Molecular Weight Distribution, Carboxylic Acidity, and Humic Substances Content of Aquatic Organic Matter: Implications for Removal during Water Treatment

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■ The characterization of dissolved aquatic organic matter present in several natural water sources as well as corresponding treated waters derived from several types of water treatment processes is presented. Important characteristics of the organic matter, including molecular weight distribution, carboxylic acidity, and humic substances content, appear to affect the removal of organic material although the results of this research do not permit one to accurately quantify source-related effects from process-related effects.

Introduction

There has been considerable attention focused on the presence of aquatic organic matter in natural waters. Results of studies on "colored" waters began to appear in the literature almost 75 years ago, marking the first documentation on the environmental significance of aquatic organic matter. Additional studies on the composition of organic matter revealed the important role of humic substances in the overall quality of a given water. Historically, humic substances are important from a water treatment perspective due to their role as precursors to the formation of chlorination byproducts such as trihalomethanes (THMs) as well as their role in the concentration and transport of inorganic and organic pollutants.

The most common approach used to minimize THMs in drinking water is to maximize precursor removals by existing clarification processes, e.g., alum coagulation. However, as reported in the literature, the extent of precursor removals by alum coagulation by both laboratory-scale and plant-scale treatments varies considerably. This variability can be due in part to both operational plant conditions as well as the source-specific characteristics of the organic material itself.

Source-related properties of aquatic organic matter which may play a role in THM reductions in water treatment processes include molecular weight distribution (1–5), functional group carboxylic acidity (1, 6), and humic substance content (7, 8).

The approach taken with the work presented herein was to evaluate the source-related effects on precursor removals by studying full-scale water treatment plants treating several different water sources. The specific objectives are to delineate the molecular weight distribution, carboxylic acidity, and humic substances content of the dissolved aquatic organic matter present in four natural water sources and to discuss how these characteristics may influence precursor removal by different treatment processes. In addition, this paper contains a comparison of aquatic organic matter and humic substances with that of a soil-derived fulvic acid.

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Experimental Methods and Procedures

Sample Location, Acquisition, and THM Formation Potentials. The specific natural water sources and treatment facilities investigated during this research are summarized as follows:

water source	location	treatment process
Grasse River	Canton, NY	conventional
Cobble Mtn Reservoir	Springfield, MA	direct filtration
Colorado River	Las Vegas, NV	direct filtration
Floridan aquifer	Daytona Beach, FL	lime softening

At the time of sampling, the primary coagulant used at Canton and Las Vegas was alum at 40–50 and 3 mg/L, respectively. Springfield employed a cationic polymer at 1.3–1.5 mg/L, and Daytona used 220 mg/L lime for softening purposes. Both Canton and Daytona used a nonionic polymer as a filter aid at 0.4–1.0 and 0.08 mg/L, respectively.

Samples of untreated and treated water were obtained from each plant and, upon receipt, were filtered through prewashed 0.45-μm filters to remove particulate matter and isolate dissolved organic matter. All of the plants investigated practiced prechlorination to varying degrees. At each facility, both instantaneous THMs and chlorine residual were measured on site, and a stoichiometrically determined amount of sodium thiosulfate was added to eliminate residual chlorine prior to sample shipment. All untreated and treated water samples were characterized according to nonvolatile total organic carbon (NVTOC), UV absorbance (254 nm, pH 7), and trihalomethane formation potential (THMFP) under the following conditions: 20 °C, pH 7, Cl_2/NVTOC = 3.0 (mass basis), and 168 h of incubation.

A Dohrmann DC-80 carbon analyzer was used for NVTOC measurements, a Perkin-Elmer Model 200 UV–visible spectrophotometer (1-cm path length) was employed for UV absorbance determinations, and trihalomethane species were measured by using a Hewlett-Packard Model 5794 gas chromatograph and an EC detector in conjunction with liquid/liquid extraction using pesticide-grade pentane.

