling studies have indicated to what degree biodegradable dissolved organic carbon (BDOC) should be removed in plants to limit bacterial regrowth. However, other works have reported that bacteria such as *Escherichia coli* can survive and even grow regardless of the low nutrient level in the distribution system. Consequently, SEDIF has introduced biological treatment into its water plants to optimise BDOC removal, and provided rechlorination facilities to attain a free chlorine residual of 0.1 mg Cl_2 l^{-1} throughout its supply system. Some slight regrowth can still be observed in the distribution system, through dissolved organic carbon consumption in the network and increases in viable bacterial counts. Nonetheless, quality control data indicate that a good bacteriological quality has been attained, with minimum quantities of disinfection by-products.

Key words | biodegradable organic carbon, biofilm, chlorine, modelling, natural organic matter, viable bacteria

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INTRODUCTION

Water distribution in France is currently going through a fascinating period as it confronts major environmental issues and policy choices. On the one hand, the last 30 years have led to a rationalised distribution and a guaranteed constant water supply, although this has demanded major investments to increase treatment capacity, interconnections, gridding and on-line reserves. It should also be noted that large cities are increasingly dependent on the treatment of particularly deteriorated surface waters. At the same time, biological filters with one or two filtration stages have considerably reduced the levels of biodegradable organic matter, resulting in an appreciable improvement in the stability of the distributed water. It is also worth mentioning the progress being made in the nanofiltration of surface water.

On the other hand, all system security improvements inevitably lead to a significant increase in the water residence time and this obviously represents a threat to the quality of the distributed water. Insofar as the Syndicat des Eaux d'Ile de France (SEDIF), responsible for water distribution in the Paris suburbs, is concerned, average residence times are from 40 to 50 h and this nevertheless represents a long period for an unprotected food product kept at ambient temperature.

Facilities such as reservoirs (80 for the SEDIF) represent an obvious outside influence, given all the potential contamination risks that they imply. It is also worth noting the works carried out on the system, a large number of which take place during the winter when the outside temperature is around 0°C. Although the system undergoes rigorous disinfection before being placed back in service, there is still a risk of contamination.

Another problem is contamination from the treatment plant itself, although the presence of cultivable coliforms at the plant outlet is rare. This was demonstrated by Bucklin *et al.* in 1991. As far as the plants are concerned, operational data also give concentrations of total and thermo-tolerant coliforms which occasionally attain around 10^6 CFU 100 ml^{-1} in river water (Gatel *et al.* 1995). Consequently, the removal of these microorganisms needs to be greater than 8 log units in order to reach a finished water concentration below 0.01 CFU 100 ml^{-1} to comply with the current standard of 0 CFU 100 ml^{-1} with a failure risk of less than 5%. In addition, heterotrophic bacteria can grow inside the distribution systems. The increase in bacterial abundance can be the source of various problems for drinking water producers and consumers, including the development of a trophic food web with the growth of higher organisms, heterotrophic plate counts higher than the recommended values, modification of the water characteristics (turbidity, taste, odour, colour), and interference in the detection of total and thermotolerant coliforms. In order to control biofilm development in distribution systems, most of the water utilities in France chlorinate the treated water, given that chloramination is not allowed under the French legislation. An alternative approach to controlling bacterial growth in distribution systems is to reduce the nutrient source required for the growth of heterotrophic bacteria which, in most cases, is the natural organic matter measured as biodegradable dissolved organic carbon (BDOC). This solution, in addition to reducing bacterial growth, offers two additional advantages: the removal of organic matter initially reduces the formation of undesirable disinfection by-products such as trihalomethanes (THM) during chlorination, and increases the stability of the chlorine residual in the distribution system by reducing the chlorine demand.

These data lead to questions concerning the microbiological harmlessness of treated surface water. This subject, studied by Payment *et al.* (1993, 1997), has revealed a significantly higher risk of waterborne gastro-enteritis for consumers of treated surface water. However, the authors are not able to draw parallels with any kind of bacteriological indicator.

The aim of this paper is to present SEDIF's management strategy to ensure the microbiological quality at the consumer tap. In order to define this management strategy, several studies were carried out concerning microbiological water quality. Various data resulting from these studies are presented in the first part of this paper. They first concern the presence and potential growth of coliforms (bacteria used as a standard faecal contamination indicator). Secondly, important data concerning the respective roles of BDOC and chlorine in controlling bacterial growth in distribution systems are summarised. Finally, recent data on water quality in the Paris suburbs distribution system are presented and discussed.

PRESENCE AND POSSIBLE GROWTH OF COLIFORMS IN DISTRIBUTION SYSTEMS

Following the sporadic occurrence of coliforms in certain drinking water distribution systems, a study was carried out on the north Paris suburbs. This aimed to provide a contamination evaluation of the biofilm fixed to the pipelines by coliforms and establish whether or not there was a potential for water contamination due to biofilm test germs (Braekman and Servais 1996). To this end, cast-iron coupons were placed on the inside surface of pipelines in 15 inspection chambers on the distribution system supplied by the Méry-sur-Oise plant, one of the SEDIF's three treatment plants. The cast-iron coupons were analysed on four different occasions after a minimum of a month and a half of incubation in the system, this period being largely sufficient to attain a balanced colonisation (Laurent and Servais 1995). The biofilm was removed by sonication and the total coliforms were counted on a specific gelose medium.

