Microbial Activity in GAC Filters at the Choisy-le-Roi Treatment Plant

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To maintain the biological stability of drinking water during distribution in large, complex networks, high standards have to be met—namely, low bacterial densities and low levels of biodegradable organic carbon. Second-stage granular activated carbon (GAC) filtration (without regeneration of carbon) is used for this purpose at the Choisy-le-Roi, Paris, France, treatment plant. Effective removal of dissolved organic carbon has been observed with such filtration—mainly because of a reduction in the biodegradable organic carbon. To study the microbial processes involved in this removal, new methods based on the use of radio-labeled tracers have been developed in order to measure the bacterial biomass and activity associated with GAC.

During the last 15 years, the deterioration of the quality of surface waters used to produce drinking water has resulted in the widespread use of granular activated carbon (GAC) filtration. Because of its large specific surface area, GAC is the ideal solid material to remove organic compounds dissolved in water. Removal of dissolved organic carbon (DOC) is important because (1) some organic substances alter taste and odor, (2) other organics may act as precursors in the formation of chlorinated compounds that may be carcinogenic, and (3) biodegradable compounds can lead to bacterial regrowth in the distribution system.

Numerous studies have been performed on the adsorption capacity of GAC for a large range of organic compounds. Filtration by GAC has proved very effective for the removal of certain compounds present at high concentrations, e.g., in reservoir water or groundwater. In the case of river water, the multiplicity and variety of the organic compounds present render the adsorption process less effective. Some studies, however, have shown that GAC columns continue to effectively remove organics far beyond the point at which the adsorption capacity would normally be saturated.[1-3] It has been suggested that this removal is the result of the activity of microbial communities that colonize the external surface and macropores of the GAC particles.[2,4,5]

During the last 15 years, the deterioration of the quality of surface waters used to produce drinking water has resulted in the widespread use of GAC. Because of its large specific surface area, GAC is the ideal solid material to remove organic compounds dissolved in water.

Therefore, it may be possible to employ the microbiological properties of the GAC instead of its adsorption capacity. Biological processes offer a potentially useful alternative because regular regeneration of the GAC is not required and biodegradable DOC is preferentially eliminated.

The available methods for studying microbial activity in GAC filters are mostly indirect methods, such as oxygen-consumption,[2] comparing the removal of specific biodegradable and nonbiodegradable compounds,[3] or studying DOC removal by sterile and nonsterile GAC columns.[6] Direct methods are limited to techniques of bacterial enumeration at the surface of GAC grains, particularly by scanning electron microscopy.[7,8] The lack of efficient methods for directly measuring microbiological activity and for characterizing and quantifying biodegradable organic matter explains the large number of unanswered questions about designing and managing GAC filters. The report of the AWWA Research and Technical Practice Committee on Organic Contaminants in 1981[9] concluded that further research in this area is needed.

The purpose of this article is to describe the application of some original methods for directly measuring bacterial biomass and activity in GAC filters. In addition, a recently developed method for determining biodegradable organic carbon in water[10] was utilized. Contrasting with the method of assimilable organic carbon determination proposed by Van der Kooij et al,[11] the objective of the method described here is to determine an absolute value of biodegradable dissolved carbon.

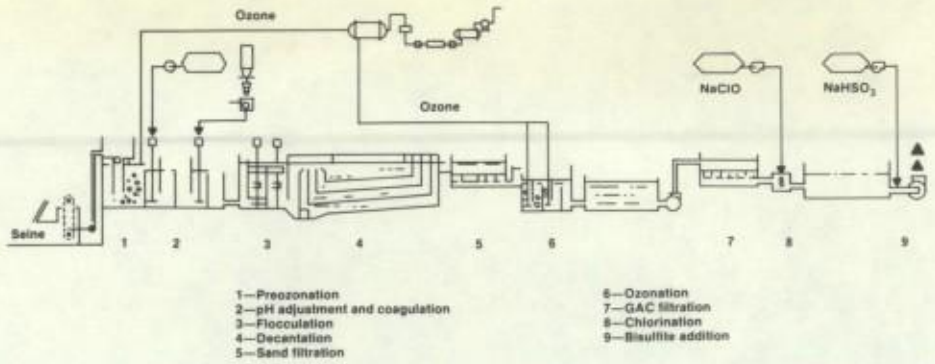

Figure 1. Schematic diagram of treatment processes at Choisy-le-Roi plant

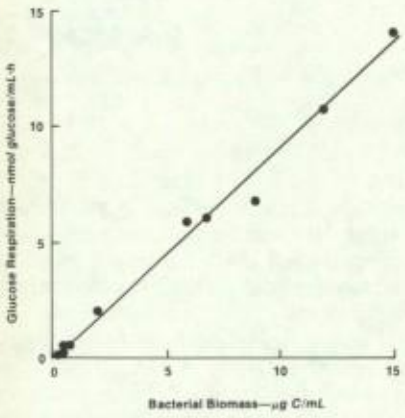

Figure 2. Plot of potential glucose respiration versus bacterial biomass ($r = 0.99$)

