Characterization of suspended particles and deposits in drinking water reservoirs


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Abstract: Suspended particles transported by drinking water were examined to understand their role in deposit accumulation and colonization in pilot and full-scale reservoirs. No pesticides were detected in the deposits but several PAH were identified. Deposits accumulated at a rate of 8 μg/cm²/day (29 g/m²/year) over a five month period. Quartz, feldspar, and amorphous iron were characterized in reservoir sediments. Sedimentation of suspended particles, mainly those composed of organic (biological) matter, was incomplete, and was not a key factor governing bacterial accumulation in the deposits (10⁴ to 10⁵ CFU/cm²). Thus, limiting bacterial nutrients - dissolved organic matter – in treated water should be the only way to control the extent of bacterial colonization of deposits.

Keywords: Bacteria; deposits; drinking water; organic matter; particles; reservoirs; X-ray analysis

Introduction

The distribution of drinking water leads in many cases to the accumulation of particulate matter as deposits in pipes and reservoirs. Such loose matter is transferable into the water phase if flushing occurs due to changes in hydraulic regime. The quality of water may be strongly affected by such resuspension events, the resulting degradation being detected not only in terms of turbidity and color, but also by an increase in microbial counts, disinfectant decay and high concentrations of metals (Fe, Al, Mn, etc.) (De Rosa, 1993; Schreiber and Schoenen, 1994; Gauthier et al., 1996).

Like most aquatic sediments, loose deposits in drinking water systems accumulate minerals, but also organic matter and bacterial biomass (Ainsworth, 1978; LeChevallier et al., 1987; Gauthier et al., 1999). This usually results in the establishment of a trophic web, which includes macroorganisms, inside distribution systems (Mouchet and Pourriot, 1992; Schreiber and Schoenen, 1994; Van Lieverloo et al., 1997) in a way which is probably similar to that observed by Creuzé des Chatelliers et al. (1991) for groundwater ecosystems, corresponding to oligotrophic conditions in the absence of light. Moreover, benthic organisms in drinking water deposits receive little or no exposure to disinfectants, because of the high reductive capacity of the organic matter in these deposits (Gauthier et al., 1999).

The accumulation rates of loose deposits in pipeworks have not been described up to now in the context of drinking water systems. In particular, while particle counting was often performed (Silverman et al., 1983; McCoy and Olson, 1986; Woodward et al., 1995;
Alere and Hanaeus, 1997), the composition of waterborne particles capable of settling inside pipe systems has only rarely been detailed (Brazos and O’Connor, 1987; Alere and Hanaeus, 1997; Gauthier et al., 1997).

In the present study, our aims were to:

i. characterize the suspended particles in water and loose deposits in reservoirs
ii. measure the accumulation rates of particulate matter in reservoir deposits,
iii. characterize the micropollutants associated to the particles as well as some signatures of mineral compounds by using X-ray diffraction,
iv. quantify the impact of suspended particulate matter (>0.8 µm) (and its removal using microfiltration), both on deposit accumulation, and on water quality downstream of a reservoir.

Methods

Experimental design

Experiments were conducted with two scales of reservoirs (pilot and full-scale), all supplied with tap water from the distribution system of the Metropolitan Area of Nancy (France). Tap water is produced from surface water with a treatment including prechlorination, aluminium sulphate coagulation, settling, sand and GAC filtration with interozonation, lime remineralization and postchlorination. Two of the small-scale pilot reservoirs (316 stainless steel, volume 12 L) were supplied in parallel with tap water, while from the other two, suspended particulate matter was removed by a 0.8 mm glass-fiber filter which was replaced every two days. This configuration allows the comparison of deposit accumulations in reservoirs supplied with filtered/unfiltered water. Moreover, analysis of the filters provides a simple characterization of the concentration and nature of the suspended particulate matter.

