Biodegradability, DBP Formation, and Membrane Fouling Potential of Natural Organic Matter: Characterization and Controllability

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Various natural organic matter (NOM) constituents were evaluated in terms of their biodegradability, disinfection byproduct (DBP) formation potentials, and membrane fouling. The biodegradability of NOM was evaluated with respect to biodegradable dissolved organic carbon (BDOC) and its inhibition control. NOM was divided into (i) colloidal and noncolloidal NOM, using a dialysis membrane with a molecular weight cutoff of 3500 Da and (ii) hydrophobic, transphilic, and hydrophilic NOM constituents, using XAD-8/4 resins. The colloidal, and noncolloidal hydrophilic, NOM were identified as being more problematic than the other components, exhibiting relatively higher biodegradability and reactivity toward DBP formation potential. A higher biodegradability especially can provide a high risk of membrane biofouling, if a membrane is fouled by highly biodegradable NOM. Colloidal, and noncolloidal hydrophilic, NOM constituents were also shown as major foulants of negatively charged membranes due to their high neutral fractions. Filter adsorber (F/A) types of activated carbons were evaluated in terms of removals of NOM, DBP formation potential, and BDOC and were compared to conventional processes and a nanofiltration membrane. The F/A process exhibited a comparatively good efficiency, especially in DBP and BDOC control, but was not so good at removing NOM. This suggests that F/A could potentially be combined with a membrane process to minimize the DBP formation potential and bio-/organic-fouling (i.e., F/A process as a pretreatment for a membrane process).

1. Introduction
Natural organic matter (NOM) has been classically fractionated into hydrophobic, transphilic, and hydrophilic constituents by XAD-8/4 resin columns (1–3). This method can provide informative characteristics for the evaluation of the efficiencies of various water treatment processes, such as coagulation, granular activated carbon (GAC), and membrane filtration, when integrated with the molecular weight (MW) distribution (4–6). For the measurement of the MW distribution of raw and treated samples, high performance (HP) size exclusion chromatography (SEC) methods have been used with both UV and online TOC detection (7, 8).

The concept of colloidal (CD) NOM was first introduced by Leenheer et al. (1) and was defined as being different from classical fractionated NOM constituents (9). Colloidal NOM (having a MW higher than 3500 Da), isolated by a regenerated cellulose dialysis membrane, was shown to contain a large portion of hydrophilic NOM constituents, such as amino sugars and/or polysaccharides, as identified by XAD-8/4 fractionation (1), FTIR and 13C NMR spectra. Due to the hydrophilic and neutral properties of amino sugars and polysaccharides, colloidal NOM can be supposed to exhibit a relatively high biodegradability and low treatability by electrostatic interaction mechanism using processes, suggesting these colloidal constituents may provide a high risk to the bioinstability in distribution systems and a high biofouling potential when they foul the membrane surface. It was revealed by the work of Cho et al. (10) that negative-charged membranes be easily fouled with the hydrophilic neutral NOM constituents.

Rigorous characterization of colloidal NOM, opposed to noncolloidal (NCD) NOM, can offer important insights into water treatment. First, its high molecular weight and the neutral properties could be integrated to provide a specific behavior for the optimization of its removal efficiency, using both size exclusion and electrostatic interaction mechanisms. To these ends, characterization methods for the molecular weight distribution of colloidal NOM, and the identification of the amino sugars and polysaccharides, need to be developed. Second, colloidal NOM may exhibit different disinfection byproduct (DBP) formation potentials, in terms of haloacetic acids (HAA), compared to noncolloidal NOM. Last, it would be informative to determine the relative biodegradability of colloidal NOM versus noncolloidal NOM in order to establish the optimum treatment processes, to evaluate the bioinstability of treated water samples, and to predict the membrane biofouling and bioinstability in distribution systems.

2. Hypotheses
It is hypothesized that (i) colloidal (CD), and hydrophilic constituents of noncolloidal (NCD), NOM exhibit higher biodegradability and HAA formation potential reactivity compared to NCD NOM and other constituents of NCD NOM, respectively, and (ii) the above two NOM constituents (i.e., CD NOM and NCD hydrophilic NOM) will have high membrane fouling potentials for negatively charged membrane surfaces due to their mostly neutral NOM fractions. These two hypotheses will be evaluated using various tools and experiments, and an alternative process will be proposed for the minimization of their problems relating to the treatment of drinking waters.