The sampling stations were characterised by chlorine residuals of approximately 0.1 mg Cl_2 l^{-1} and a biofilm of around 10^6 total bacteria $\cdot$ cm^{-2}. On completion of the

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Table 1 | Average characteristics of the pilot system before *E. coli* injection (*n*=3) (Fass *et al.* 1996)

	Treated water entering the pilot	Distributed water after 24 h of residence	Biofilm
Total cells (cell ml^{-1} or cells cm^{-1})	2.3×10^5	2.6×10^5	4.3×10^6
Viable cells (CFU ml^{-1} or CFU cm^{-1})	9.4×10^3	3.2×10^3	2.8×10^5
Culturable coliforms (CFU 100 ml^{-1} or CFU cm^{-1})	0	0	0
TOC (mg C l^{-1})	2.3	1.9	—
DOC (mg C l^{-1})	2.3	1.7	—
BDOC (mg C l^{-1})	0.7	0.4	—
PH	7.8	8	—
Temperature (°C)	19	22	—
Chlorine (mg Cl_2 l^{-1})	<0.01	<0.01	—

four campaigns, nine sampling points had been colonised by coliforms, representing approximately 10% of the total number of samples. The observed values varied between 1 and 5 coliforms per coupon (surface area: 0.8 cm^2). It would not seem that the presence of coliforms increases with the time that the cast-iron coupons are incubated in the system. On the basis of these observations, the average number of total coliforms per pipeline surface unit has been estimated at ± 0.2 total coliform cm^{-2} of pipeline. Despite the low occurrence frequencies, it can be calculated that the sloughing off of the entire biofilm, with an average of 0.2 coliform cm^{-2}, in a 100 mm pipeline would result in a water phase content of 8 coliforms 100 ml^{-1}, which seems far from negligible. Although this calculation is approximate given the lack of precision on the estimated number of coliforms per surface unit of pipeline, it confirms that the biofilm can act as a 'reservoir' for total coliforms in the system.

In the light of these results, the possibility of coliform or *Escherichia coli* (the bacteria used as a faecal indicator) growth should be examined within the conditions to be found in a distribution system. Experimental demonstrations of *E. coli* behaviour and its ability to survive or grow in the drinking water distribution system have been designed to this end (LeChevallier 1990; Camper *et al.* 1991; Szewzyk *et al.* 1994; Vander Kooij 1997). The International Water Centre loop pilot system in Nancy, France (NANCIE) has been used for experimental injections of *E. coli* (Fass *et al.* 1996; Parent *et al.* 1996) in the absence of free chlorine. *E. coli* studied in this experiment was cultivated in a nutrient broth, then starved during 24 h at 20°C in sterilised drinking water before being injected into the pilot system. Culturable *E. coli* were then counted on a selective medium using lactose and tergitol 7 (2 days of incubation at 37°C) (AFNOR T90-414).

The system characteristics after the 6-week stabilisation period at 17°C (average water residence time in the loop: 12 h), and before injection of *E. coli*, are summarised in Table 1. An inoculum of *E. coli* (1×10^{11} CFU) was injected (one single injection) into the water in the loop. The CFU measured in the water phase and in the biofilm, plotted as function of time, are shown in Figure 1. The distribution between the water phase and biofilm was measured 1 h after the injection: 1% of the *E. coli* was found in the biofilm and 99% in the water. During the

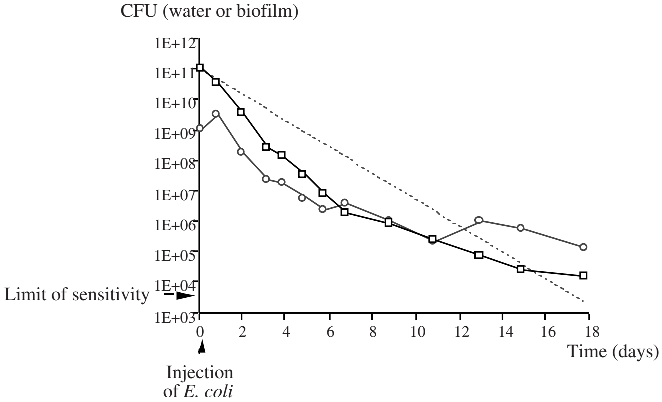

Figure 1 | Behaviour of *Escherichia coli* experimentally introduced into the distribution system (squares, water; circles, biofilm; dotted line, theoretical washout) in the absence of chlorine residual (after FASS *et al.* 1996).

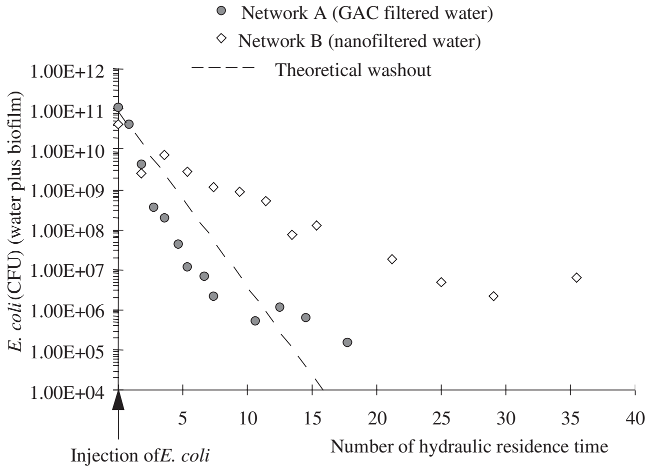

Figure 2 | Density of *E. coli* (CFU) (water plus biofilm) in the first loop of network A supplied with GAC water (hydraulic residence time=24 h per loop) and network B supplied with nanofiltered water (hydraulic residence time=12 h per loop). Without chlorine residual (after Sibille *et al.* 1998).