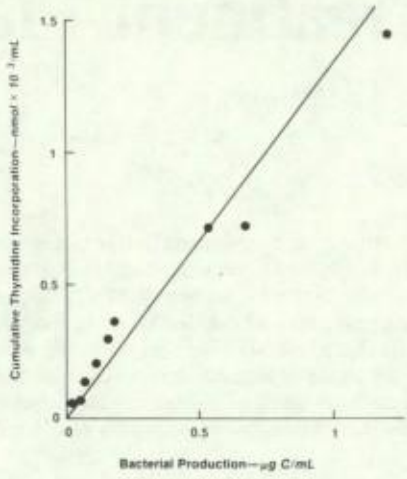

Figure 3. Relationship between cumulative thymidine incorporation and bacterial production in GAC samples ($r = 0.97$)

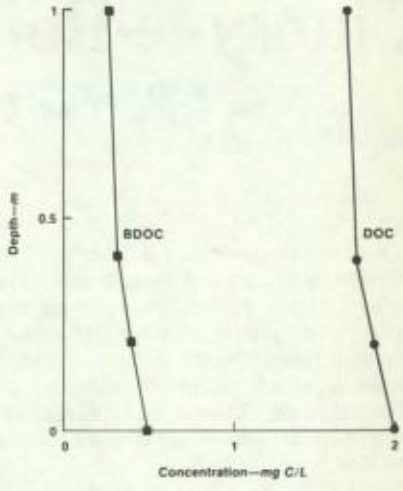

Figure 4. Concentrations of DOC and BDOC in the interstitial water collected at different depths of GAC filter 38 in March 1986 (*depth 0 corresponds to the top of the filter*)

TABLE 1
Characteristics of GAC filtration at Choisy-le-Roi plant

Parameter	Value
Particle density of GAC wetted with water—*kg/L*	1.28
Porosity of the bed	0.45
Effective size (particle diameter for which 10 percent of the medium by weight is smaller)—*mm*	0.8
Uniformity coefficient	1.8
Iodine number (AWWA B604-74)—*mg/g*	925
Filtration velocity—*m/h*	5–9
Medium depth—*m*	1
Empty bed contact time—*min*	7–12
Surface area of filter—m^2	117
Number of filters in the plant	34
Last reactivation of the GAC	Two years before the beginning of the study in August 1984

These methods were applied at the Choisy-le-Roi drinking water treatment plant, where GAC filtration had been used for two years before the beginning of the present study as second-stage filtration without GAC regeneration to take advantage of the microbial process of organic carbon removal. The GAC filters used at the present time were installed by simply replacing sand in several of the first-stage filters with GAC, without any modification of their hydraulic or geometric characteristics. The results presented in this article confirm the effectiveness of the second-stage filtration step. The work that is described in this article is part of a large program intended to improve the design of a second generation of GAC filters to be built at Choisy-le-Roi in the near future.