3. Materials and Methods
3.1. Sample Preparations and NOM Characterization.
A concentrated NOM solution from the Nakdong River (DOC = 400 mg-C/L) was made using an RO membrane (polyamide thin-film-composite (TFC); Saehan, Korea) with a molecular weight cutoff (MWCO) of smaller than 100 Da. The concentrated sample was then filtered by a 0.45 μm regenerated cellulose microfilter. The NOM source water was from the Nakdong River, which is located in the southern part of Korea. Various NOM fractions (including colloidal NOM) were isolated from the water of the Nakdong river (NR−SW) using the method developed by Leenheer et al. (1), employing a regenerated cellulose dialysis membrane with a MWCO of...
TABLE 1. Water Quality of Bulk NOM (Source Water) and NOM Isolates/Fractions

<table>
<thead>
<tr>
<th>NOM</th>
<th>pH</th>
<th>conductivity (μs/cm)</th>
<th>DOC (mg/L)</th>
<th>UV absorbance at 254 (cm⁻¹)</th>
<th>SUVA (L m⁻¹ mg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>raw</td>
<td>7.15</td>
<td>1509</td>
<td>2.25</td>
<td>0.0408</td>
<td>1.81</td>
</tr>
<tr>
<td>CD</td>
<td>7.03</td>
<td>1419</td>
<td>2.31</td>
<td>0.0577</td>
<td>2.49</td>
</tr>
<tr>
<td>NCD HP</td>
<td>7.09</td>
<td>1521</td>
<td>2.12</td>
<td>0.0680</td>
<td>3.25</td>
</tr>
<tr>
<td>NCD TP</td>
<td>7.05</td>
<td>1477</td>
<td>2.24</td>
<td>0.0494</td>
<td>2.16</td>
</tr>
<tr>
<td>NCD HL</td>
<td>7.04</td>
<td>21 (m/s/cm)</td>
<td>0.84</td>
<td>0.0065</td>
<td>0.77</td>
</tr>
</tbody>
</table>

3500 Da (Spectra/Por-3, U.S). The concentrated NOM solution was poured into the dialysis membrane, consecutively followed by 0.1 M HCl (for removal of salts and low molecular weight NOM), 0.2 M hydrofluoric acid (HF) (for removal of silica gel), and a pure water (for removal of excess HF and fluorosilic acid), as background solutions. The portion remaining inside the dialysis membrane and the constituents of the various background solutions (i.e., HCl, HF, and pure water) are defined as the colloidal NOM and as noncolloidal NOM, respectively (1). The colloidal and noncolloidal NOM were further separated into hydrophobic, transphilic, and hydrophilic NOM constituents, using XAD-8/4 resins, which were further defined as NCD HP (hydrophobic), NCD TP (transphilic), and NCD HL (hydrophilic) NOM, respectively. The water qualities of the various NOM constituents are listed in Table 1.

Molecular weight separation was performed by high performance size exclusion chromatography (HPSEC) using a 30 cm TSK-505 (Toyopearl HW 50S, 30 μm resin, separation range: <5 x 10⁶ Da) column with an inner diameter of 0.8 cm. The HPLC (LC600, Shimadzu) was coupled with a UV detector (SPD-6A UV detector, Shimadzu) operating at 254 nm. The HPSEC mobile phase was prepared from a phosphate buffer (0.0024 M NaH₂PO₄, pH 6.8) and 0.096 M NaCl, with a total ionic strength of 0.1 M. An in-line degassing unit was installed to eliminate inorganic carbon and dissolved oxygen, which can cause interference, or react, with the mobile or stationary phases. The mobile phase flow rate was 1 mL/min, with a sample injection volume of 200 μL. UV absorbance (UVA) data were collected every second with a digital signal processor using commercialized data acquisition software. Under the same operating conditions, the reproducibility of the UVA chromatograms was virtually indistinguishable from replicated injections. The standard solutions used for the construction of a MW calibration curve were made with sodium polyaryl sulfonates (PSS) (210 (Fluka, Switzerland), 1800, 4600, 8000, and 18000 Da (Poly science, Sigma Aldrich, US)).