Instantaneous THM represents the concentration of THMs in the water at the time of sampling. All collected samples are analyzed immediately upon receipt for instantaneous THM. Terminal THM is the concentration of THMs after the prescribed set of chlorine/precursor reaction conditions as mentioned earlier. All collected samples were also analyzed for terminal THM under the aforementioned conditions. The difference between these two measurements is reported as THMFP.

Apparent Molecular Weight Fractionation. Apparent molecular weight (AMW) fractionation of dissolved organic matter was accomplished by ultrafiltration (UF). AMW distributions were determined by using a stirred cell with membranes characterized by nominal molecular weight cutoffs of 500, 1000, 5000, 10 000, and 30 000 (YCO5,

water	NVTOC,[a] mg/L	UV abs[b]	pH	turb, NTU	inst THM, μg/L	THMFP, μg/L
Grasse River/untreated	7.71	0.314	7.1	3.70	1.6	716
Grasse River/treated	2.58	0.048	6.4	0.65	53.0	107
Floridan aquifer/untreated	8.27	0.212	7.0	0.15	1.9	519
Floridan aquifer/treated	6.40	0.082	8.3	0.09	79.0	254
Cobble Mtn Reservoir/untreated	2.54	0.066	6.1	0.57	2.0	194
Cobble Mtn Reservoir/treated	2.18	0.040	5.9	0.26	7.8	136
Colorado River/untreated	3.02	0.045	8.2	0.44	1.1	167
Colorado River/treated	2.89	0.025	8.4	0.25	12.9	126

[a] Nonvolatile total organic carbon. [b] 254-nm wavelength and pH 7.0.

YM2, YM5, YM10, and YM30; Amicon Inc.). Sample aliquots was processed through the range of membranes in parallel, yielding a series of permeates, each containing all molecular weight fractions below the indicated molecular weight cutoff. All permeates were characterized according to NVTOC, UV absorbance, and THMFP. Further discussions on UF fractionations may be found elsewhere (9).

Soil-Derived Fulvic Acid Extraction and Related Jar Testing. A soil-derived fulvic acid was extracted from a Michigan peat soil by using well-established procedures (10, 11). The fulvic acid solution was made by adding a fulvic material to a 10 mg/L concentration and sodium bicarbonate to a 0.001 M level with subsequent adjustment to a pH of 7.0 with HCl. This untreated water was characterized in a similar manner to that employed for the natural water sources. In addition, several jar test experiments employing aluminum sulfate as a metallic coagulant were also conducted to simulate conventional treatment and direct filtration. The aluminum doses employed were 0.4 and 4.0 mg/L as Al for direct filtration and conventional treatment, respectively. Mixing conditions for simulation of both types of treatment involved rapid mixing in a 1-L beaker for 1 min at 100 rpm followed by 10 min of slow mixing at 30 rpm (Phipps-Bird Stirrer, Richmond, VA). Simulation of conventional treatment involved a quiescent settling period of 30 min followed by filtration through a prewashed 0.45-μm filter, while direct filtration simulation involved only the 0.45-μm filtration step immediately after mixing.

Humic Substances Content: Hydrophobic/Hydrophilic Characterization. Adsorption chromatography using a XAD-8 resin (Rohm and Haas, Philadelphia, PA) was utilized to fractionate the dissolved organic matter present in both untreated and treated water samples into hydrophobic and hydrophilic fractions. The procedure involved acidification of a 1.0-L aliquot to pH 2.0 and application to a $^1/_2$ in. diameter column of resin at a flow rate of 5 mL/min. After application, the column was eluted with 0.1 N NaOH, the eluent representing the hydrophobic fraction; the original effluent from the column was collected and designated as the hydrophilic fraction. Mass balances conducted between column influent and the hydrophobic and hydrophilic fractions indicated that, on the average, at least 95% of the organic carbon can be accounted for by this procedure. All column influent and hydrophilic samples were characterized according to NVTOC and THMFP, as described previously. These parameters for the "unconcentrated" hydrophobic fraction were calculated as the difference between the column influent and the hydrophilic effluent for each sample.