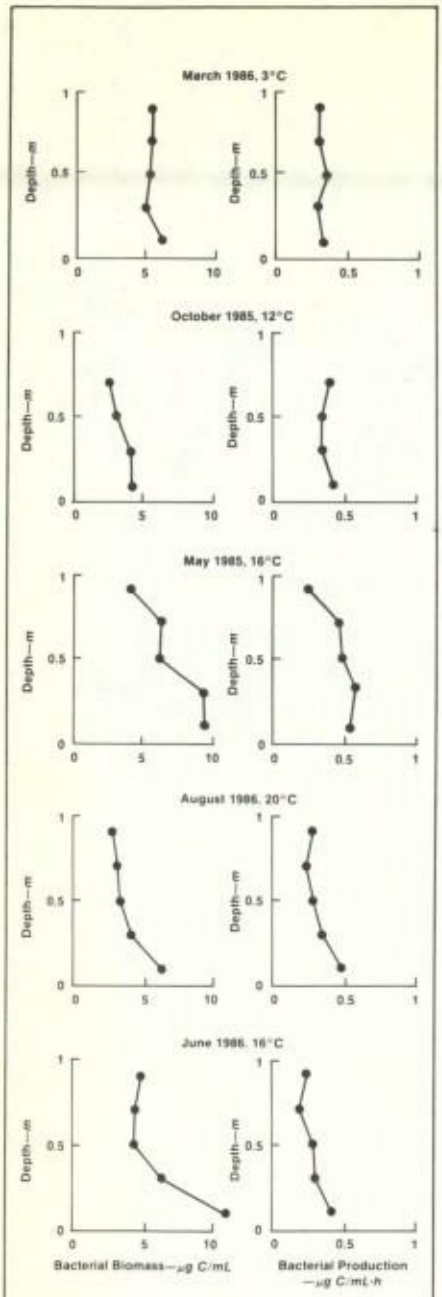

Figure 5. Bacterial biomass and production as a function of depth in GAC filter 38 at different seasons in 1985 and 1986 (*depth 0 corresponds to the top of the filter*)

Material and methods

Choisy-le-Roi treatment plant. The Choisy-le-Roi plant, located in southeast Paris, produces 800,000 m^3/d of water. Raw water is withdrawn from the Seine River above Paris. In addition to classical treatments such as coagulation, flocculation, and sedimentation, the treatment train (Figure 1) includes: (1) sand filtration, during which ammonia is removed by nitrifying bacteria and suspended solids are eliminated, (2) ozonation with a dose of 1–2 mg O_3/L, (3) filtration on GAC, (4) chlorination (1–2 mg/L with a contact time of 2–4 h), and (5) dechlorination with bisulfite to ensure a chlorine residual of 0.5 mg/L in the distribution system.

Sampling. Most measurements described in this article were performed on GAC filter 38 at the Choisy-le-Roi plant. The main characteristics of the geometry and operation of this filter are listed in Table 1. The GAC in the filter was loaded two years before the beginning of the study in August 1984 and has never been regenerated.

The Choisy-le-Roi plant, located in southeast Paris, produces 800,000 m^3/d of water. Raw water is drawn from the Seine River above Paris.

Samples of influent water can be collected easily from the water overlying the filter; effluent water can be collected directly after passage through the filter from a tap in the filtered water collector. Moreover, the filter is equipped with a permanent sampling device, allowing collection of samples of interstitial water at various depths in the GAC bed.

The GAC samples were taken from a small raft floating on the water overlying the filter by using a specially devised corer that allowed 50-mL GAC samples to be collected at various depths in the filter.

Measurements with water samples. ***Dissolved organic carbon.*** The DOC was measured with a total carbon analyzer* using ultraviolet-promoted persulfate oxidation of organic carbon, followed by infrared spectrophotometric detection of the carbon dioxide (CO_2) produced by the oxidation. Samples were preserved with a few drops of a saturated mercuric chloride solution and were stored in sealed, precombusted glass ampules. The accuracy of the determinations is about 2 percent in the range 0–3 mg C/L.

Biodegradable organic carbon. The biodegradable fraction of DOC (BDOC) was determined according to the bioassay procedure developed by Servais et al.[10] A 200-mL water sample is sterilized by filtration through a 0.2-μm-pore-size membrane carefully rinsed first with distilled water (400 mL) then with the water sample (200 mL). A 2-mL inoculum containing autochthonous bacteria is added. The inoculum is in fact raw water filtered through a 2-μm-pore-size filter. The inoculated sample is incubated in the dark at 20 ± 0.5°C for four weeks. Two replicates, 20-mL subsamples, are collected for DOC determination at the beginning of the incubation (just after adding the inoculum) and at the end of the incubation. The BDOC value is calculated as the difference between the mean values of the initial and the final DOC. The precision of this method is estimated to be 0.05 mg C/L.[12]

Bacterial biomass. Bacterial numbers were determined by epifluorescence microcospy after acridine orange staining (AODC) following the procedure of Hobbie et al,[13] using an epifluorescence microscope† equipped with a 100-W mercury lamp. The numbers of bacteria per millilitre were estimated from enumeration on 10 fields; at least 20 cells were counted on each field. Bacterial sizes were estimated visually by comparison with a calibrated grid, and biovolumes were calculated by treating rods and cocci as cylinders and spheres, respectively.[14] A conversion factor of 1.2×10^{-13} g C/μm^3 was used for calculating biomass from biovolume.[14]

Measurement with GAC samples. ***Bacterial biomass.*** Because direct microscopic enumeration of bacteria attached to activated carbon is not possible (because of the size and the surface irregularity of the solid support), a different approach was developed for estimating the bacterial biomass in GAC samples. This approach consists of measuring the bacterial potential activity under standard conditions and relating this to the size of the active population of bacteria. For this purpose, measuring the production of $^{14}CO_2$ by respiration of added ^{14}C-glucose at a saturating concentration was found convenient. The radioactive substrate is added at a high concentration in order to saturate the biological uptake process, the maximal capacity of which is measured. This measurement is independent of the substrate concentration but depends on the specific activity of the added labeled substrate. It gives no information about the real uptake rate of the substrate but is an estimation of the size of the active bacterial population.