6 days following the injection of *E. coli*, the number of CFU fell significantly due to washout, entry into a non-culturable stage, grazing and lysis. During this period, the coliform decrease was more rapid than might have been expected from the theoretical washout line, whose curve was calculated on the basis of the system's dilution rate (volume/flow rate). Beyond day 6, the curve changes and the number of *E. coli* became higher in the biofilm than in the water phase, suggesting adaptation and growth of the *E. coli* attached to the pipe wall. This observation was reinforced by the fact that after day 12 the total number of recovered *E. coli* was higher than might have been expected from the theoretical washout. Calculated growth rate of fixed *E. coli* at day 18 gave a value of 0.005 h^{-1} (doubling time = 5.7 days).

This experiment showed that *E. coli* growth can occur in the biofilm of a drinking water distribution system. It is therefore not surprising to find some *E. coli* in distributed waters even if there were no *E. coli* at detectable concentrations in the treated water. Chlorination is largely used to control bacterial regrowth and its effect on *E. coli* injected into the system was investigated in the same study. Six days after the *E. coli* injection, chlorine was continuously added to obtain a concentration of 0.5 mg Cl_2 l^{-1}. As soon as chlorine became detectable in the system, coliforms in the water phase were completely inactivated. As previously reported (Herson *et al.* 1987; Berman *et al.* 1998; LeChevallier *et al.* 1988*a*, *b*, *c*) the fixed *E. coli* as well as indigenous fixed bacteria were more difficult to inactivate than suspended ones. However, in our system, *E. coli* was more sensitive to chlorine than the indigenous heterotrophic bacteria.

The same type of experiment was carried out to compare the influence of two natural organic matter levels (Sibille *et al.* 1998). Two loops were respectively supplied with GAC filtered water (Network A) and nanofiltered water (Network B). The average DOC level for the nanofiltered water was 0.3 mg C l^{-1}; the BDOC was below the detection limit. A nanofiltered water supplied system has a poor microbial ecosystem in the water phase (5×10^7 bacterial cells l^{-1}), and in the biofilm (7×10^6 bacterial cells cm^{-2}). *E. coli* was injected using the same protocol as described above. Figure 2 shows that during a first phase, *E. coli* in the GAC water (network A) disappeared much faster than in the nanofiltered water (network B). The ability of *E. coli* to colonise network B was unexpected, given that the concentration of bio-available organic matter was very low and because of the presence of viable autochthonous bacteria. In fact, the *E. coli* decay curve in network B (0.001 h^{-1}) was lower than the theoretical dilution rate (0.083 h^{-1}), suggesting that *E. coli* adapted and grew in the distribution system. This major difference in the behaviour of *E. coli* in the two networks

(A and B) may be indirect proof of high and low (undetectable) protozoa grazing in the respective networks. Other possible factors could be the presence of bacteriophages or exoenzymes at a higher level in the GAC water. In contrast, the conventionally treated water network (GAC) allowed the establishment of a much greater trophic food web, thus limiting *E. coli* development.

IMPACT OF BDOC AND CHLORINE ON BACTERIAL GROWTH IN DISTRIBUTION SYSTEMS

As we have seen, chlorination, before and sometimes during distribution, is a solution often used to limit coliform growth. However, this measure cannot completely control bacterial development in the systems. The reaction of the chlorine with the organic matter and the walls leads to a reduction of disinfectant concentration and its action on the microbial fauna during the transit of the water along the system. Maintaining a significant chlorine residual throughout a large distribution system, including those zones where there are high residence times, requires certain chlorine application conditions at the plant outlet that are incompatible with consumer expectations and the new standards governing oxidation by-products. An alternative to chlorination in controlling bacterial growth in the systems consists of reducing the BDOC that would later serve as a substrate for the bacteria in the systems. Reduction of the BDOC concentration in the treated water also provides the following advantages: on the one hand it reduces the formation of organochlorines during chlorination and, on the other, reduces the chlorine consumption rate in the system and thus improves the stability of the disinfectant residual during distribution.

To improve knowledge on the respective impacts of the chlorine and biodegradable organic matter on the dynamics of bacteria in the distribution systems, a series of studies were simultaneously carried out on pilot plants (Mathieu *et al.* 1992; Paquin *et al.* 1992; Sibille *et al.* 1998) and on full-scale systems (Servais *et al.* 1992, 1993, 1995*a*; Block *et al.* 1993) over the last few years. Among the results provided by these studies, it is worth noting the setting of a BDOC threshold level at 0.15 mg C l^{-1} (Prévost *et al.* 1993, 1998) below which the water can be considered as being biologically stable. In other words, the BDOC does not evolve during the water distribution even if there is no chlorine residual, bacterial growth is very limited and there is no possible development of a trophic food web.

These studies also showed that the introduction of a stage aimed at reducing the biodegradable organic matter content during the treatment process always significantly improved the microbiological quality of the water in the system and made it possible to reduce the chlorine rate applied at the treatment plant outlet. For example, biological filtration can be used to reduce BDOC at the plant outlet and minimises bacterial growth in the system (Prévost *et al.* 1998). The evolution of different parameters according to the residence time has been compared in two networks in the suburbs of Montreal (Canada). Although these two networks are supplied by two treatment plants with identical raw water, one is equipped with activated carbon biological filtration (the Sainte-Rose plant) while the other is not (Pont-Viau plant). The BDOC in the water produced by the Sainte-Rose plant is 0.2 mg C l^{-1} as against 0.75 mg C l^{-1} for the other plant. The results show that better bacteriological conditions are maintained at the end of the network for the Sainte-Rose plant by applying a very low level of residual disinfectant than for the Pont-Viau plant which has a much higher disinfection level. Auvers-sur-Oise in the Parisian suburbs provides another example (Randon *et al.* 1995; Laurent *et al.* 1999). This city has been supplied with nanofiltered water (containing BDOC of around 0.1 mg C l^{-1}) since February 1993. The reduction in BDOC using nanofiltration has led to a reduction in the applied chlorine rate to 0.1 mg Cl_2 l^{-1}, and improved the bacteriological quality of the water (Figure 3).

