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SUPPLY OF ORGANIC MATTER AND BACTERIA TO AQUATIC ECOSYSTEMS THROUGH WASTE WATER EFFLUENTS

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Abstract—In order to study the impact on the river Seine of the waste water effluents from the city of Paris and its suburbs, a detailed characterisation was made of both raw and treated effluents from the three main treatment plants in this area which differ both in size and type of treatment. The waste water samples were subjected to analyses of the following pools of carbon: dissolved organic carbon (DOC), particulate organic carbon (POC), biodegradable fractions of DOC (BDOC) and of POC (BPOC), the biochemical oxygen demand (BOD). Inorganic and organic forms of nitrogen and phosphorous, total bacterial biomass and nitrifying bacterial biomass were also investigated in parallel. On the basis of the results of the analysis performed, a specific load per inhabitant and per day (expressed in g inh^{-1} d^{-1}) for raw and the different types of treated waste water was calculated for each variable considered in this study. For raw water, the specific loads of TOC ranged between 26.4 and 28.3 g C inh^{-1} d^{-1} with particulate organic matter constituting the main part (70–76%) and the biodegradable fraction representing between 60 and 75%. Concerning micro-organisms, the average specific load of total bacteria was around 2 g C of biomass inh^{-1} d^{-1}, the nitrifying biomass represented 0.3–2.5% of the total bacterial biomass. Depending on the type of treatment, the specific load of TOC in treated water ranged between 3 and 10.8 g C inh^{-1} d^{-1}, it corresponded to removal percentages in the range 59–89%. Total bacterial biomass (0.05–0.33 g C inh^{-1} d^{-1}) was always lower in treated than in raw water. A significant correlation was observed between BTOC (sum of BDOC and BOPC) and BOD. BPOC represented 68% of BTOC in raw water and 43% in treated water. The total biomass of bacteria constituted 8% of the BTOC.

Key words—waste water, bacterial biomass, organic matter, biodegradability, nitrifying bacteria

INTRODUCTION

Degradation of organic matter by heterotrophic bacteria is one of the major processes controlling the oxygen level of aquatic ecosystems and thus their quality. In most aquatic ecosystems, organic matter has a mainly autochthonous origin but, for rivers flowing through urbanised areas, waste water effluents can be the major source of organic matter.

The effluents from the Achères treatment plant, which treats the greater part of the waste water from the 10 million inhabitants of Paris and its suburbs, strongly influence the ecological parameters of the river Seine. The effluents are an important source of organic matter with a heavy input of nitrogen and phosphorus, as well as a source of heterotrophic bacteria whose activity causes significant oxygen depletion immediately downstream of the effluent discharge point (Servais and Garnier, 1990, 1993; Garnier *et al.*, 1992a, b). Moreover, the ecological parameters of the river Seine are affected by the input of nitrifying bacteria which play a role in the oxygen deficit in the lower reaches of the river and its estuary (Chesterikoff *et al.*, 1992).

In the scope of the multidisciplinary study of the river Seine, ecological models aimed at a better understanding of the river ecological processes were developed; they were than used to test rehabilitation scenarios (Billen *et al.*, 1993; Even and Poulin, 1993; Even *et al.*, 1998). These models, contrarily to most models describing organic matter degradation, explicitly takes into account the compartment of the heterotrophic and nitrifying bacteria. These models require, as input data, a characterisation of the organic matter brought by the treatment plants effluents (biodegradable and refractory parts of dissolved and particulate organic carbon) rather than the classically used parameters such as biochemical oxygen demand (BOD) and chemical oxygen

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demand (COD). These parameters are often insufficient to correctly predict the impact of waste water release on an aquatic ecosystem.

This paper deals with a characterisation of both raw and treated effluents from the three main treatment plants in the Paris suburbs which differ in both size and type of process. We analysed the dissolved and particulate organic matter and separated it into biodegradable and refractory fractions using a recently developed bioassay (Servais *et al.*, 1995) which is based on measurements of dissolved organic carbon and particulate organic carbon. Beside the carbon measurements, we analysed the nitrogen and phosphorus content of dissolved and particulate organic matter; inorganic nitrogen and phosphate were also estimated as well as total bacterial biomass and the biomass of nitrifying bacteria in raw and treated water.

In addition, the objectives of the present study were to establish a specific load per inhabitant and per day (expressed in g inh^{-1} d^{-1}) for the raw and the treated waste water in terms of ecological variables and to test the possibility of extrapolating the variables characterising the waste water from classical BOD measurements by investigating simple relationships between classical and ecological variables.

MATERIAL AND METHODS

Sampling program

The three main waste water treatment plants in the Paris suburbs (Achères, Valenton and Noisy-le-Grand) were investigated in the course of this study (Fig. 1). These plants have different treatment processes and treatment capacities (Fig. 2, Table 1). In dry weather periods, samples of raw water from each plant were collected and treated waters were sampled at different points along the treatment lines (Fig. 2). The samples from the three plants allowed us to investigate the effects of five types of treatment (Table 1, Fig. 2). To establish the relationships presented below, previous data obtained in dry weather in June 1992 at the Achères treatment plant were also used.

The analyses were made on mean daily samples collected at each plant over a 24 h period with refrigerated ($< 6°C$) automatic samplers. Bioassays and potential nitrifying activity measurements started just after the samples had been collected. Formaldehyde (2% final concentration) was added to samples for bacterial enumeration and phosphoric acid (3% final concentration) to samples for DOC measurements; samples for POC, nitrogen and phosphorus estimates were freezed at $-20°C$.

Suspended matter

Suspended matter (SM) was estimated as the weight of material retained on a Whatman GF/F membrane per volume unit after drying of the filter for 2 h at 120°C. The filtered volumes ranged between 40 and 200 ml.

Carbon analysis

The following pools of carbon were analysed on the waste water samples: dissolved organic carbon (DOC), particulate organic carbon (POC), the biodegradable fractions of DOC (BDOC) and of POC (BPOC), the biochemical oxygen demand (BOD).