During the experimental procedure, 1 mL of ^{14}C-glucose‡ solution (1 m*M* glucose containing 0.1–1 μCi) was added to a 2-mL GAC sample in a penicillin bottle closed with a rubber septum. The high concentration of added glucose was necessary to saturate the uptake process because of the important adsorption on the GAC of the added substrate. The sample consisted of GAC and water in the same proportion as in the studied filter (about 75 percent w/w of water).

After 3 h of incubation at 20°C, the sample is acidified by adding 2 mL of 10 percent sulfuric acid through the septum

*Model 80, Dohrmann Div., Xertex Corp., Santa Clara, Calif.
†Ernst Leitz, Wetzlar, Federal Republic of Germany
‡Amersham Corp., Buckinghamshire, England

TABLE 2

Reduction in dissolved organic carbon by GAC filtration

Date	DOC in Influent *mg C/L*	DOC in Effluent *mg C/L*	Reducton in DOC *mg C/L*
Aug. 18, 1984	1.85	1.40	0.45
May 22, 1985	2.95	2.65	0.30
Oct. 28, 1985	1.70	1.40	0.30
Oct. 29, 1985	1.75	1.50	0.25
Oct. 30, 1985	1.70	1.35	0.35
Oct. 31, 1985	1.95	1.30	0.65
Mar. 3, 1986	2.35	1.65	0.70
Mar. 4, 1986	2.05	1.25	0.80
Mar. 5, 1986	1.85	1.45	0.40
Mar. 7, 1986	1.80	1.65	0.15
June 5, 1986	2.65	2.30	0.35
Aug. 25, 1986	1.95	1.70	0.25
Aug. 26, 1986	2.80	2.50	0.30
Aug. 28, 1986	1.85	1.10	0.75

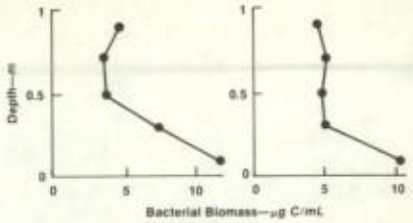

Figure 6. Vertical profiles of bacterial biomass in GAC filter 38 just before and after a washing cycle in June 1986 (*depth 0 corresponds to the top of the filter*)

TABLE 3

Reduction in biodegradable and nonbiodegradable dissolved organic carbon by GAC filtration

Date	Influent		Effluent		Reduction			
	BDOC *mg C/L*	NBDOC *mg C/L*	BDOC *mg C/L*	NBDOC *mg C/L*	BDOC *mg C/L*	BDOC *percent*	NBDOC *mg C/L*	NBDOC *percent*
Aug. 18, 1984	0.90	0.95	0.55	0.85	0.35	39	0.10	11
May 22, 1985	0.70	2.20	0.60	2.10	0.10	14	0.10	5
Oct. 28, 1985	0.45	1.55	0.35	1.40	0.10	22	0.15	10
Oct. 30, 1985	0.50	1.45	0.20	1.30	0.30	60	0.15	10
Oct. 31, 1985	0.50	1.50	0.20	1.30	0.30	60	0.20	13
Mar. 3, 1986	0.50	1.40	0.25	1.20	0.25	50	0.20	14
Mar. 5, 1986	0.60	1.45	0.35	1.35	0.25	42	0.10	7
Mar. 7, 1986	0.40	1.50	0.20	1.50	0.20	50	0	0
June 4, 1986	0.85	1.80	0.65	1.70	0.20	24	0.10	6
Aug. 25, 1986	0.55	1.45	0.30	1.40	0.25	45	0.05	3
Aug. 26, 1986	0.70	2.10	0.50	2.00	0.20	29	0.10	5