Within the context described above, it is important to be able to test easily the accumulated impacts of chlorine, BDOC, temperature and biomass suspended in the water on the bacterial growth process in the systems. Given the complexity of the bacterial dynamics in distribution systems, it appeared worthwhile to develop a mathematical model to calculate the evolution of the water's microbiological quality. Using experimental

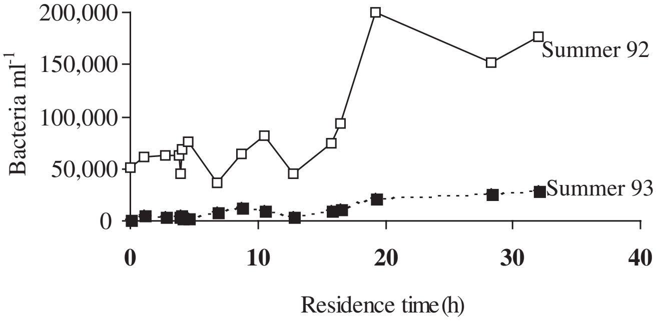

Figure 3 | Bacteria counts by epifluorescence microscopy in Auvers-sur-Oise distribution system (northern Parisian suburbs) plotted against residence time, before (summer 1992) and after (summer 1993) feeding with nanofiltered water (after Randon *et al.* 1995; Laurent *et al.* 1999).

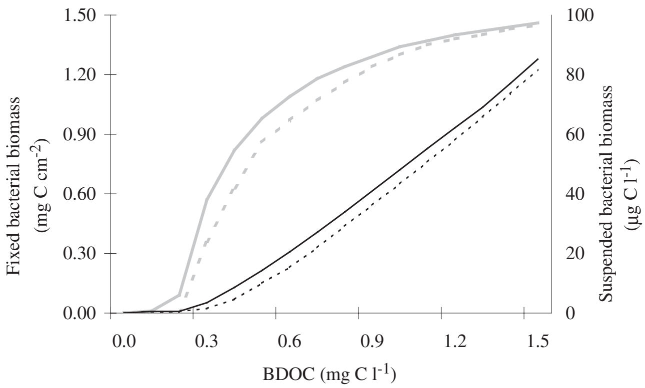

Figure 4 | Evolution, as a function of the BDOC concentration in the discharged water, of the maximum fixed (grey lines) and free (black lines) bacterial biomass reached in the system. The dotted lines represent the values obtained with a free chlorine residual at the plant outlet of 1 mg Cl_2 l^{-1} and the solid lines represent the values obtained with no chlorine residual.

microbiological studies carried out on different drinking water systems, a model calculating the dynamics of bacteria and biodegradable organic carbon (BDOC) was developed: the SANCHO model (Servais *et al.* 1992, 1994, 1995*b*; Laurent *et al.* 1997).

The SANCHO model considers the following: interactions between the organic matter and the bacteria, interactions between the internal pipeline surfaces and the bacteria, chlorine consumption, and the impact of chlorine on bacteria. The SANCHO model (Servais *et al.* 1995a) calculates the spatial variations in equilibrium of BDOC, free residual chlorine, and free and fixed bacterial biomass. This calculation is made for a mass of water circulating for known periods in different pipeline diameters. In addition to the water residence times in the different types of pipelines, the model requires information concerning the characteristics of the water supplying the network: chlorine residual, BDOC and biomass in suspension. To validate this model, comparisons between experimental results and those calculated by the model are made for different distribution systems (Laurent *et al.* 1997). A good concordance has been observed between the experimental results and those calculated by the model for a large number of situations that are characterised by very different chlorine and BDOC contents in the water supplying the systems.

Once validated, a SANCHO type model could be used to predict the effect of certain modifications to the quality of the water supplying a system on the bacterial dynamics within the given system. This model could therefore be very useful in assessing the relative and respective roles of chlorine and biodegradable organic matter in controlling bacterial growth in the system. The model can be used to show that the maximum of free and fixed bacterial biomass values encountered in a system are not particularly influenced by the application of chlorine (Figure 4). It is the maximum position according to residence time in the system that is influenced. The more chlorine there is, the greater the development of the bacterial biomass in the system after a long residence time. The figure also shows that BDOC reduction considerably reduces the development of bacteria in the system. With a BDOC content of around 0.1 mg C l^{-1}, bacterial growth becomes insignificant. This fully concurs with previously obtained experimental results (Servais *et al.* 1993; Prévost *et al.* 1993).

MANAGEMENT STRATEGY FOR THE PARIS SUBURBS DISTRIBUTION SYSTEM

Given the experimental data presented above, the water services should therefore target the removal of organic matter as well as the uniform distribution of chlorine throughout the network. The reduction of organic matter and, in particular, biodegradable organic matter (BDOC), has been described elsewhere (Bablon *et al.* 1988; Van der Kooij *et al.* 1989; Servais *et al.* 1991; Urfer *et al.* 1997) and remains a primary goal. However, it should be noted that a reduction in the concentration of biodegradable organic matter is not an end in itself as far as the sanitation authorities are concerned, and that the benefits of removing BDOC can only be demonstrated by giving negative examples. This point can become critical within the framework of a debate on the price of water or when the treatment process is being changed. It is considered that the greater the BDOC reduction, the better the water.