For DOC analysis, the samples were filtered through pre-combusted (4 h at 550°C) fibreglass Whatman GF/F filters. The DOC concentration was determined with a Dorhmann DC180 Total Carbon Analyser (Rosemount Analytical Division, Santa Clara, USA) using ultra-violet persulfate oxidation of organic carbon, followed by infrared spectrophotometric detection of the produced CO_2. For the POC analysis, the samples 1–5 ml were filtered through a pre-combusted fibreglass filter (Whatman GF/F). Organic matter retained on the filter was oxidised by catalytic combustion; the CO_2 produced was determined with the same detector as for the DOC analysis. The accuracy of the DOC and POC data was around 0.05 mg C l^{-1}. Total organic carbon (TOC) was calculated as the sum of DOC and POC.

The biodegradable fraction of DOC (BDOC) and POC (BPOC) was measured in parallel according to Servais *et al.* (1995). The water sample was incubated at $20 \pm 0.5°C$

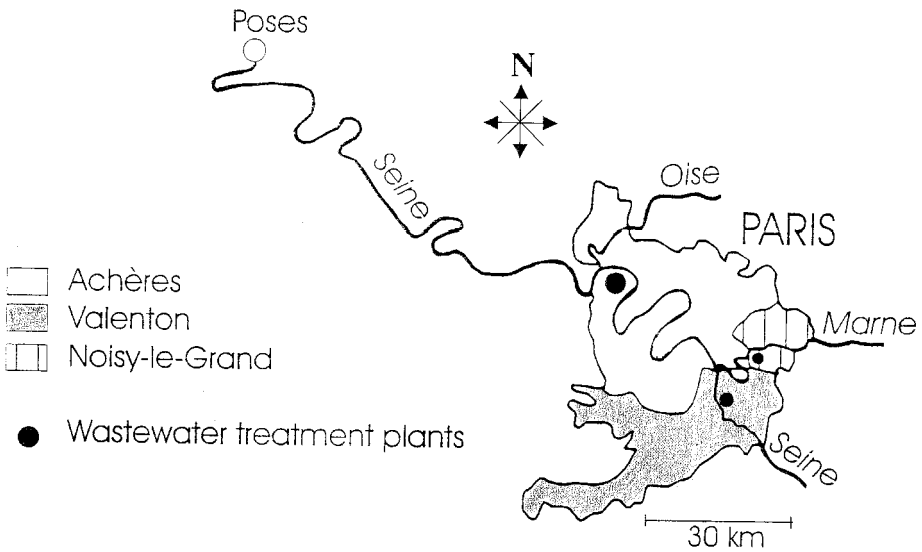

Fig. 1. Location of the three studied treatment plants and of their catchment areas (Achères (107750 ha), Valenton (68800 ha), and Noisy-le-Grand (12850 ha)).

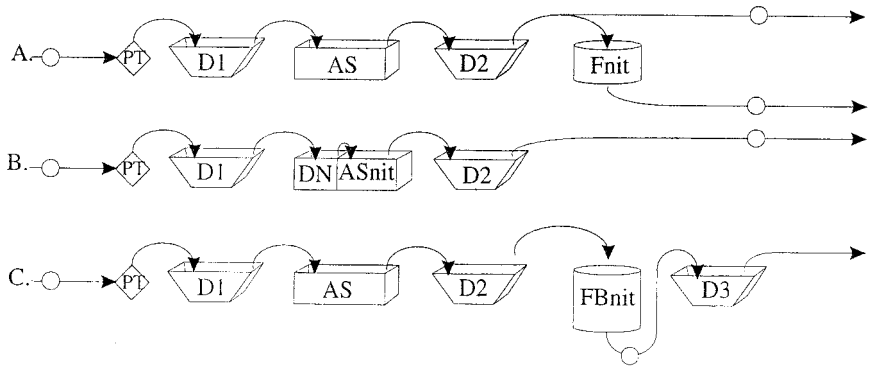

Fig. 2. Schematic representation of the treatment lines of the plants (Achères (A), Valenton (B) and Noisy-le-Grand (C)). Symbols for the different treatments: PT: primary treatment. D1,2,3: primary, secondary and tertiary decantation. AS: Activated sludge reactor (ASNIT: aerobic area; DN: anaerobic area). F NIT: Biofilter (BIOSTYR process, OTV) pilot for nitrification (treatment capacity of the pilot: 30000 m^3 d^{-1}). FB NIT: Fixed-bed reactor with nitrification (SESSIL process). Circles represent the sampling points.

in aerobic conditions and subsamples for DOC and POC measurements were collected from the batch just after the start of the incubation and after 45 d (a period long enough to reach stable values of DOC and POC); the remaining organic carbon was considered as the refractory part of the organic matter. BDOC and BPOC were calculated as the difference between the concentrations, of DOC and POC respectively, at the beginning of the batch experiment and the stable values reached at the end of the incubation which were defined as the refractory fraction of DOC and of POC. The biodegradable fraction of TOC (BTOC) was calculated as the sum of BDOC and BPOC.

BOD was determined by measuring oxygen consumption in diluted samples incubated over 5 d at 20°C according to AFNOR (1994).

Nitrogen analysis

The different forms of inorganic nitrogen were determined on samples filtered on a Whatman GF/F membrane: ammonium by indophenol blue colorimetry according to Slawyc and McIsaac (1972), nitrite by the method of sulphanilamide (Jones, 1984) and nitrate after reduction into nitrite by cadmium in a basic medium followed by nitrite dosage (Jones, 1984). Kjeldhal nitrogen was determined on unfiltered samples according to AFNOR (1994); total organic nitrogen (TON) was estimated as the difference between Kjeldhal nitrogen and ammonium. The particulate nitrogen was determined on material retained on pre-combusted Whatman GF/F filters using an Antek 700 Total Nitrogen Analyser where nitrogen is estimated by chemiluminescence after oxidation at high temperature. Since the quantity of inorganic nitrogen on particles can be neglected, particulate organic nitrogen (PON) was assimilated to particulate nitrogen. Dissolved organic nitrogen (DON) was estimated by the difference between TON and PON.