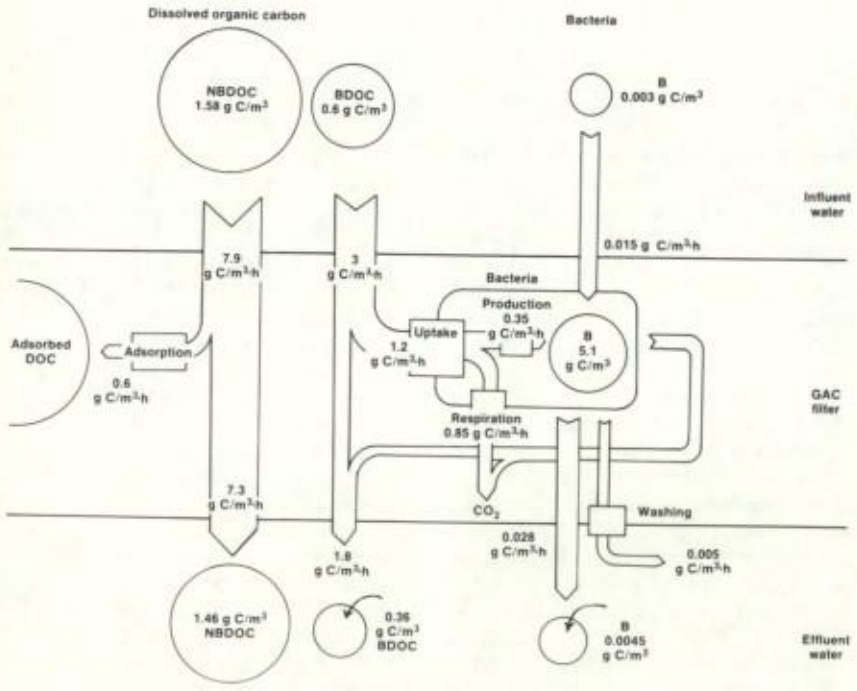

Figure 7. Representation of the overall functioning of a GAC filter at the Choisy-le-Roi plant calculated on the basis of the average values for all parameters measured during the course of the study

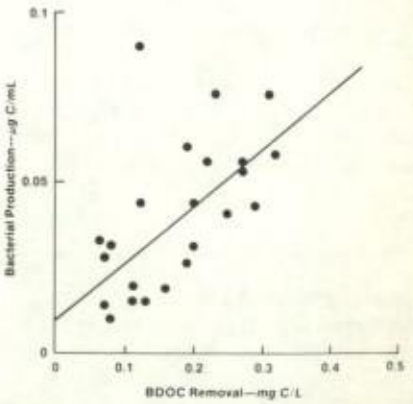

Figure 8. Relationship between bacterial production (estimated for the period corresponding to the contact time during filtration) and the BDOC removal achieved during this contact time at the Choisy-le-Roi plant

and is then bubbled for 10 min to extract the CO_2 that is trapped in a mixture of two packings* (1:4 vol:vol).[15] Radioactivity is determined by liquid scintillation.†

To convert the values of potential glucose respiration rate into bacterial biomass, this method has been calibrated with suspensions of bacteria detached by the early washing procedure from an activated carbon filter. Potential glucose respiration measurement and bacterial enumeration by the AODC method were performed on the same samples containing various concentrations of bacteria. The result shows a good correlation ($r = 0.99$) between both measurements, with the correspondence factor 1.1 μg C of bacterial biomass per nmole glucose respired per hour (Figure 2).

Bacterial production. For estimating bacterial production in GAC samples, the method of (methyl-^{3}H) thymidine incorporation proposed by Fuhrman and Azam[16,17] for the measurement of bacterial production in aquatic environments was adapted. This method consists of determining bacterial biomass production from measurement of the synthesis rate of bacterial DNA. This rate is estimated by the incorporation rate of a labeled precursor of DNA, thymidine. In aquatic environments, a concentration of 5–15 n*M* of ^{3}H-thymidine is usually used to saturate the incorporation process. In the case of a GAC sample, because of the adsorption of part of the thymidine, it was determined that a concentration of at least 50 n*M* was necessary.

During the experimental procedure, 1 mL of 200-n*M* (methyl-^{3}H) thymidine solution‡ (specific activity 40–50 Ci/mmol) and 1 mL of a 200-n*M* cold thymidine solution are added to a 2-mL GAC sample (containing GAC and water as for the measurement of potential glucose respiration). The sample is incubated for 3–4 h at in situ temperature. At the end of incubation, 100 μL of an adenosine triphosphate solution§ (25 g/L), 100 μL of a DNA (from herring sperm) solution§ (0.75 g/L), and 2 mL of 1 *N* sodium hydroxide (NaOH) are added. The sample is then heated for 1 h at 100°C to extract the DNA; after cooling, it is centrifuged for 10 min at 3,000 rpm. One millilitre of the supernatant is collected, added to 5 mL of 10 percent trichloroacetic acid, and cooled for 10 min. It is then filtered through a 0.2-μm-pore-size membrane,** and the radioactivity associated with the filter is counted by liquid scintillation. Control tests for the whole procedure with added ^{14}C-labeled DNA†† showed that the efficiency of DNA recovery is >90 percent.