In essence, the hydrophobic fraction of the aquatic organic matter isolated by adsorption chromatography represents an "operational" definition of aquatic humic substances (2, 8, 12, 14, 15). It should be noted that this method of defining humic material has been shown to

account for anywhere between 85% and 100% of the visible color found in waters (8). The hydrophilic fraction of the aquatic organic matter, represented by the material not adsorbed onto the XAD-8 resin, is "operationally" defined as non-humic substances which comprise the remainder of the dissolved organic matter. Simple carbohydrates, uronic acids, and hydroxy acids represent examples of typical hydrophilic molecules which will not adsorb to the XAD-8 resin.

Potentiometric Titrations: Carboxylic Acidity. The procedure described herein provides an operational definition of carboxylic acidity and is based on a modification of the method used by Perdue et al. (13). Potentiometric titrations with a strong base were conducted to determine the carboxylic acidity of the hydrophobic acids isolated with the XAD-8 resin. Titrations were made in a 200-mL three-neck distillation flask in which a positive nitrogen atmosphere was maintained. Aliquots of the concentrated hydrophobic material were adjusted to pH 3.0, stripped with nitrogen for 10 min, and then titrated by stepwise additions of carbonate-free 0.05 M NaOH from a 5-mL, submerged-tip microburet with 0.01-mL gradations. All samples and blanks contained NaCl at a concentration of 0.1 M to maintain a constant ionic strength. Titrations of aliquots of 0.1 M NaCl solution were used to estimate a blank correction. Eight blank replicates were used to predict the error associated with this experimental method. The procedure used is based on a titration end point of pH 8.0 for carboxylic acidity, as defined by Thurman and Malcolm (14).

Results and Discussions

General Characteristics of Waters. Important characteristics of the various untreated water sources as well as corresponding treated waters are summarized in Table I. All of the waters were derived from low turbidity sources which contained low to high levels of dissolved aquatic organic matter, as evidenced by the range of absorbance and NVTOC levels associated with the various sources. Moreover, the THM reactivity (i.e., μg of THM/mg of NVTOC) of the aquatic organic matter also varied significantly from source to source.

Apparent Molecular Weight Distributions. Two of the most common methodologies currently used to determine molecular weight distribution of aquatic organic matter are gel permeation chromatography (GPC) and ultrafiltration (UF). Research by the authors (9) compared the two methods using common water sources and found that both GPC and UF provided comparable trends in the relative molecular weight distribution of dissolved organic matter. However, the GPC method generally indicated somewhat higher molecular weights than UF and was more significantly affective by pH conditions. While GPC and UF cannot provide absolute values of molecular weight like more sophisticated analytical techniques, they both provide an "index" of AMW that can be used for relative

Table II. Apparent Molecular Weight Distribution of Untreated Water Sources and Corresponding Treated Waters

water	permeate NVTOC,[a] mg/L					
	<0.5K	<1.0K	<5.0K	<10.0K	<30.0K	<0.45 μm
Grasse River/untreated	0.93	2.29	3.03	7.41	7.56	7.71
Grasse River/treated	0.58	1.22	2.46	2.46	2.51	2.58
Floridan aquifer/untreated	1.50	3.67	7.80	8.16	8.22	8.27
Floridan aquifer/treated	1.10	2.80	5.81	6.12	6.22	6.30
Cobble Mtn Reservoir/untreated	0.77	0.99	1.16	2.46	2.49	2.54
Cobble Mtn Reservoir/treated	0.54	0.87	1.10	2.14	2.24	2.18
Colorado River/untreated	1.36	2.11	2.35	2.84	2.88	3.02
Colorado River/treated	1.19	1.89	2.21	2.74	2.77	2.89
fulvic acid/untreated	1.33	1.67	2.03	2.44	4.10	4.83

water	permeate UV absorbance[b]					
	<0.5K	<1.0K	<5.0K	<10.0K	<30.0K	<0.45 μm
Grasse River/untreated		0.046	0.086	0.290	0.302	0.314
Grasse River/treated	0.002	0.013	0.035	0.043	0.044	0.046
Floridan aquifer/untreated	0.011	0.070	0.168	0.224	0.230	0.233
Floridan aquifer/treated						
Cobble Mtn Reservoir/untreated	0.010	0.011	0.017	0.066	0.067	0.067
Cobble Mtn Reservoir/treated	0.001	0.008	0.013	0.042	0.043	0.041
Colorado River/untreated	0.022	0.032	0.035	0.046	0.047	0.048
Colorado River/treated	0.011	0.017	0.025	0.028	0.030	0.035
fulvic acid/untreated	0.017	0.034	0.035	0.078	0.173	0.212