Loose deposits were collected from 13 full-scale reservoirs after annual draining before cleaning. Sediment traps were placed in one full-scale reservoir (450 m³) and each of the small-scale reservoirs for a five month period, from May to October 1997. Two types of sediment trap were used: in two of the 12 L pilot reservoirs, the total surface of the bottom (400 cm²) was used to collect loose deposits, while in all the other reservoirs, glass tubes with a flat bottom (15 × 45 mm, Polylabo, France) were used. These glass tubes were regularly collected to evaluate the mass, organic matter and bacterial content of the accumulated loose deposits. In order to compare the accumulation of bacteria in presence/absence of mineral deposits, glass tubes were in some cases filled with 163 ± 2 mg of Siran microporous glass beads. The thickness of the corresponding deposit layer never exceeded 2–3 mm in any case after five months.

Analytical procedure

Deposit samples dedicated to microbiological analysis were diluted in 20 mL mineral solution and sonicated for 15 s (Labsonic 2000 U sonicator, 19 mm probe, 20 W). Enumeration of cultivable bacteria was performed by pour-plating appropriate dilutions into glucose-free nutrient agar (AFNOR T90-402). Plates were incubated at 22°C for 14 days to allow enumeration of slow-growing bacteria. Prior to chemical analysis, deposits were frozen and lyophilized. Dry weight was obtained after overnight drying at 105°C, and the carbon and nitrogen contents were obtained with a Carlo Erba 1108 elementary analyzer. Standard errors were obtained from triplicate sample analysis.

The concentration and volatile fraction of suspended particles collected on precombusted glass fiber filters (Millipore ref. AP40) was computed from the mass differences of the filter after 105 and 550°C drying and from the measured volume of filtered water (108 to 144 L, corresponding to 36 to 48 hours of filtration). Carbon and nitrogen contents in suspended particles were obtained using a similar procedure to the one used for the
deposits, after a fast 37ºC drying of the filters. Duplicate analysis resulted from analysis of
the two filters placed in parallel.

Results and discussion
Suspended particles in drinking water
Suspended particulate matter in tap water supplying the reservoirs fluctuated between 51
and 128 µg/L, 64% of it consisting of organic matter as measured by the volatile solids tech-
nique (Table 1). Nevertheless, even though it represents the major part of the suspended
particles, the particulate organic matter concentration is negligible compared to that of the
dissolved organic matter: the concentration of particulate carbon (Table 1) only represents
1% of the total organic carbon (TOC) measured in the supply water during the period of the
study (21.3 µg/L versus 1 670 µg/L).

One should also note that the mass concentration of suspended particles is also negligi-
ble compared to that of the dry residue (about 200 mg/L) in this tap water. The fraction of
organic matter in suspended particles was remarkably stable during the five months of the
study, which was confirmed by the fairly constant carbon fraction (27±2.4%). From previ-
ous studies (data not shown), we found that organic carbon composes more or less 34% of
the organic matter evaluated through the volatile solids measurement. The high organic
content of the suspended particles also resulted from the retention on glass-fiber filters not
only of organic particles, but also of biological material such a large bacteria and other
organisms (protozoa, rotifers, nematodes). This was confirmed by microscopic examina-
tion of the filters after DAPI staining.

Loose deposits in the full-scale reservoir
Unlike suspended particles, loose deposits characterized in 13 of the reservoirs of the same
distribution system contained only a minority fraction of organic matter, on average 18.9 ±
6.6% of dry weight, as expressed from the volatile solids measurements, and 5.0 ± 2.5% of
dry weight, as expressed through the organic carbon analysis (Gauthier et al., 1996;
Gauthier et al., 1999). Deposits were mainly composed of minerals, including iron oxides
(19%), insoluble sand materials (18%), aluminium hydroxides (15%), calcium carbonates
(10%) and manganese oxides (3%). A substantial amount of material (16%) also remained
undetermined following the analytical procedure performed to characterize these sedi-
ments. The ratio between organic and mineral matter content in deposits found here
(approximately 10–20% for organic matter versus 80–90% for mineral matter) is in agree-
ment with other studies (Schreiber and Schoenen, 1994) and is explained by the better
settling ability of mineral particles, as these have a higher density than organic particles.