Powdered NOM samples (prepared by a freeze drier and mixed with KB) were analyzed by FTIR spectroscopy (FT/IR-460 Plus, Jasco, Japan) to determine the aminosugars, polysaccharides, and aromatic carbon double rings, with the instrument resolution adjusted to 2.0 cm⁻¹. Dissolved organic carbon (DOC) concentration and UVA were measured using total organic carbon analyzer (Sievers 820), UV-visible spectrophotometer (UV-1601, Shimadzu), respectively. The DOC for all of the samples were measured three times and averaged, and only values with coefficient of variance (c.v.) lower than 3% were accepted.

3.2. Biodegradable Dissolved Organic Carbon (BDOC) Measurement. Biodegradable organic carbon (BDOC) measurements were performed using a sand media (sand with an average diameter of 0.5 mm and a uniformity coefficient of 1.7) fixed with bacteria that had been acclimatized to the natural source water (Nakdong River) for approximately 30 days. 100 ± 10 g of the bacteria fixed sand, with an associated biofilm, was placed in a 500 mL flask, and a 300 ± 10 mL sample was added. The BDOC tests were conducted with aeration of the sample (one diffused air bubble was diffused approximately once a second) and incubated at a room temperature in a dark room until the DOC level of the sample reached a minimum value, which was generally 5 days (actual incubation periods were longer than 5 days). The difference between the initial and final DOC values was taken to be the BDOC of the sample. These procedures for BDOC measurement were taken from already published papers (11–13). Various NOM constituents can exhibit different DOC concentrations and conductivities, which may influence the BDOC results. Thus, the DOC concentrations and conductivity of all the samples were adjusted to similar values; for the hydrophilic NOM isolated from the XAD resin procedures, which contains the maximum conductivity, an electrodialysis (ED) membrane process (Tokuyama Corp., Japan) was introduced to reduce the sample conductivity (see Table 2).

The electrodialysis unit was equipped with cation and anion exchange membranes and operated in a constant voltage (30 V) mode, with a 0.03 M NaCl concentration solution.

3.3. DBP Formation Potential Measurements. Various NOM solutions were chlorinated using concentrated HOCI solution, with a chlorine dosage level based on 3 times the dissolved organic carbon (DOC) concentration and 7.5 times the NH₄⁺ concentration. The chlorinated samples were incubated at 20 °C for 72 h (the residual chlorine concentrations were between 0.8–1.0 mg/L for all of the tested samples), and the HAA formation potential (HAAFP) was estimated using a modified EPA 552 microextraction method employing diazomethane for the esterification (14). Five species of HAA were measured by GC (HP 5890 Series II Plus), using an auto sampler (HP 6890 Series) with ECD detection.

3.4. Tested Processes Description and Fouling Preparation. An NF pilot plant unit, equipped with six 2540 modules of ESNA (Hydranautics, polyamide TFC, MWCO=250), was built at the existing conventional drinking water treatment plant (the City of Chongwon, Korea) to evaluate the membrane system in terms of DOC, BDOC, and DBP (focusing on HAA) removals. Other NF and UF pilot plant units were operated to obtain NOM-fouled membranes, one equipped with an NF (HL, Desal., polyamide TFC, MWCO=300) and one with an UF membranes (GM, Desal., polyamide TFC, MWCO=8000). There were also activated carbon (with both Calgon and Norit used separately; both coal-based) filter adsorber (F/A) pilot plants (with a capacity of 13.0 x 6 m³/d; 0.3 m x 0.3 m x 1.2 m (effective activated carbon depth), sand filter depth of 25 cm) at the same location, which was compared to the NF pilot system, in terms of NOM and DBP formation removals. Conventional treatment processes are comprised of coagulation (chemical precipitation with alum), sedimentation, sand filtration, and disinfection processes.
Influent water was introduced after the sedimentation process, into both the NF membrane and F/A systems. The zeta potential values of the membranes were determined from electrophoretic mobility measurements made using a commercially available electrophoresis measurement apparatus (ELS-8000, Photal, Otsuka Electronics, Japan) employing a plate sample cell (1.5) Polystyrene latex particles (diameter 520 nm, Otsuka Electronics, Japan) coated with hydroxy propyl cellulose, with a molecular weight of 300 000 (Scientific Polymer Products, Japan), were used as mobility-monitoring particles. These were dispersed in a 0.01 M KCl solution to prevent the interactions with, or adsorption onto, the quartz cell surface during the measurements.