[a] Nonvolatile total organic carbon. [b] 254-nm wavelength and pH 7.0.

comparisons. Consequently, although specific apparent molecular weight (AMW) numbers derived from UF are presented herein, the emphasis in the following discussion is placed on the observation of major trends and not absolute values.

Table II contains the AMW distributions of the dissolved aquatic organic matter of untreated and treated waters as well as NVTOC and UV absorbance of various UF permeates. THM yields of the various untreated and treated waters for each AMW fraction have been previously presented (5).

The general AMW distributions of aquatic organic matter were found to vary from source to source. There was little dissolved organic matter found with an AMW above 10 000. On the contrary, all of the natural waters contained a significant amount of organic material with an AMW of below 500. The Grasse River and the Cobble Mountain Reservoir samples contained significant amounts of organic matter in the AMW range of 5000–10 000 while the Colorado River contained significant material in the 500–1000 AMW range. The Floridan aquifer contained significant amounts of organic material in both the 500–1000 and 1000–5000 AMW ranges.

Different water treatment processes may vary in their ability to remove specific molecular weight fractions of organic matter. All of the treatment processes were rather ineffective in removing dissolved aquatic organic matter with an AMW of less than 500. With the exception of the Canton conventional treatment plant processing water from the Grasse River, there was ineffective removal in the 500–1000 AMW range. Both the conventional plant as well as the Floridan aquifer (Daytona) softening plant proved effective in removing organic matter in the 1000–5000 and 5000–10 000 ranges. The two direct filtration facilities, the Cobble Mountain Reservoir (Springfield) and Colorado River (Las Vegas) plants, only achieved small removals of organic matter in each of the various AMW ranges.

A comparison of the levels of NVTOC and UV absorbance found in the UF permeates reveals that various treatment processes preferentially remove the UV-absorbing fraction of the aquatic organic matter. Although certain other groups of organic compounds absorb UV light to varying degrees, humic substances are particularly capable of this absorbance. Hence, it appears that the various treatment processes preferentially remove humic substances over other constituents of aquatic organic matter.

For comparison purposes, the AMW distribution of a 10 mg/L solution of the soil-derived fulvic acid is also defined in Table II. This soil-derived fulvic acid was isolated from a peat soil by using an 1-butanol extraction step as opposed to XAD-8 isolation. It can be seen that the largest amount of material falls within the 10 000–30 000 and <500 AMW ranges. The significant amount of material found in the 10 000–30 000 AMW range is in contrast to observations for the natural water sources mentioned previously.

Humic Substances Content: Hydrophobic/Hydrophilic Characterization. A summary of the hydrophobic/hydrophilic content of untreated and treated waters (Table III) confirm the importance of hydrophobic organic compounds, i.e., humic substances, as the primary contributor of THM precursors in natural waters. Moreover, the hydrophobic fraction also constitutes a significant portion of the overall NVTOC. In all of the waters studied, the THM reactivity or yield of the hydrophobic fraction was significantly higher than the corresponding hydrophilic fraction. However, it is important to note the significant contribution of the hydrophilic, or ostensibly nonhumic, material to both the NVTOC and THMFP of a given water. Somewhat surprisingly, hydrophilic compounds contributed as much as 65% of the NVTOC and 56% of the THMFP associated with Colorado River water. Various treatment plants along the Colorado River have experienced difficulty in reducing the THMFP (16). Supposedly, the interactions between the hydrophilic material and the chemical coagulants used are not conducive to effective removal of THM precursors from this particular source.