Once the treatment to remove as much organic matter as possible from the water to be distributed has been defined, it is then possible, using the SANCHO model, to study the chlorine rate to be injected to achieve as wide a system cover as possible. The aim is to have a minimum residual free chlorine level of around 0.1 mg Cl_2 l^{-1} at all points in the system to avoid any risk of local contamination by biofilm coliforms (usually total coliforms, or thermotolerant coliforms). It is worth questioning the interest of this a priori fight against contamination by germs that have no sanitary significance, but it remains a fact that once the quality of the produced water is guaranteed and BDOC level minimised, chlorine is the main means used to fight organisms, whether or not these are pathogenic. The works previously cited also demonstrate that limiting BDOC to concentrations lower than the detection level does not prevent the multiplication of the test germs present in the biofilm. Even though, in the long term, the indigenous flora in the systems will out-compete faecal indicators (Vander Kooij 1997), the system manager is obliged to take constant conservation measures to limit the multiplication of germs, some of which may be pathogenic. It is in this particular sphere that sanitary issues are involved in this approach.

The other goal is to have a relevant, easily understood and readable on-site indicator: the absence of chlorine is immediately readable by the operators who can then take the appropriate bleed/rinse measures if malfunctions are detected, and report the problem without having to wait for gelose culture results. These results are known to give an incomplete understanding of the reality of the situation and the level of water contamination (LeChevallier and McFeters 1985; McFeters *et al.* 1986).

From an operational point of view, the next goal to be attained having reduced BDOC levels is to distribute chlorine throughout the system, or at least in the main parts of the system. One of the first consequences is the increasing number of chlorination installations able to distribute chlorine through to the furthest parts of the system. The target is to have an equal chlorine distribution throughout the system, close to 0.1 mg Cl_2 l^{-1}.

To avoid increasing the disinfectant dose at the treatment plant, which would result in higher concentrations of chlorine in the water delivered to the customers closest to the plant, the SEDIF decided to install several booster stations within the system. These installations are generally found in large reservoirs to compensate for chlorine losses caused by the residence times in these storage structures (Gatel *et al.* 1996). A hydraulic model is also used to identify the main pipeline to be used to boost the disinfectant. The effect on the chlorine residual downstream is checked. As a result, 60 booster units have been installed throughout the suburbs of Paris systems. A local problem can be treated by the local chlorination unit, providing the operator with a great deal of flexibility in managing the distribution system. In parallel, 61 continuous chlorine analysers have been installed throughout the suburbs systems, with the analysis results transmitted by telephone to a quality control monitor.

On the basis of information obtained from the chlorine analysers and control panels, two types of local action can be taken to prevent stagnation. The 'accelerator' is used to transfer water from a zone with a high disinfectant level to a zone where there is a lower disinfectant level. This mechanism prevents water stagnation while avoiding any losses. This has led to ten accelerators being installed in the suburbs of Paris systems. 'Automatic valves' are also used to create an artificial consumption on hydrants. As the mechanism is programmable, the flow can be time-controlled and carried out during convenient periods.

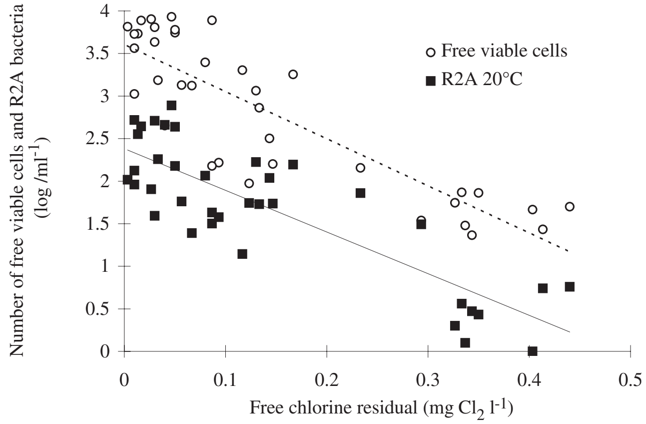

Figure 5 | Number of bacteria as a function of free chlorine residual concentration in the Parisian suburbs distribution system. The dotted line represents the linear regression for the respiring (CTC+) bacterial cells ($y=-5.56\,X+3.61$, $r^2=0.74$) the plain line represents the linear regression for the R2A counts cells ($y=-4.89\,X+2.38$, $r^2=0.70$).

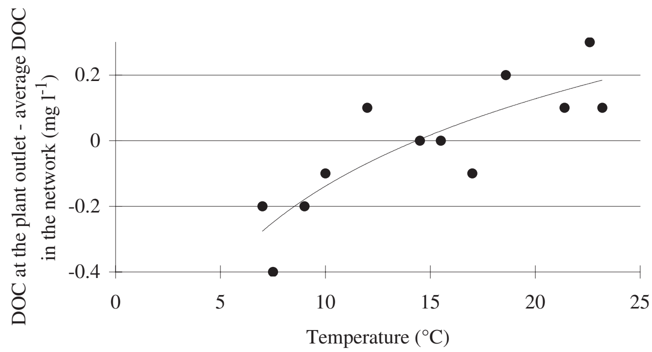

Figure 6 | DOC consumption in the network, as a function of water temperature ($y=-0.38\ \ln(X)-1.02$, $r^2=0.70$).