Fouled NF and UF membranes were obtained from the pilot-scale membrane filtration units, which had been operating for 6 months at the drinking water treatment plant. Fouls were desorbed from the fouled membrane surfaces by stirring with 0.1 M NaOH for at least 5 days, and the solutions were then filtered through the 0.45 μm microfilter.

3.5. Measurement Reproducibility and Analytic Uncertainty. The uncertainties for the NOM removals (based on 3 replicate measurements by the TOC analyzer) range 2–5% based on DOC; recall that only DOC values with c.v. less than 3% were used for analyses otherwise the experiments were performed again or resampled. The same strategy was applied for the determination of disinfection byproduct formation potential (i.e., HAAFP). Measurements of molecular weight distribution for all samples were performed two times, and those results were almost identical for every measurement. BDOC measurements were performed for two times, and corresponding standard deviations were provided in related figures.

4. Results and Discussion

4.1. NOM Characteristics. The water qualities and basic NOM characteristics are listed in Table 2; raw water (i.e., RO concentrated NOM solution, filtered with a 0.45 μm filter) exhibited a relatively low specific UVA (SUVA=UVA at 254 nm/DOC) value. Other NOM solutions, including colloidal and noncolloidal NOM constituents, were adjusted to exhibit similar DOC levels to each other for further experiments (such as DBP formation potential and BDOC tests); the conductivity values for the noncolloidal (NCD) hydrophilic NOM were relatively high, compared to the other constituents, because the pH of NOM solutions in the XAD-8/4 isolation experiments was adjusted to below 2.0 with 5 M HCl. The fractions of colloidal (CD) and NCD NOM, from the total NOM, were 32.0 and 55.6%, respectively, based on a mass balance in terms of mg C (see Table 3).

TABLE 3. Relative Fractions of Various NOM Based on Mass (in the Unit of mg Carbon): Colloidal (CD) and Noncolloidal (NCD) NOM Fractions Were Isolated with Dialysis Bag with Nominal MWCO of 3500 Da

<table>
<thead>
<tr>
<th>fractions</th>
<th>colloidal NOM (= 7.73 mgC)</th>
<th>noncolloidal NOM (= 13.48 mgC)</th>
<th>missing NOM</th>
<th>total (mgC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass (mgC)</td>
<td>HP</td>
<td>TP</td>
<td>HL</td>
<td>HP</td>
</tr>
<tr>
<td>%</td>
<td>2.27</td>
<td>2.51</td>
<td>2.95</td>
<td>7.64</td>
</tr>
<tr>
<td></td>
<td>9.4&lt;sup&gt;b&lt;/sup&gt;(9.7, 9.2)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10.4&lt;sup&gt;b&lt;/sup&gt;(10.4, 10.3)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>12.2&lt;sup&gt;b&lt;/sup&gt;(11.9, 12.5)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>31.5&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>%</td>
<td>31.0</td>
<td>32.0</td>
<td>37.0</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> HP, TP, and HL NOM constituents were fractionated using XAD-8/4 resins. <sup>b</sup> By the XAD-8/4 resins elution method. <sup>c</sup> By the XAD-8/4 resins effluent method; the first and second values are estimated with DOC levels of effluent samples at different times corresponding to 1.6 and 7.8 bed volumes, respectively.

These results also exhibit that the NOM with a relatively high MW (i.e., CD NOM) is comprised of similar HP, TP, and HL NOM fractions (i.e., 31:32:37%), but the HP NOM is the major constituent of the NCD NOM (i.e., 50%). It should be noted that the HP NOM is further divided into three different constituents: hydrophobic, transphilic, and hydrophilic NOM. Thus, all six NOM fractions could be fractionated. The NCD HP exhibited the highest fraction (31.5%), and the fractions of other NOM constituents ranged from 9.4 to 14.7%. Based on the combined CD and NCD NOM fractions, the HP, TP, and HL NOM percentages were 40.9, 19.8, and 26.9, respectively. These results also exhibit that the NOM with a relatively high MW (i.e., CD NOM) is comprised of similar HP, TP, and HL NOM fractions (i.e., 31:32:37%), but the HP NOM is the major constituent of the NCD NOM (i.e., 50%). It should be noted...
that fractionations of colloidal NOM may be interfered with the pore size of the XAD resins; the average pore sizes of the XAD resins and the upper limits of the molecular weights of both CD and NCD NOM constituents are listed in Table 4. As shown in Table 4, the XAD-8 pore size is much larger than the MW upper limit of CD NOM; however, the XAD-4 pore size is slightly higher than the MW upper limit of CD NOM (i.e., 10,000 versus 8000 Da). Thus, it should be noted that the fraction values of the transphilic and hydrophilic NOM constituents of the CD NOM could be influenced by size exclusion interference.