Phosphorus analysis

Phosphate was measured by spectrophotometry according to AFNOR (1994). Total dissolved phosphorus (TDP) was estimated on filtered samples on pre-combusted Whatman GF/F membranes and total particulate phosphorus (TPP) on material retained on the same type of filters. The filtered samples and the filters were mineralised with a persulfate solution in a basic medium (Pujo-Pay and Raimbault, 1994); the phosphate was estimated after mineralisation. Dissolved organic phosphorus was determined as the difference between TDP and phosphate.

Bacterial biomass

Total bacterial biomass – Total bacterial numbers were determined by epifluorescence microscopy at 1000× magnification after DAPI (4–6-diamino-2-phenylindole, final concentration: 10 μg ml^{-1}) staining according to the procedure by Porter and Feig (1980). To break up aggregates, the samples were sonicated for 20 s with a Labsonic

Table 1. Characteristics of studied waste water treatment plants

Treatment plant	Sampling date	Equivalent inh. treated	Treated discharge (m^3 d^{-1})[a]	General characteristics of the treatment plants
Achères	March 1, 1994	7000000	2372000	high load activated sludge (water residence time; 2–3 h
Achères, BIOSTYR	March 1, 1994	92000	30000	high load activated sludge followed by biofiltration for nitrification (BIOSTYR process)
Valenton	April 5, 1994	1000000	253000	high load activated sludge including an aerobic and an anaerobic stage (water residence: 10 h)[b]
Noisy-le-Grand, DEC II	June 22, 1994	110000	28000	activated sludge in aerobic conditions (water residence time: 3–4 h)
Noisy-le-Grand, SESSIL	June 22, 1994	110000	28000	activated sludge in aerobic conditions followed by a tertiary nitrification treatment (SESSIL process)[c]

[a]The treated discharges concerns the sampling date.
[b]The first part of this activated sludge process is in anaerobic conditions (no aeration) with denitrification occurring while the second part of the process is in aerobic conditions with nitrification occurring.
[c]In the SESSIL process waste water trickles along long narrow suspended plastic strips colonised by bacteria. A tertiary decantation normally follows this biological treatment but was out of order during sampling.

(Braun, Melsungen, Germany) at 30 W before being prepared for microscopy. A minimum of 600 bacteria were counted and classified into 24 size classes by comparison with an eye piece graticule to determine biovolume. Biomass was estimated from the abundance and biovolume distribution by means of the carbon/biovolume conversion factor proposed by Simon and Azam (1989) which varies according to cell volume and tends to the asymptotic value of 1.3×10^{-13} g C μm^{-3} for cells larger than 0.4 μm^3. The biomass was calculated for two size classes: small bacteria (greatest dimension less than 1 μm) and large bacteria (1 μm and more).

Nitrifying bacterial biomass – Potential nitrifying activity (i.e. in optimum conditions of temperature and substrate) was measured in waste water as the difference in $H^{14}CO_3^-$ incorporation between two subsamples, one control and one treated with specific nitrification inhibitors (N-serve and chlorate) (Brion and Billen, 1998). A conversion factor of 0.11 μmole of C incorporated per μmole NH_4^+ oxidised was used (Brion and Billen, 1998). Potential nitrifying activities, proportional to nitrifying biomass, were converted into nitrifying biomass by means of the maximum specific activity (AS_{max}) of ammonium and nitrite oxidising bacteria. AS_{max} was determined experimentally on pure cultures of *Nitrosomonas europea* (NCIMB 11850) and *Nitrobacter winogradskyi* (NCIMB 11846) by measuring simultaneously the N oxidation rate and the total biomass. An AS_{max} of 0.21 and 0.05 μmol Nox. μg C^{-1} h^{-1} were found respectively for nitrite and ammonium oxidising bacteria (Brion and Billen, 1998). Total nitrifying biomass was determined according to the following equation:

$$NIT = \frac{PNA}{ASnit1} + \frac{PNA}{ASnit2}$$

where NIT represents total nitrifying biomass (μg C l^{-1}), PNA: potential nitrifying activity (μmol N l^{-1} h^{-1}), Asnit1: maximum specific activity (μmol Nox. μg C^{-1} h^{-1}) of *Nitrosomonas europaea* and ASnit2: maximum specific activity (μmol Nox. μg C^{-1} h^{-1}) *Nitrobacter winogradskyi*.

Precision of the analyses

All analyses were done in duplicate on integrated samples obtained over a 24 h period. In the conditions of our study, all variables have values far above the detection limits. Precision better than 5% was obtained for dissolved inorganic N and P. Precision was around 10% for organic matter and total suspended matter, and around 20% for bacteria epifluorescence counts and potential nitrifying activity.

Calculation of specific charges

In order to compare the different treatment plants, the variables measured in the raw and treated waste water were calculated in terms of specific load, i.e., the amount discharged per inhabitant-equivalent and per day. This calculation requires to know the daily waste water volume per capita. Such a volume was calculated considering a daily charge in BOD of 54 g per inhabitant as proposed by the WHO (1982). The daily waste water volume per capita expressed in cubic meter was easily estimated by dividing this value of 54 g inh^{-1} d^{-1} by the concentration of BOD in the raw water (mg/l). For the different treatment plants, this volume was calculated as follows: 324 l inh^{-1} d^{-1} for Achères, 266 l inh^{-1} d^{-1} for Valenton and 257 l inh^{-1} d^{-1} for Noisy-le-Grand. The specific load of the raw water in the different treatment plants was calculated by multiplying the concentration of a given variable by the daily volume per inhabitant of the corresponding plant.