Conversion of thymidine incorporation rates into bacterial biomass production remains uncertain. Several authors proposed theoretical conversion factors; however, these factors are based on several unproved assumptions.[17-19] In the recent literature, most authors prefer to use an empirical conversion factor determined for each environment studied.[20-23] Such a calibration was established by following bacterial biomass increase and thymidine incorporation in a GAC sample. A 200-cm^3 sample of GAC from a filter was autoclaved, and 100 mL of river water sterilized by 0.2-μm filtration was added. The sample was inoculated by adding 10 mL of river water filtered through a 2-μm membrane‡‡ to retain microzooplankton and was then incubated at 20°C under agitation for two days. Subsamples were taken out every 5–8 h to determine bacterial biomass by the potential glucose respiration method and thymidine incorporation. The observed relationship between bacterial production deduced from bacterial biomass measurements and cumulative thymidine incorporation is shown in Figure 3. From this figure, it was deduced that 1 nmol of thymidine incorporated into bacterial DNA corresponds to a bacterial production of 750 μg C. This conversion factor was used to calculate bacterial production in GAC filters from the ^{3}H-thymidine incorporation rates in GAC samples.

TABLE 4

Enumeration of bacteria in the influent and effluent of GAC filter 38

Date	Bacteria—*number* × 10^6/*mL*		
	Influent	Effluent	Difference
March 3–7, 1986	0.30	0.40	0.10
June 4, 1986	0.06	0.23	0.17
August 25, 1986	0.26	0.31	0.05
August 26, 1986	0.11	0.18	0.07
August 27, 1986	0.06	0.11	0.05
August 28, 1986	0.06	0.13	0.07

TABLE 5

Bacterial biomass evacuated by filter washing

Date	Bacterial Biomass in Filter* *g C/m²*	Bacterial Biomass Evacuated by Filter Washing	
		g C/m²	*percent*
March 3, 1986	3.68	0.14	3.8
March 7, 1986	8.34	0.37	4.4
June 4, 1986	6.16	0.30	4.9
August 25, 1986	3.34	0.28	8.4

*Calculated from the bacterial biomass measurement as a function of depth in the GAC filter

Results

DOC and BDOC reduction. Dissolved organic carbon was determined in the influent and effluent water of GAC filters on 14 occasions between August 1984 and August 1986. The results are presented in Table 2. In the influent water, DOC concentrations ranged from 1.70 to 2.95 mg C/L. In all cases, a significant reduction of DOC by GAC filtration was observed; the difference of DOC between influent and effluent ranged between 0.15 and 0.8 mg C/L.

Knowledge of the BDOC concentration in the influent and effluent is more useful. Using the bioassay procedure developed by Servais et al,[12] BDOC in the influent and effluent was determined on several occasions. The results are presented in Table 3. In the influent, BDOC varied from 0.4 to 0.9 mg C/L, amounting to 21–49 percent of the total DOC (mean 28 percent). This rather high BDOC value may be surprising, considering that the water previously underwent sand filtration. It was shown, however, that the ozone treatment following sand filtration was responsible for an increase in the BDOC fraction at the expense of the refractory fraction.[10] In view of the objective of avoiding bacterial regrowth in the distribution network, it is important to eliminate BDOC. The results of Table 3 show that the observed reduction consists mainly of a decrease in the biodegradable fraction. A mean value of 40 percent of the BDOC was eliminated by passage through the GAC filter, while only 8 percent of the refractory fraction was

*Carbo-Sorb, Packard Instrument Co., Downers Grove, Ill., and Lipoluma, Lumac, Schaesberg, the Netherlands
†Tri-Carb, Packard Instrument Co., Downers Grove, Ill.
‡Amersham Corp., Buckinghamshire, England
§Boehringer Mannheim Diagnostics, Houston, Texas
**Sartorius Filters, Hayward, Calif.
††Nuclepore Corp., Pleasanton, Calif.

retained. This strongly suggests that biological activity, instead of adsorption processes, is responsible for most of the reduction of DOC during GAC filtration at the Choisy-le-Roi plant.