WATER QUALITY DATA IN THE PARISIAN SUBURBS DISTRIBUTION SYSTEM

Sampling campaigns have been designed to assess the distributed water quality in terms of bacteriological and chemical results. These campaigns are scheduled on an annual basis, with 15–80 grab sample each week, depending on the season and the criticality of the parameter in terms of compliance. As far as the above-mentioned results are concerned, the first issue to be raised concerns the number of bacteria. Culturable cells were counted on R2A medium (20°C, 3 days), total counts were carried out after staining cells with DAPI and viable cells were evaluated by the CTC method.

Figure 5 shows the abundance of bacteria as a function of free chlorine residuals (results from the northern suburbs of Paris, 1994). Free chlorine residuals rank from near zero for remote areas, or storage tanks, to 0.4 mg Cl_2 l^{-1} at the plant outlet or near the chlorine booster stations. R2A counts ranged from a few colonies ml^{-1} at high chlorine concentration, to 103 for low chlorine zones. CTC counts were a least ten times greater. Linear relationships in semi-log plots can be established for both bacteria counts, which explain 70–74% of the data variability. Although the two regression lines were in parallel, there was no direct relationship between R2A and CTC counts. Similar results were observed on a pilot scale, as discussed earlier by Mathieu *et al.* (1992), and the free chlorine residuals were confirmed to be one of the major parameters influencing bacteria counts in distributed water. This reduction could not be established for total number of cells (including living and dead cells).

Other results obtained from the eastern suburbs of Paris (1997) showed some dissolved organic carbon (DOC) consumption in the network, which seemed to depend on the temperature (Figure 6). When the temperature of the distributed water was below 15°C, the DOC content of the water samples generally remained above the DOC concentration of the water at the plant outlet, which shows no consumption, and there is potentially some release of organic compounds in the network. When the water temperature exceeded 15°C, the DOC content of the water samples was generally below its value at the plant outlet, demonstrating a DOC consumption in the network. This result is consistent with the SANCHO model simulations, demonstrating that despite the presence of chlorine residual, natural organic matter is consumed in the network. However, it should be noted that the DOC consumption never exceeded 0.2 mg C l^{-1}, which was very limited and linked to the low DOC level at the plant outlets (less than 2 mg C l^{-1}).

Another issue is the THM level formed in the network. The formation of THM within the system is highly dependent on the contact period. It has been noted that measures aiming to reduce the water's residence time in

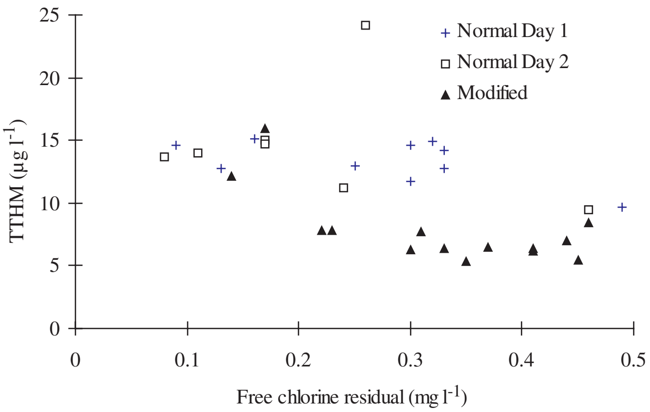

Figure 7 | Effect of residence time modifications on chlorine and TTHM levels. (Day 1 and Day 2: two sampling campaigns without residence time modification; modified situations=reduction of the residence time).

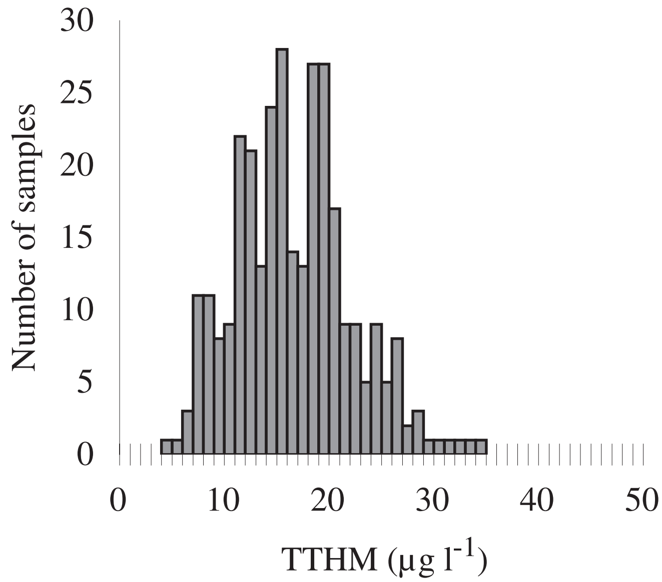

Figure 8 | TTHM levels in the southern Parisian suburbs (1994 and 1995).

the small diameter pipelines and increasing the chlorine level (opening hydrants and closing valves) have resulted in reduced THM concentrations. Figure 7 presents the results of these modifications as carried out on the second height pressure zone in Montreuil (eastern suburbs of Paris) in 1996. The modified situation had the effect of increasing the average chlorine level from 0.23 to 0.33 mg l^{-1}. In parallel, the average total THM (TTHM) level fell from 13.9 $\mu g\, l^{-1}$ to 7.8 $\mu g\, l^{-1}$. This shows that among the first measures to be taken when trying to anticipate a deterioration in the water quality, an artificial reduction of residence time remains a priority once the removal of organic matter has been optimised.