RESULTS AND DISCUSSION

Specific load of raw water

The specific loads of the various forms of carbon, nitrogen and phosphorous in the raw water reaching the treatment plants fell inside quite a narrow range (Table 2). As specific load of raw waste water

Table 2. Specific loads of the raw waste water from the different treatment plants (Achères, Valenton et Noisy-le-Grand) and average specific charge for the three treatment plants with standard deviation (SD)

Variables	Achères (g inh^{-1} d^{-1})	Valenton (g inh^{-1} d^{-1})	Noisy-le-Grand (g inh^{-1} d^{-1})	Average raw water (g inh^{-1} d^{-1})	SD (g inh^{-1} d^{-1})
SM	82.4	77.1	71.4	77.0	5.50
DOC	6.6	6.4	8.5	7.2	1.16
BDOC	4.6	4.8	6.6	5.3	1.10
POC	19.8	20.7	19.8	20.1	0.52
BPOC	11.0	15.5	12.3	12.9	2.32
TOC	26.4	27.1	28.3	27.3	0.96
BTOC	15.6	20.3	18.9	18.3	2.41
BOD	54.0	54.0	54.0	54.0	
N-NH_4	7.67	9.10	9.76	8.84	1.07
N-NO_3	0.14	0.11	0.10	0.12	0.02
N-NO_2	0.14	0.00	0.00	0.05	0.08
TON	2.95	5.88	3.08	3.97	1.66
DON	1.38	3.88	0.72	1.99	1.67
PON	1.57	2.00	2.36	1.98	0.40
Total N	10.90	15.09	12.94	12.98	2.10
P-PO_4	0.74	1.04	1.05	0.94	0.18
DOP	0.12	0.06	0.26	0.15	0.10
TPP	1.06	1.07	1.00	1.04	0.04
Total P	1.92	2.17	2.31	2.13	0.20
Total bacteria (g C inh^{-1} d^{-1})	0.89	2.87	2.27	2.01	1.02
Bacteria <1 µm	0.10	0.35	0.27	0.24	0.13
Bacteria >1 µm	0.79	2.52	1.99	1.77	0.89
Nitrifying bacteria (mg C inh^{-1} d^{-1})	53.51	8.08	13.37	24.99	24.84

was similar for most of the variables whatever the site investigated, the differences between the different treatment plants can be considered as representing the variability of the results, that is between 10 and 20%. Based on the results gathered on raw water, we assumed that the data shown on treated water must be considered with a precision around 20%. However, variability is much greater for heterotrophic and nitrifying bacterial biomass.

To calculate the specific loads, we used the value of 54 g BOD inh^{-1} d^{-1} proposed by the WHO (1982). This value is also used in the legal definition of the inhabitant-equivalent in some European countries. Moreover, a recent review (DeCuyper and Loutz, 1992) concerning data obtained in different countries for per capita BOD load gives values in the range of 30–117 g BOD inh^{-1} d^{-1} but most of the values are in a smaller range (45–60 g BOD inh^{-1} d^{-1}). The average of the 16 values quoted in the above review is 52 g BOD inh^{-1} d^{-1}, very close to the value we used.

The specific loads of SM ranged between 71.4 and 82.4 g inh^{-1} d^{-1} with an average value of 77 g inh^{-1} d^{-1}, in the upper range (from 20 to 86 g inh^{-1} d^{-1}) of those mentioned by DeCuyper and Loutz (1992).

Concerning the organic carbon, the specific loads of TOC ranged between 26.4 and 28.3 g C inh^{-1} d^{-1}. The particulate organic matter constituted the main part of the TOC (70–76%). The biodegradable fraction represented between 60 and 75% of the TOC. The average value of the specific TOC load in raw water (27.3 g C inh^{-1} d^{-1}) can be compared with the result of the rough calculations of TOC from BOD measurements. We obtain a calculated specific TOC load of 33.8 g C inh^{-1} d^{-1} which is not far from our average experimental estimate (27.3 g inh^{-1} d^{-1}) by taking a ratio of COD/BOD of 2 (DeCuyper and Loutz, 1992), and considering a theoretical oxygen demand of 3.2 g of oxygen per g of carbon for the organic matter. The latter value is based on the composition of the raw waters in the Achères treatment plant in terms of proteins, carbohydrates and lipids estimated by Barillier (1992) and on the theoretical oxygen demand of these different compounds (Pitter and Chuboda, 1990).

The specific load of total nitrogen ranged between 10.9 and 15.1 g N inh^{-1} d^{-1} with an average of 13 g N inh^{-1} d^{-1}; ammonium was the dominant form (60–76%) followed by organic nitrogen (24–39% of the total nitrogen). The average value of 13 g N inh^{-1} d^{-1} is higher than the value reported by the WHO (1982) which is 9 g N inh^{-1} d^{-1} but it does not disagree with DeCuyper and Loutz (1992), who proposed, in their review on waste water composition, values between 6 and 16 g N inh^{-1} d^{-1}.

The specific loads in total phosphorus ranged between 1.9 and 2.3 g P inh^{-1} d^{-1}. Orthophosphates and phosphorus linked to particles (particulate organic phosphorus and phosphate adsorbed on particles) were the two main pools of phosphorus in raw water. The average specific load of total phosphorus (2.1 g P inh^{-1} d^{-1}) was not very high compared to the value of 3.4 g P inh^{-1} d^{-1} of total phosphorous load mentioned by Verbanck *et al.* (1989) for Brussels (Belgium) where detergents constituted the main source (2 g P inh^{-1} d^{-1}). In the Paris area, it seems that a constant decrease of phosphorous load has been observed in the recent years (SIAAP, pers. com.).

Up to now, bacteria in waste water effluents have been studied mainly from a sanitary point of view, in particular the removal of faecal bacteria by different types of treatment was investigated (Hirn, 1980; Miescier and Cabelli, 1982). There are some published estimates of the total bacterial biomass present in activated sludge and fixed-bed reactors using various methods (Plate count, ATP measurement, estimates of enzymatic activity such as dehydrogenase, proteolytic, glucosidasic activity, etc.) (Nouvion *et al.*, 1987; Guliano *et al.*, 1988; Nybroe *et al.*, 1992; Lemmer *et al.*, 1994) but the supply of heterotrophic bacteria through waste water did not receive much attention. In our study, the average specific load of total bacteria was around 2 g C inh^{-1} d^{-1}. The range of values of bacterial biomass found in the different treatment plants is much higher than that of the other variables. Bacteria larger than 1 μm represented around 90% of the total biomass in the raw water of the three plants. We have shown previously that these large bacteria were predominant in waste water and much more active in the biodegradation process in the river Seine than the small autochthonous bacteria (Servais and Garnier, 1990, 1993; Garnier *et al.*, 1992a, b). For nitrifying bacteria, the specific load varied widely from one plant to another, from 8 to 53.5 mg C inh^{-1} d^{-1}. These specific loads represented 0.3–2.5% of the total bacterial biomass.