X-ray diffraction analysis allows a semi-quantitative identification of crystalline elements
collected in freeze dried samples. Quartz (SiO₂) represented the main element and was
found in all reservoir deposits. Feldspar (Si₃AlO₈ + K, Na, or Si₂Al₂O₆Ca) was system-
tically associated with the highest concentration in quartz. Iron carbonate oxides
(siderite, goethite, lepidocrocite, magnetite, and hematite) were found only in pipe

<table>
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<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Average value</th>
<th>Standard deviation</th>
<th>Number of analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration of particles</td>
<td>mg/L</td>
<td>78.8</td>
<td>18.1</td>
<td>90</td>
</tr>
<tr>
<td>Volatile fraction</td>
<td>% of dry weight</td>
<td>63.9</td>
<td>6.9</td>
<td>131</td>
</tr>
<tr>
<td>Total particulate C</td>
<td>% of dry weight</td>
<td>27.1</td>
<td>2.4</td>
<td>9</td>
</tr>
<tr>
<td>Total particulate C</td>
<td>mg C/L</td>
<td>21.3</td>
<td>4.1</td>
<td>9</td>
</tr>
<tr>
<td>TOC in water</td>
<td>mg C/L</td>
<td>1670</td>
<td>210</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1 Characteristics of suspended particles and TOC in water
sampling from hydrant flushed. However amorphous iron oxihydroxides were frequently observed in reservoirs deposits (by coupling scanning electron microscopy, back scattered electron imaging, and EDS analysis), associated sometimes to bacteria cells, or other minerals: Mn, P, S, Cu, quartz, feldspar, etc.

Pesticides were not detected in reservoir deposits (detection level: 0.1 to 1 µg/g dry weight). Only PAH were identified and measured (Table 2) and were linked to localized sources (bitumen) as reported in some other situations (De Rosa, 1993; Maier et al., 1997).

Deposit accumulation in full-scale reservoir

For unfiltered waters, loose deposits were accumulated at a rate of 8 µg/cm²/day in sediment traps placed on the floor of the reservoir (Figure 1), which explains the thinness of the layer of mud found in most reservoirs of the distribution system studied during the annual inspection and cleaning (Gauthier et al., 1999). By comparing the suspended matter concentration (average 78.8 mg/L) to the average flux of water through the reservoir (675 m³/day) and to its surface area (100 m²), we evaluated that the measured accumulation rate is seven times less than what could be expected if 100% of the suspended particulate matter (78.8 mg/L) had been deposited. This seems logical, since most of the suspended particulate matter is organic and thus should have poor settling capacity. This also confirms the fact that sediments characterized in the same distribution system are mainly composed of minerals. The loose deposit rate measured here in controlled conditions (8 µg/cm²/day – 29 g/m²/year) is comparable to those which may be computed from the data obtained by Schreiber and Schoenen (1994), which range from approximately 0.5 – 46 mg/cm²/day (as evaluated from sampling during annual inspection/cleaning of reservoirs). The same authors also found through their measurements

<table>
<thead>
<tr>
<th>PAH</th>
<th>Concentrations in mg/kg</th>
</tr>
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<tbody>
<tr>
<td>fluoranthene</td>
<td>1.7 - 17</td>
</tr>
<tr>
<td>benzo(3-4) and (11-12) fluoroanthene</td>
<td>0.7 - 6</td>
</tr>
<tr>
<td>benzo(3-4) pyrene</td>
<td>0.5 - 6</td>
</tr>
<tr>
<td>benzo(1-12) perylene</td>
<td>0 - 15</td>
</tr>
<tr>
<td>indeno(1-2-3) pyrene</td>
<td>0 - 7</td>
</tr>
<tr>
<td>phenanthrene</td>
<td>+++</td>
</tr>
<tr>
<td>anthracene methyl</td>
<td>+</td>
</tr>
<tr>
<td>benzo-fluorene</td>
<td>+</td>
</tr>
<tr>
<td>benzo-anthracene</td>
<td>+</td>
</tr>
<tr>
<td>benzo-phenanthrene</td>
<td>+</td>
</tr>
</tbody>
</table>