Determinations of DOC and BDOC were also performed on interstitial water collected at different depths within the GAC filter. A typical profile is presented in Figure 4. Organic carbon was mainly reduced in the upper 40 cm of the filter. Clearly, the top 40 cm of the filter is responsible for most of the reduction in BDOC, indicating that an increase of filter depth or of contact time would not result in a proportional improvement in filtration performance.

Bacterial biomass and activity. Numerous determinations of bacterial biomass and production were performed in the period May 1985–August 1986. Figure 5 shows bacterial biomass and production as a function of depth in the GAC filter at different times. Each profile presented in this figure is the average of several (two to seven) determinations performed during one week. Bacterial biomass in the filter ranged from 2.5 to 10.9 μg C/cm^3. Because the mean biovolume of the bacteria observed in the washing water of the filter was 0.18 μm^3, a carbon content of 21.6×10^{-15} g C per bacterium was calculated, and bacterial abundance in the filter was then estimated to be 1.15×10^8 to 5.1×10^8 bacteria/cm^3.

Bacterial production varied from 0.2 to 0.6 μg C/cm^3·h. From these measurements, the bacterial growth rates can be calculated as the ratio between bacterial production and bacterial biomass. They were in the range of 0.038–0.160/h (mean value 0.069/h), indicating a rather rapid turnover of bacterial biomass.

A distinct vertical stratification of bacterial biomass and activity, with values decreasing with depth, was observed at ambient temperatures >15°C (May 1985, June 1986, and August 1986). At lower temperatures (October 1985, March 1986), no such vertical variations are observed.

Input and output of bacterial biomass. Bacteria in the influent and effluent water of the GAC filter were counted directly on several occasions (Table 4). In all cases, bacteria seemed to be more numerous in the outflow than in the inflow. This indicates a small net exportation of bacterial biomass from the filter into the outflow. The values found in the effluent of the GAC in this study are slightly higher than those found by Albat et al[24] in the effluent of GAC filters at the Mery-sur-Oise plant (range 0.041 $\times 10^6$ to 0.15 $\times 10^6$ bacteria/mL). This exportation of bacterial biomass, however, is very low, in terms of organic carbon (mean 0.0003 mg C/L), with respect to the decrease in BDOC achieved by the filter.

Effect of filter washing. GAC filters are washed routinely every 50–100 h of continuous working in summer and after several days in winter. During the washing cycle, the water level is drained to the GAC surface, followed by 2 min of air scour at 30 m/h, air scour and backwashing (10 m/h) until the water level reaches the washing troughs, and water backwash at 25 m/h for 20 min.

In order to test the effect of filter washing on bacteria fixed in the GAC filter, bacterial biomass was determined for GAC samples collected just before and after such a washing cycle. Figure 6 shows the vertical biomass profiles before and after washing of the filter in June 1986. The profiles do not show significant biomass decrease caused by the washing. Moreover, despite the application of air scour, washing does not break the vertical stratification of the biomass.

Direct enumeration of the bacteria in the wash water evacuated by countercurrent flow at the end of the wash cycle allowed evaluation of the bacterial biomass eliminated from the filter during washing (Table 5). These data indicate that only a limited fraction (4–8 percent) of the bacterial biomass fixed on GAC was eliminated during washing.

Moreover, comparisons of bacterial enumeration of the outlet water just before and after washing the filter have shown no significant difference in the exportation of bacterial biomass. These observations lead to the conclusion that washing the filter does not significantly affect microbiological function.

Organic carbon transformations. The data presented previously provide a coherent description of the processes involved in DOC elimination in a biological GAC filter. Figure 7 is a diagram of these processes, summarizing all the data that has been presented in this article on filter 38 at Choisy-le-Roi.

The average values of carbon mass rates within the filter have been calculated and converted into g C/m^3·h, taking into account a 1-m depth, a water filtration velocity of 5 m/h (usual velocity allowed in these first-generation GAC filters), and a frequency of countercurrent washing of one every 50 h.