The molecular weight distributions of the various NOM constituents are shown and compared in Figure 1. The CD NOM (with a MW higher than 3500 Da) exhibited a significantly large portion in the MW ranges above approximately 2000 Da. Even though the CD NOM includes a large portion of TP and HL NOM constituents with relatively low levels of aromatic compounds, they were successfully detected with UVA detection, as shown in Figure 1. The NCD HP, TP, and HL NOM constituents exhibited MW distributions in a decreasing order.

### 4.2. Biodegradability of Various NOM Constituents

The colloidal (CD) and noncolloidal (NCD) NOM had almost the same hydrophilic NOM fraction, while the CD NOM had a relatively low hydrophobic (i.e., aromatic) NOM fraction compared to the NCD NOM. This is a probable reason for the greater biodegradability of the CD NOM compared to the NCD NOM, as shown in Figure 2. The hydrophobic, transphilic, and hydrophilic NOM constituents included in NCD NOM showed an increasing order in their BDOC/DOC ratios, as anticipated. However, this was only true for the NOM samples where the salt had been removed via the electrodialysis membrane process. The BDOC value for the hydrophilic constituent of the NCD NOM was significantly lower than that of the colloid.
low for the samples with higher conductivities, compared to those with lower conductivities (after the ED process for salts removal, as opposed to before). These facts lead to the supposition that the BDOC experiments were significantly influenced by high salt concentrations.

To demonstrate the relatively high biodegradability of the colloidal NOM, FTIR spectrum, and molecular weight (MW) distribution analyses were conducted on the samples, both before and after the BDOC experiments (see both parts (a) and (b) of Figure 3). As shown in Figure 3(a), various peaks, corresponding to amino sugars and/or polysaccharides, of the CD NOM, disappeared after the BDOC experiments: N-acetyl groups at 1042 cm\(^{-1}\), methyl groups at 1384 cm\(^{-1}\), and two different amides groups at 1540 and 1643 cm\(^{-1}\). This can support the following hypothesis: colloidal NOM is biodegradable due to its nonaromatic constituents, such as amino sugars and polysaccharides. The molecular weight distribution results might also support the following hypothesis: the intensities of the MW distribution of the CD NOM were more significantly reduced after the BDOC experiments, compared to those in the bulk NCD NOM, suggesting that the CD NOM portion is more biodegradable than the bulk NCD NOM. Meanwhile, there was no significant difference when comparing the relative fractions of the CD and NCD NOM constituents.

4.3. DBP Formation Potential. The various NOM constituents were evaluated with respect to their chlorinated disinfection byproduct formation potentials and treatability using alternative processes, including filter adsorber type granular activated carbon and a nanofiltration (NF) membrane. The colloidal and noncolloidal hydrophilic NOM constituents exhibited relatively higher HAA reactivity than the NCD hydrophobic and NCD transphilic NOM constituents (see Figure 4). From this the colloidal NOM and NCD hydrophilic NOM constituents were identified as providing two major problems: i.e., higher biodegradability and DBP formation potentials.