+++ presence not quantified ; + traces

Table 2  Micropollutants measured in reservoir deposits

Figure 1  Accumulation of deposits in the full-scale reservoir as a function of time (n=3)
that for six of the reservoirs examined (out of seven), the accumulated quantity of deposits corresponds to the sedimentation of only a very small quantity (<10 µg/L) of the suspended particulate matter present in the water, which correlates well with our observations.

**Accumulation of bacteria in sediment traps of small reservoirs**

Accumulation of cultivable bacteria in deposits (by deposition and/or growth) was strongly dependent on the nature of the mineral support lying in the sediment traps placed on the bottom of the reservoirs: microporous Siran glass beads accumulated ten times more CFU/cm² than loose deposits accumulated naturally over the five month period. The level of bacteria found in these deposits (2.5×10⁴ – 2×10⁵ CFU/cm²) are slightly lower than measurements taken by other authors (LeChevallier et al., 1987; DeRosa, 1993, Schreiber and Schoenen, 1994; Gauthier et al., 1999), even though differences in expression of the results (per mL, per cm² or per g of dry weight) make it difficult to compare these data directly. The removal of particles by filtration upstream of the small reservoir produced no effect, either on the density of bacteria in reservoir deposits or on the water quality at the outlet of the reservoir:

1. no significant turbidity (data not shown) difference was measured for water at the outlet of reservoirs supplied with unfiltered/filtered water, and concentrations of HPCs were also similar (after two months of work, 500 to 2000 CFU/mL were measured according to the season);
2. the kinetics of accumulation of bacteria were identical for the deposits in the two types of reservoirs during the five month period (Figure 2), and resulted in bacterial densities (about 10⁶ CFU/cm²) higher than those found in natural sediments which could be due to the flocculation of aluminium hydroxides.

This means that the particulate fraction of organic matter (larger than 0.8 mm) transported with water has a negligible role in the accumulation of bacteria in loose deposits and on regrowth events downstream. At the same time, the removal of microorganisms such as protozoa or rotifers (which may be predators for bacteria) by a microfiltration treatment system placed upstream of the ecosystem formed by the deposits does not result in higher bacterial counts, at least according to HPC measurements. These results suggest a contrario that dissolved organic matter is the primary material for bacterial growth in deposits and reinforces the need to control the dissolved organic matter in order to control the bacterial colonization of distribution systems, using, for example, nanofiltration treatments (Sibille et al., 1997).

![Figure 2 Accumulation of cultivable bacteria (HPCs) in deposits of reservoirs supplied with filtered and unfiltered water (n=3)](https://iwaponline.com/ws/article-pdf/1/4/89/109075/89.pdf)
Conclusion
In the experimental and full-scale configurations we tested, suspended particulate matter is not a key factor in controlling bacterial accumulation in deposits. By contrast, the presence of mineral deposits may lead to very high numbers of bacteria/surface unit, some types of deposits being much more favorable to bacterial accumulation than others. PAH, but not pesticides, were found associated with some deposits. Thus, the reduction of suspended particulate matter in drinking water systems appears important mainly to limit the accumulation of micropollutants and also of mineral deposits which constitute a favorable medium for bacterial and invertebrate growth. Colonized deposits are susceptible to affect water quality during a resuspension event, and treatments such as microfiltration are not sufficient to prevent this colonization or to improve the biostability of water during distribution. The removal of dissolved organic matter from surface water at the treatment plant should remain the priority if microbial problems resulting from regrowth and the colonization of pipewalls and deposits are to be avoided.

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References