The values presented in Figure 7 were estimated as follows:

- The organic matter (BDOC and nonbiodegradable DOC [NBDOC]) content of the influent and effluent was calculated as the average of the data presented in Table 3.
- Bacterial biomass in the influent and effluent water was calculated from the average bacterial enumeration (Table 4) and estimations of bacterial cell size (see Methods section).
- Uptake of BDOC (1.2 g C/m^3·h) by bacteria is the difference between BDOC in the influent water and the effluent water (BDOC adsorption is considered to be negligible).
- Adsorption of NBDOC (0.6 g C/m^3·h) is the difference in NBDOC between the influent and effluent waters.
- Bacterial production (0.35 g C/m^3·h) is the mean value of the measurements performed in the filter by the thymidine incorporation method.
- Bacterial respiration (0.85 g C/m^3·h) is the difference between bacterial uptake and production.
- The bacterial biomass exported by the countercurrent washing (0.005 g C/m^3·h) represents an exportation of 5 percent of the fixed biomass every 50 h.
- The fixed bacterial biomass is calculated from the average measurements performed in the filter (Figure 5) by the potential glucose respiration method.

These calculations indicate good agreement between the mean observed value of BDOC reduction through filtration (equivalent to 1.2 g C/m^3·h) and the mean measured value of bacterial production (0.35 g C/m^3·h). Indeed, if the BDOC reduction is considered to result entirely from bacterial uptake, a bacterial growth yield factor of 0.29 is implied, which is in good agreement with direct estimates in similar water that gave a growth yield factor of 0.3.[10] Thus, bacterial heterotrophic activity quantitatively explains the decrease in BDOC observed during filtration; of the 1.2 g C/m^3·h retained in the filter, 0.85 g are respired and eliminated in the form of CO_2 and 0.35 g are used for bacterial biomass synthesis.

The fact that bacterial heterotrophic activity is responsible for BDOC removal in the filters is confirmed by Figure 8. In this figure, bacterial production has been plotted against BDOC removal for all the situations sampled at the Choisy-le-Roi plant; a fairly good correlation ($r = 0.70$) is obtained.

The budget of bacterial biomass in a GAC filter is rather complex. It involves input with the influent, production, and mortality (namely by grazing) within the filters, and output with the outflow or during washing. As indicated by Figure 7, part of the biomass produced within the filter or brought in by the influent is exported by the outflow, either during washing cycles (1 percent) or during filtration (8 percent). However, because only 9 percent of the bacterial biomass produced is evacuated from the filter by these two processes, it seems that the major part (91 percent) of the biomass produced is eliminated by mortality within the filter itself. From the authors' calculated budget, this process seems very important in controlling the steady-state level of bacterial biomass fixed on a filter. In aquatic ecosystems, grazing by protozoa (mainly nano-sized flagellates and ciliates) is generally

considered to be the major process of removal of bacterial biomass.[25,26] A significant population of heterotrophic protozoans was detected in the GAC filter. It is likely that protozoan grazing plays a determinant role in eliminating bacteria growing in a filter.

Discussion and conclusion

In order to maintain biological stability of drinking water during distribution in large and complex networks, high standards have to be met—namely, low bacterial densities and low levels of biodegradable organic carbon.

Biological GAC filters used for several years without carbon regeneration, thus taking advantage of their microbiological properties rather than their adsorption capacities, have proved to be quite effective for reducing dissolved organic matter during drinking water treatment. For a good understanding and rational management of such filters, new methods to measure bacterial biomass and activity associated with GAC need to be developed. The procedures described in this article, which are both informative and experimentally simple, can serve this purpose well. They allowed the microbiological nature of the DOC reduction achieved by biological GAC filtration to be demonstrated. Furthermore, they provide a clear description of the processes involved.

In the present configuration of the Choisy-le-Roi plant, these processes can be summarized in the following way: No prechlorination occurs at the head of the treatment line, ensuring maximum effectiveness of biological activity; an ozonation step, just after sand filtration, converts some refractory organic compounds into biodegradable organic matter, which reaches a level of about 0.6 mg C/L; and within the GAC filter, during an EBCT of about 12 min, 40 percent of this organic carbon is converted into CO_2 and bacterial biomass, yielding a concentration of 0.35 mg C/L in the outflow water.

Only a very small part of the biomass produced (7 percent) is exported with the outflow; the remaining part is either evacuated during the countercurrent washings or eliminated biologically through predation. The elimination of bacteria from the outflow is easily achieved using chlorine disinfection before the water is delivered to the distribution network. Chlorination at this stage presents fewer drawbacks than it would at previous treatment stages, in which the presence of ammonium ion and more organic carbon could lead to the formation of undesirable chlorinated compounds, or than it would in the distribution network where it is difficult to manage.

The measurements of bacterial biomass and activity performed in the GAC filter through a seasonal cycle revealed a difference between winter and summer, a stratification of biomass and activity in the filter being observed in the latter and not in the former. This indicates better elimination of the most easily biodegradable compounds at higher temperatures.

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