Specific loads in treated water

The specific loads in the treated water were calculated as described for raw water (Table 3).

Due to very efficient removal of suspended matter by the different plants (from 83% at Achères to 98% at Valenton), the specific loads of SM are low in the treated water (between 1.3 g inh^{-1} d^{-1} at Valenton and 14.3 g inh^{-1} d^{-1} at Achères).

The treated specific loads of TOC ranged from 3 to 10.8 g C inh^{-1} d^{-1}; this corresponds to removal percentages in the range of 59–89% (Fig. 3). In percentage, the reduction of POC (71–96%) was always higher than that of DOC (26–67%). The removal of DOC in mg C l^{-1} was approximately similar to the BDOC abatement with a very limited abatement of the refractory fraction of DOC. This shows that the dissolved fraction was removed

Table 3. Specific load in water treated by the different processes

Variables	Achères (g inh^{-1} d^{-1})	BIOSTYR (g inh^{-1} d^{-1})	Valenton (g inh^{-1} d^{-1})	Noisy-le-Grand, DEC II (g inh^{-1} d^{-1})	Noisy-le-Grand, SESSIL (g inh^{-1} d^{-1})
SM	14.3	4.0	1.3	5.4	3.9
DOC	4.9	3.6	2.1	3.4	3.2
BDOC	2.5	1.3	0.7	1.9	1.5
POC	5.8	1.9	0.9	2.1	1.5
BPOC	1.6	0.2	0.4	1.3	0.8
TOC	10.8	5.5	3.0	5.5	4.7
BTOC	4.1	1.5	1.1	3.2	2.3
BOD	12.2		1.0	3.6	2.8
$N\text{-}NH_4$	9.01	1.23	0.02	7.68	1.70
$N\text{-}NO_3$	0.08	7.12	5.84	1.31	6.89
$N\text{-}NO_2$	0.02	0.05	0.01	0.31	0.71
TON	1.95	1.14	0.55	0.95	0.71
DON	1.20	0.79	0.42	0.49	0.33
PON	0.75	0.35	0.13	0.46	0.38
Total N	11.06	9.54	6.42	10.26	10.01
$P\text{-}PO_4$	0.75	0.89	0.95	1.07	1.05
DOP	0.16	0.11	0.11	0.09	0.15
TPP	0.33	0.06	0.17	0.11	0.08
Total P	1.24	1.06	1.23	1.27	1.28
Total bacteria (g C inh^{-1} d^{-1})	0.33	0.15	0.05	0.19	0.07
Bacteria <1 μm	0.04	0.03	0.02	0.03	0.03
Bacteria >1 μm	0.29	0.12	0.03	0.16	0.04
Nitrifying bacteria (mg C inh^{-1} d^{-1})	3.44	1.29	3.56	4.52	23.68

mainly through the process of biodegradation rather than through a physico-chemical process. In contrast, the percentages of POC and BPOC removal were very similar which indicates that proportionally the refractory and the biodegradable fractions of POC are removed with a same effectiveness. This means that the impact of biodegradation on particulate organic matter in activated sludge was low compared to the decantation which was the major process in removing POC. A comparison of the efficiency of the three plants in removing organic matter by decantation and activated sludge treatment shows that the Achères plant was less efficient than Noisy-le-Grand and Valenton plants. The Valenton plant was found to be the most performant. This is due to different procedures of the decantation stage as well as to different residence times of water in the activated sludge process. The removal of BDOC by the activated sludge process clearly improved with increasing the residence time: 46% at Achères, 71% at Noisy-le-Grand, 85% at Valenton. Data on organic matter also show that the nitrification biofilter (BIOSTYR process) significantly increased the removal of TOC: 59% removed by decantation and activated sludge versus 79% if the tertiary treatment is added. This impact is due both to biodegradation (removal of BDOC) and to physical retention of POC by this kind of biofilter.

In the absence of denitrification, the specific loads in treated water (11.1 g N inh^{-1} d^{-1} at Achères and 10.26 g N inh^{-1} d^{-1} at Noisy-le-Grand) were not greatly decreased compared to the raw water specific loads (average 13 g N inh^{-1} d^{-1}) while it was reduced to 6.4 g N inh^{-1} d^{-1} at Valenton after treatment in the aerobic–anaerobic activated sludge (Fig. 4). In the absence of nitrification, ammonium was the dominant form of nitrogen in treated water as it was the case in raw water. Tertiary nitrification treatment tested at Achères and at Noisy-le-Grand efficiently converted ammonium into nitrate (ammonium reduced by 85%). In Valenton the long residence time in aerobic conditions resulted in a complete nitrification of the effluents.

The specific load of total phosphorus was quite similar in the various types of treated water (on average 1.22 g P inh^{-1} d^{-1}) although it seems that the biofiltration slightly increased the removal of DOP and TPP. In all cases, phosphate was the dominant form of phosphorous in treated water (60–85% of the total phosphorous). With the different tested treatments, the removal of total phosphorus ranged from 35 to 45%; the removal concerned the particulate fraction.

In all cases, the bacterial biomass was significantly lower in the treated water (specific load in the range of 0.05–0.33 g C inh^{-1} d^{-1}) than in the raw water (average specific load: 2.01 g C inh^{-1} d^{-1}); the removal of total bacterial biomass amounts to 73–92% (Fig. 5). Total bacterial biomass in the treated effluents was dominated by large-size bacteria.