The result of this dual policy, to remove organic matter and maintain a 0.1 mg l^{-1} level of residual free chlorine, can be illustrated by a parallel presentation of results on chlorination by-products and the results concerning the compliance of distributed water. The distribution histogram showing TTHM levels is presented in Figure 8. The results concern samples taken in 1994 and 1995 in the southern Suburbs of Paris. The TTHM concentration showed an average of 15.6 $\mu g\, l^{-1}$ and was always lower than 34 $\mu g\, l^{-1}$. Over the same period, over 99.5% of samples contained no total coliforms.

The Syndicat des Eaux d'Ile de France has started up a surface water nanofiltration unit for the north Paris suburbs. In the system already supplied by a nanofiltration unit (Auvers-sur-Oise), the TTHM levels always remained below 12 $\mu g\, l^{-1}$ (Randon *et al.* 1995) providing bacteriological results that were similar in terms of bacteriological compliance and, as indicated above, much better for the bacterial biomass.

CONCLUSIONS AND PROSPECTS

The need to maintain a residual level of free chlorine in the system is closely linked to the desire to reduce both sanitary and non-compliance risks. This paper has shown that the biofilm in drinking water systems contains total coliforms. The presence of total coliforms in the biofilm can on occasion be the source of contamination in distributed water, leading to possible non-compliances.

In addition, we have stated that the growth of a few *E. coli* strains is possible in the ecosystem represented by drinking water supply systems. This growth has been proved possible even where there is no measurable quantity of BDOC in a system.

Chlorine is an efficient way to fight against these faecal contamination test germs and the regrowth phenomena within the system. This paper also notes the results showing that the effect of the chlorine level is essentially to slow down bacterial growth and that reducing the biofilm necessarily requires that the concentration of organic matter in the produced water is limited. This organic matter reduction also limits the distributed water's chlorine demand and, as a result, allows the chlorine distribution zone to be extended.

Depending on the water's residence time in the system, it may be necessary to have chlorine booster stations to limit the doses of chlorine injected at the system entry point. This has the effect of preserving the organoleptic qualities of the distributed water. It can thus be seen that by limiting the quantity of organic matter in the water and by maintaining a residual chlorine level of around 0.1 mg l^{-1}, it is possible to distribute a water that largely complies with standards (less than 1% of results present total coliforms). The TTHM concentrations are always lower than 34 $\mu g\ l^{-1}$.

Investments underway aim to further reduce the level of injected chlorine and the TTHM formed, thanks to improved organic matter and micropollutants reduction. The long-term prospects are relatively difficult to assess given that we are confronted with a resources preservation policy alongside new standards concerning bromates and pesticides by-products. It is clear that priority should be given to the investments required by these latter two objectives.

REFERENCES

Bablon, G., Ventreque, C. and Aimr, B. 1988 Developing a sand-GAC filter to achieve high rate biological filtration. *J. Am. Wat. Wks Assoc.*, **80**, 12–47.

Berman, D., Rice, E. W. and Hoff, J. C. 1988 Inactivation of particle associated coliform by chlorine and monochloramine. *Appl. Environ. Microbiol.*, **54**, 507–512.

Block, J. C., Haudidier, K., Paquin, J. L., Miazga, J. and Lévi, Y. 1993 Biofilm accumulation in drinking water distribution systems. *Biofouling*, **6**, 333–343.

Braekman, T. and Servais, P. 1996 Contamination du biofilm par les germes tests. *SEDIF International Report*.

Bucklin, K. E., McFeters, G. A. and Amirharajah, A. 1991 Penetration of coliforms through municipal drinking water filters. *Wat. Res.*, **25**(8), 1013–1017.

Camper, A. K., McFeters, G. A., Characklis, W. G. and Jones, W. L. 1991 Growth kinetics of coliform bacteria under conditions relevant to drinking water distribution systems. *Appl. Environ. Microbiol.*, **57**, 2233–2239.

Fass, S., Dincher, M. L., Reasoner, D., Gatel, D. and Block, J. C. 1996 Fate of *Escherichia coli* experimentally injected in a drinking water distribution pilot system. *Wat. Res.*, **30**, 2215–2221.

Gatel, D., Mercier, M., Volk, C. and Joret, J. C. 1995 Control of bacterial regrowth in distribution systems: influence of BDOC and chlorine residual. *Wat. Supply*, **13**-2, South Africa 275–290.

Gatel, D., Henriet, C., Braekman, T., Servais, P., Maret, A. and Cavard, J. 1996 Impact of reservoirs on drinking water quality. *WQTC Proceedings*, CD rom.

Herson, D. S., McGonigle, B., Payer, M. A. and Baker, K. H. 1987 Attachment as a factor in the protection of Enterobacter cloacae from chlorination. *Appl. Environ. Microbiol.*, **53**, 1178–1180.

Laurent, P. and Servais, P. 1995 Fixed biomass estimated by potential exoproteolytic activity. *Can. J. Microbiol.*, **41**, 743–752.

Laurent, P., Servais, P., Prévost, M., Gatel, D. and Clement, B. 1997 Testing the SANCHO model on distribution systems. *J. Am. Wat. Wks Assoc.*, **89**(7), 92–103.

Laurent, P., Servais, P., Gatel, D., Randon, G., Bonne, P. and Cavard, J. 1999 Microbiological quality before and after nanofiltation. *J. Am. Wat. Wks Assoc.*, **91**(10), 62–72.

LeChevallier, M. W. 1990 Coliform regrowth in drinking water: A review. *J. Am. Wat. Wks Assoc.*, **82**, 74–86.

LeChevallier, M. W. and McFeters, G. A. 1985 Enumerating injured coliforms in drinking waters. *J. Am. Wat. Wks Assoc.*, **77**, 81–87.