4.4. Treatability of NOM in Terms of DBP Formation Potential and BOM. The three different water samples, raw, F/A, and NF membrane treated, were compared with respect to their HAAFP and BDOC values, as shown in Figure 5. This revealed that the F/A process could provide comparative effective removals of the HAAFP and the BDOC when water samples, treated by sedimentation process, were used as the influent, although its efficiency was not as high as the NF membrane. The values of the HAAFP for most of the F/A treated samples were less than 60 \(\mu g/L\), suggesting that the F/A process could possibly be a cheap alternative to the DBP control process (i.e., a retrofit process). To evaluate the efficiencies of the F/A process further, experiments on the removals of DOC, HAAFP, and BDOC were conducted over time and compared to the raw and sedimentation process treated water samples (see Figure 6(a)−(c)). The F/A process appeared not much more efficient at removing the NOM constituents.
than the coagulation/sedimentation processes (i.e., conventional processes) in terms of the DOC, while the F/A process was very effective in reducing the HAAFP. This fact is in good agreements with the results (HAAFP was efficiently removed by GAC with high removal degrees) reported by Owen et al. (19). During the experimental period, with the March sample only, the HAAFP exceeded the 60 μg/L, the regulatory level set by the D/DBP rule of the US EPA. From the perspective of the BDOC, the F/A process was also effective in reducing the BDOC levels, with the exception of the March case, compared to the coagulation/sedimentation processes. The BDOC levels for the water treated by the sedimentation process were sometimes higher than those in the raw water samples (see Figure 6(c)). Conversely to the BDOC results, the hydrophilic fractions (not an absolute value) in the F/A treated samples were even higher than those in the samples treated by the sedimentation process, as shown in Figure 7(a). This leads to the notion that the F/A process can effectively control the BDOC fraction, included in the influent NOM samples but is not an efficient process for the reduction of the hydrophilic NOM fraction. In contrast, the F/A process can, to some degree, reduce the hydrophobic NOM fraction but not the transphilic NOM fraction (see both parts (b) and (c) of Figure 7). The similar results were reported by two different groups; it was found that NOM with high SUVA value (i.e., hydrophobic portion) could be very effectively removed by specially coal-based carbon (almost 100% at initial stages) and powdered activated carbon (PAC) (approximately 90% removals with 30 mg/L dose of PAC (20, 21)).

4.5. Membrane Foultants. As hypothesized, the hydrophilic NOM and colloidal NOM constituents were found to be major fouling components, as depicted in Figure 8, parts (a) and (b), respectively. There was a slight increase in the hydrophilic NOM fractions as a membrane foulant when desorbed from the NF (HL) and the tight UF (GM) membranes. The colloidal NOM fractions also exhibited relatively high values (i.e., 43% for both membranes) as membrane foulants, considering the fractions of colloidal and noncolloidal NOM fractions in the raw water were approximately
molecular weight distribution of the colloidal NOM components; i.e., foulants exhibit relatively high molecular weight distribution, compared to the feed NOM. The zeta potential of the clean and NOM-fouled UF membranes also support the notion that neutral NOM, including amino sugars (typical of colloidal NOM constituents), are major foulants; i.e., the negative surface charge of the clean membrane increases significantly (i.e., toward less negative values), as described in Table 5. From the FTIR spectrum, it was found that (i) there are significant reductions in the IR peaks, including carboxyl (at 1250 cm⁻¹) and aromatic carbon (near at 1500 cm⁻¹), with NOM-fouled membrane compared to the clean membrane and (ii) there are two major IR peaks corresponding to the carbonyl (at 1045 cm⁻¹) and amide (at 1655 cm⁻¹) of the N-acetyl groups, which are indicative of the amino sugars of the colloidal NOM (1, 17) (see both parts (a) and (b) of Figure 10).

Acknowledgments

This work was supported by a grant (code 4-1-2) from Sustainable Water Resources Research Center of the 21st Century Frontier Research Program through Water Reuse Technology Center at GIST.

Literature Cited


32 and 55.6%, respectively, which also supports the second hypothesis.

Foulants from the NOM-fouled NF and tight-UF membranes had somewhat higher BDOC/DOC ratios compared to that of the raw water NOM, as shown in Figure 8(c). This was probably due to neutral NOM fouling of the negatively charged membrane surface, which occurs more easily than with the acidic NOM, and neutral NOM are mostly comprised of polysaccharides and/or amino sugars, which form major portions of the colloidal NOM (1, 7, 17). Figure 9 supports the supposition that the membrane foulants have the

| TABLE 5. Characterization of NOM-Fouled Membranes, as Compared to Clean Membranes* |
|----------------------------------------------|------------------|------------------|
| membrane | zeta potential at pH7.0 | contact angle (°) |
| clean | NOM fouled | clean | NOM fouled |
| GM | -20.00 | -0.40 | 58.4(1.4) | 33.8(2.3) |
| HL | -1.00 | -0.30 | 41.4(2.1) | 49.6(1.3) |

* Values in parentheses are standard deviations.

FIGURE 9. Molecular weight distributions of various membrane foulants against raw water NOM.

FIGURE 10. FTIR spectra of (a) clean and fouled GM membranes and (b) various membrane foulants.

FIGURE 11. Zeta potential at pH7.0 contact angle (°) for clean and fouled GM membranes.


Received for review January 16, 2004. Revised manuscript received October 10, 2004. Accepted October 19, 2004. ES049919Z.