In general, the nitrifying bacterial biomass was lower in the treated water (specific loads in the range of 1.3–4.5 mg C inh^{-1} d^{-1}) than in the raw water Table 3. Nitrifying bacteria are probably produced within the sewer system before reaching the treatment plant. Such hypothesis could explain the higher content in the raw water at Achères as com-

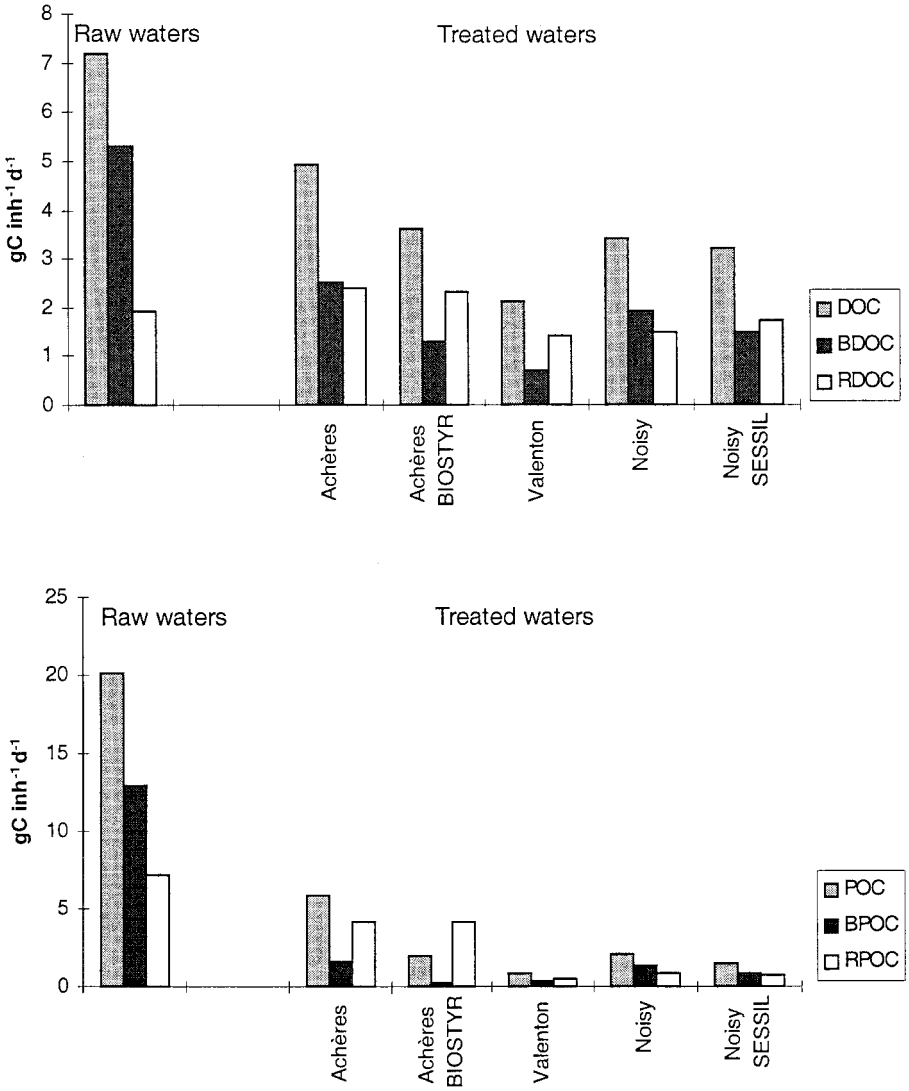

Fig. 3. Specific loads per inhabitant-equivalent and per day of the different forms of organic carbon in raw water (average value) and in the treated water.

pared to the other two plants that have smaller catchments. Most of the nitrifying biomass produced within the treatment process is retained by decantation, except in the case of the Noisy-le-Grand SESSIL process where the amount of nitrifying bacteria is higher in treated effluents (23.7 mg C inh^{-1} d^{-1}), probably because of the failure of the tertiary decantation treatment at the time of sampling Table 1. The nitrifying biofilter system at Achères (BIOSTYR) produces the lowest nitrifying biomass (1.3 mg C inh^{-1} d^{-1}), probably because of the large contact surface and mechanical efficiency of the biofilter. The effluents of the nitrifying–denitrifying activated sludge system at Valenton have intermediate values of specific loads of nitrifying biomass (3.6 mg C inh^{-1} d^{-1}) which are not higher than those in effluents without nitrifying activated sludge.

Whereas a clear decrease is observed between specific load of bacteria (total and nitrifying) from raw to treated waters, further investigations would be necessary to really quantify the impact of each of the process due to the variability of the results between plants.

Relationships between variables

The above characterisation of waste water differs from the classical approach, based mainly on biochemical oxygen demand (BOD) measurements. In order to extrapolate the variables of interest from classical BOD measurements, we investigate possible relationships between key variables.

A significant correlation was observed ($r^2 = 0.91$, $n = 23$) when BTOC values were plotted against BOD for raw and treated water (Fig. 6). BTOC represents the organic matter in the samples biode-

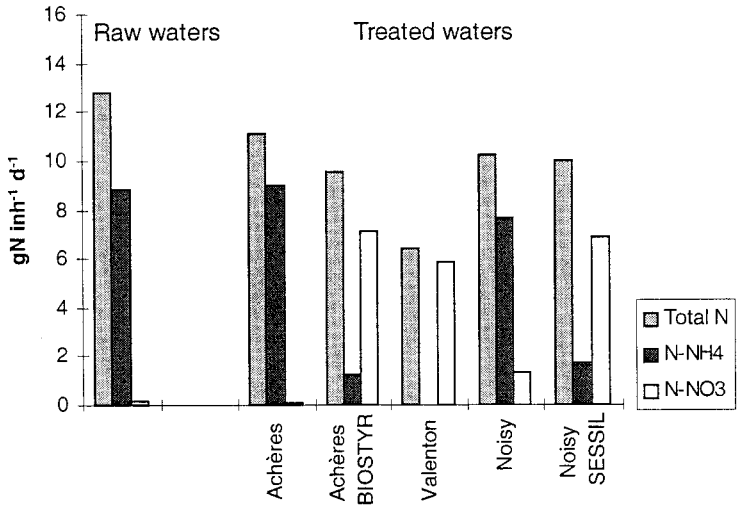

Fig. 4. Specific loads per inhabitant-equivalent and per day of the different forms of nitrogen in raw water (average value) and in treated water.

graded over a period of a month and a half, while BOD is the oxygen consumption due to the oxidation of organic matter over a 5 d period. The regression line passing through the origin has a slope of 0.35 indicating that 2.86 mg of BOD corresponds to 1 mg of BTOC. This slope is not significantly different when raw water and the treated water are independently considered. If the incubation periods had been similar, the expected ratio would have been 3.2 g of oxygen per g of carbon (see above). If we consider BTOC as an ultimate BOD this would mean a ratio between 5 d BOD and ultimate BOD of 0.89 (2.86/3.2). Hammer (1986) reported a ratio between 5 d BOD and ultimate BOD around 0.8 which is a little lower than the value found in the present study. It is possible that some nitrification occurs in some of our BOD tests causing an overestimate of the oxygen consumed for carbon oxidation and thus a overestimation of the BOD/BTOC ratio.