LeChevallier, M. W., Cawthon, C. D. and Lee, R. G. 1988a Factors promoting survival of bacteria in chlorinated water supplies. *Appl. Environ. Microbiol.*, **54**, 649–654.

LeChevallier, M. W., Cawthon, C. D. and Lee, R. G. 1988b Inactivation of biofilm bacteria. *Appl. Environ. Microbiol.*, **54**, 2492–2499.

LeChevallier, M. W., Cawthon, C. D. and Lee, R. G. 1988c Mechanisms of bacterial survival in chlorinated drinking water. *Wat. Sci. Technol.*, **20**, 145–151.

McFeters, G. A., Kippin, J. S. and LeChevallier, M. W. 1986 Injured coliforms in drinking water. *Appl. Environ. Microbiol.*, **6**, 312–318.

Mathieu, L., Paquin, J. L., Block, J. C., Randon, G., Maillard, J. and Reasoner, D. 1992 Paramètres gouvernant la prolifération bactérienne dans les réseaux de distribution. *Sciences de l'Eau*, **5**, 91–112.

Paquin, J. L., Block, J. C., Haudidier, K., Hatemann, P., Colin, F., Miazga, J. and Levi, Y. 1992 Effet du chlore sur la colonisation bactérienne d'un réseau expérimental de distribution d'eau. *Sciences de l'Eau*, **5**, 399–414.

Parent, A., Fass, S., Dincher, M. L., Reasoner, D., Gatel, D. and Block, J. C. 1996 Control of coliform growth in drinking water distribution system. *J. CIWEM*, **10**, 442–445.

Payment, P., Franco, E. and Siemiatycki, J. 1993 Absence of relationship between health effects due to tap water consumption and drinking water quality parameters. *Wat. Sci. Technol.*, **27**(3/4), 137–143.

Payment, P., Siemiatycki, J., Richardson, L., Renaud, G., Franco, E. and Prévost, M. 1997 A prospective epidemiological study of gastrointestinal health effects due to the consumption of drinking water. *Int. J. Environ. Health Res.*, **7**, 5–31.

Prévost, M., Coallier, J., Lafrance, P. and Rompré, A. 1993 Canadian perspective on microbial regrowth in distribution systems. *Proc. AWWA Technology Transfer Conference 'Bugs, molecules and surfaces', Big Sky, USA*, pp. 39–55.

Prévost, M., Coallier, J., Rompré, A., Servais, P., Laurent, P. and Lafrance, P. 1998 Suspended bacterial biomass and activity in drinking water distribution systems: impact of water treatment. *Wat. Res.*, **19**, 903–911.

Randon, G., Servais, P., Laurent, P., Tanghe, N. and Cavard, J. 1995 Study of the behavior of a distribution system supplied by a nanofiltration unit. *Am. Wat. Works Assoc. WQTC Proceedings*, 1019–1032.

Servais, P., Billen, G., Ventresque, C. and Bablon, G. 1991 Microbial activity in granular carbon filters at the Choisy-le-Roi treatment plant. *J. Am. Wat. Wks Assoc.*, **83**(2), 62–68.

Servais, P., Billen, G., Laurent, P., Levi, Y. and Randon, G. 1992 Studies of BDOC and bacterial dynamics in the drinking water distribution system of the northern Parisian suburbs. *Sciences de l'Eau*, **5**, 69–89.

Servais, P., Laurent, P. and Randon, G. 1993 Impact of biodegradable dissolved organic carbon (BDOC) in bacterial dynamics on distribution systems. *Am. Wat. Works Assoc. WQTC-Proceedings*, pp. 963–980.

Servais, P., Laurent, P., Gatel, D. and Prévost, M. 1994 Modelling bacterial dynamics in distribution systems. *Am. Wat. Works Assoc. WQTC-Proceedings*, 1237–1250.

Servais, P., Laurent, P., Billen, G. and Gatel, D. 1995a Development of a model of BDOC and bacterial biomass fluctuations in distribution systems. *Sciences de l'Eau*, **8**, 427–464.

Servais, P., Laurent, P. and Randon, G. 1995b Comparison of the bacterial dynamics in various french distribution systems. *J. Wat. Suppl. Res. & Technol.-Aqua*, **44**, 10–17.

Sibille, I., Sime-Ngando, T., Mathieu, L. and Block, J. C. 1998 Protozoan bacterivory and *Escherichia coli* survival in drinking water distribution networks. *Appl. Environ. Microbiol.*, **64**, 197–203.

Szewzyk, U., Manz, W., Amann, R., Scgkeufer, K. H. and Stenstrom, T. A. 1994 Growth and *in situ* detection of pathogenic *Escherichia coli* in biofilms of a heterotrophic water bacterium by use of 16S and 23S rRNA directed fluorescent oligonucleotide probes. *FEMS Microbiol. Ecol.*, **13**, 169–176.

Urfer, D., Huck, P. M., Booth, S. D. J. and Coffey, B. M. 1997 Biological filtration for BOM and particle removal: a critical review. *J. Am. Wat. Wks Assoc.*, **89**(12), 83–98.

Vander Kooij, D. 1997 Multiplication of coliforms at very low concentrations of substrates in tap water. In *E. coli: Problem and Solution*. Kay, D. and Fricker, C. (eds), pp. 195–207.

Van der Kooij, D., Hijnen, W. A. M. and Kruithof, J. C. 1989 Effects of ozonation, biological filtration and distribution on the concentration of easily assimilable organic carbon (AOC) in drinking water. *Ozone Sci. Engr*, **11**, 297.