The calculated regression line could be very useful for converting the classical BOD measurements made in all treatment plants to control the functioning of the various processes into biodegradable carbon unit (BTOC).

The relationships between biodegradable particulate organic carbon (BPOC) and BTOC were different in raw and treated water (Fig. 7). Both correlations are significant and the slopes of the regression lines passing through the origin are respectively 0.68 for the raw and 0.43 for the treated water. These slopes show that the particulate part is greater in raw than in the treated water, such findings confirm that water treatments are more efficient in removing particulate than the dissolved organic carbon. By means of these relationships,

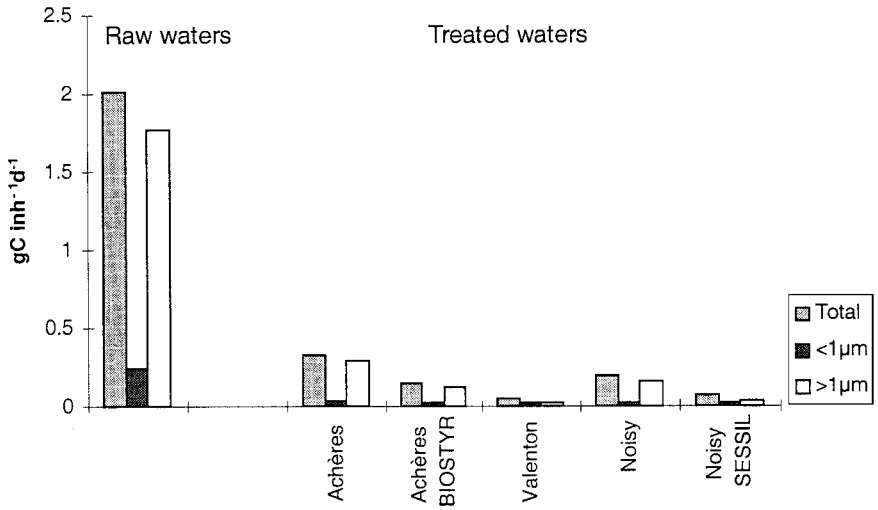

Fig. 5. Specific loads per inhabitant-equivalent and per day of bacterial biomass in raw water (average value) and in the treated water.

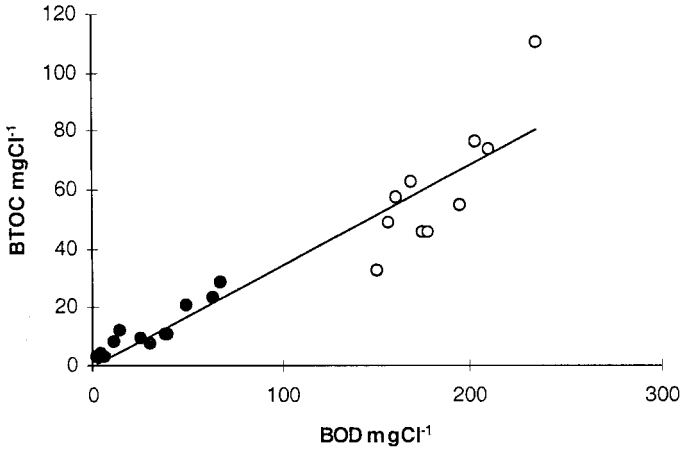

Fig. 6. Relationship between BOD and biodegradable total organic carbon (BTOC) for raw (○) and treated water (●). Regression straight line passing through the origin: BTOC = 0.35 × BOD ($r^2 = 0.91$, $n = 23$).

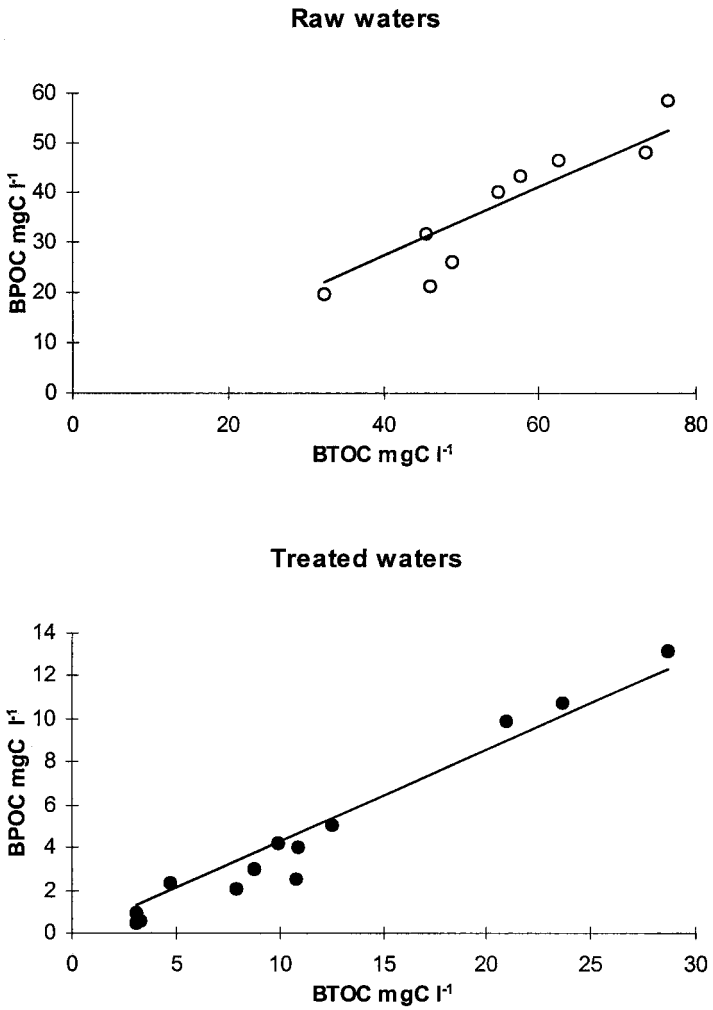

Fig. 7. Relationship between biodegradable particulate organic carbon (BPOC) and biodegradable total organic carbon (BTOC) for raw (○) and treated water (●). Regression straight lines passing through the origin: BPOC = 0.68 × BTOC ($r^2 = 0.83$, $n = 9$) (raw water); BPOC = 0.43 × BTOC ($r^2 = 0.95$, $n = 13$) (treated water).

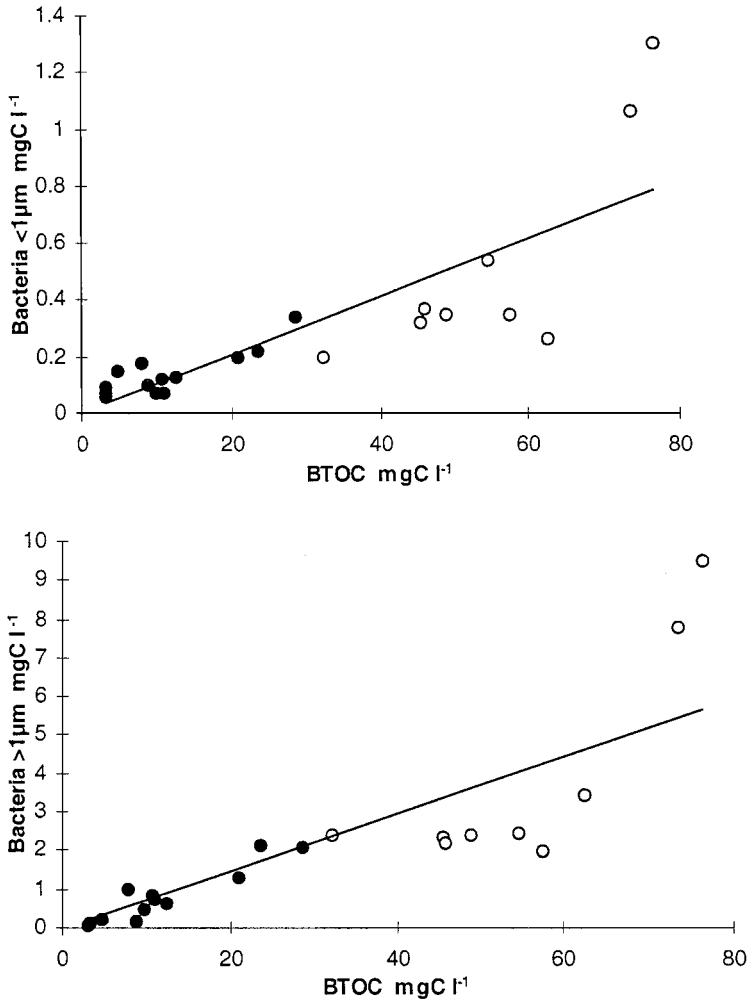

Fig. 8. Relationship between bacterial biomass and BTOC for raw (○) and treated water (●). (a) Small (< 1 μm) bacteria (BBs) and (b) large (> 1 μm) bacteria (BBl). Regression straight lines passing through the origin: BBs = 0.01 × BTOC ($r^2 = 0.69$, $n = 22$) (small bacteria); BBl = 0.07 × BTOC ($r^2 = 0.71$, $n = 22$) (large bacteria).

BPOC and BDOC can be deduced from BTOC values.

Biomass of small (< 1 μm) and large bacteria (> 1 μm) were plotted against BTOC (Fig. 8). The correlations are statistically significant and the slopes of regression lines indicate a ratio between bacterial biomass and BTOC of 0.01 for the small bacteria and 0.07 for the large ones. The bacterial biomass in the plants effluents was mainly composed of large bacteria as the biomass of large bacteria represents on average 1% of the BTOC while the biomass of large bacteria represents 7% of raw and treated effluents (Fig. 8). These results are in agreement with Garnier *et al.* (1992a) who found that large bacteria dominated in the effluents of the Achères plant. The similarity of the large bacteria/total biomass ratios in raw and treated water tends to support the idea that these large bacteria originate in the sewage system rather than in the activated sludge (Seidl *et al.*, 1998).

CONCLUSIONS

The results obtained from the analysis of treated and untreated waste water of various treatment plants in the Paris suburbs allowed to define specific loads of different parameters such as organic matter, nutrients and micro-organisms. These loads were expressed in g inh^{-1} d^{-1}. For raw water, the specific loads of TOC ranged between 26.4 and 28.3 g C inh^{-1} d^{-1} with particulate organic matter constituting the main part (70–76%) and the biodegradable fraction representing between 60 and 75%. Concerning micro-organisms, the average specific load of total bacteria was around 2 g C of biomass inh^{-1} d^{-1}; the nitrifying biomass represented 0.3–2.5% of the total bacterial biomass. Depending on the type of treatment, the specific load of TOC in treated water ranged between 3 and 10.8 g C inh^{-1} d^{-1}; it corresponded to removal percentages in the range 59–89%. Total bacterial biomass (0.05–0.33 g C inh^{-1} d^{-1}) was always lower in treated than in

raw water. Such a description of the effluents characteristics ameliorates the understanding of the bacterial dynamics in a polluted river. Furthermore, ecological models describing the functioning of the river Seine can be run by using these state variables as a gauge of anthropic disturbance (Billen *et al*., 1993; Even and Poulin, 1993; Even *et al*., 1998).

In addition, Figs 6–8 show interesting relationships between various variables. A significant correlation was observed between BTOC and BOD with an average BTOC/BOD of 0.35. BPOC represented 68% of BTOC in raw water and 43% in treated water. The total biomass of bacteria constituted 8% of the BTOC. These relationships can be used to roughly approximate the composition of this effluent in terms of BTOC, BDOC, BPOC and bacterial biomass when the BOD of an effluent (raw or treated) is known. These parameters are essential for modelling the impact of waste water discharge in a river according to ecological models developed by Billen *et al*. (1993), Even and Poulin (1993) and Even *et al*. (1998).

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