The advisability of using peat- or soil-extracted humic substances in laboratory studies as an alternative to natural aquatic organic matter has been discussed by previous researchers (2). As shown in Table III, the overall THM reactivity of the peat-derived fulvic acid is within the range of waters studied. However, the percent of the overall dissolved organic matter accounted for by the hydrophobic

Table III. Hydrophobic/Hydrophilic Characterization of Untreated Water Sources and Corresponding Treated Waters

water	overall water			hydrophobic fraction[c]			hydrophilic fraction		
	NVTOC,[a] mg/L	THMFP,[b] µg/L	THMFP/ NVTOC, µg/mg	NVTOC,[a] mg/L	THMFP,[b] µg/L	THMFP/ NVTOC, µg/mg	NVTOC,[a] mg/L	THMFP,[b] µg/L	THMFP/ NVTOC, µg/mg
Grasse River/untreated	7.71	716	93	4.39	501	114	3.32	215	65
Grasse River/treated	2.58	107	62	1.41	48	34	1.17	59	50
Floridan aquifer/untreated	8.27	519	63	4.82	363	75	3.45	156	45
Floridan aquifer/treated	6.30	254	53	3.20	134	42	3.10	120	39
Cobble Mtn Reservoir/untreated	2.54	194	78	1.24	118	95	1.30	76	58
Cobble Mtn Reservoir/treated	2.18	136	66	1.09	83	76	1.09	53	49
Colorado River/untreated	3.02	167	55	1.05	73	69	1.97	94	48
Colorado River/treated	2.89	129	45	0.95	52	55	1.94	77	40
fulvic acid/untreated	4.83	314	64	3.53	253	72	1.30	61	47
fulvic acid/0.4 mg/L Al	4.25			2.92			1.33		
fulvic acid/4.0 mg/L Al	2.02			0.90			1.12		

[a] Nonvolatile total organic carbon. [b] Trihalomethane formation potential. [c] Operationally defined humic substances content.

Table IV. Percent Reductions in NVTOC and THMFP Achieved by Various Plants

plant	hydrophobic		hydrophilic		overall water	
	NVTOC	THMFP	NVTOC	THMFP	NVTOC	THMFP
Grasse River	68	90	65	73	66	85
Floridan aquifer	34	63	10	23	24	51
Cobble Mtn Reservoir	12	30	16	30	14	30
Colorado River	9	29	1	18	4	23

content, i.e., operationally defined as humic substances, is much higher for the peat-derived fulvic acid than that found for the various natural waters. The trend is even more pronounced considering the higher carbohydrate content normally found in soil fulvic acids when compared to aquatic fulvic acids (14). Consequently, results derived from treatability studies employing soil- or peat-derived humic materials may lead to an overestimation of NVTOC and THMFP percent reductions during treatment of natural waters. Theoretically, it may be possible to obtain more comparable treatment results from studying soil- or peat-derived fulvic acid by the addition of low molecular weight hydrophilic model compounds.

Each of the treatment facilities produced waters with decreased THMFP/NVTOC ratios or yields for both the hydrophobic and hydrophilic fractions in comparison to the corresponding fractions in the original untreated water source. Observed decreases were greater for the hydrophobic than the hydrophilic fraction. Such an observation is particularly important when considering the acknowledged role of hydrophobic humic material as THM precursors vs. the somewhat surprising role of hydrophilic matter in forming a significant fraction of the THMFP.

Percent reductions in THMFP were consistently higher than corresponding NVTOC reductions, a finding in agreement with results presented in the literature (11) (Table IV). Not only are hydrophobic organic compounds more reactive in producing THMs but are also the most likely to be removed during clarification treatment. Moreover, the lime-softening process for the Floridan aquifer had similar THMFP and NVTOC reduction trends as noted for the cationic coagulants, suggesting similar removal capabilities.

Prechlorination may play a significant role in terms of the absolute values reported in Tables III and IV. Prechlorination dosages at Canton, Las Vegas, Springfield, and Daytona were 1.5, 2.2, 1.0, and 13.0 mg/L, as Cl_2, respectively. Christman et al. (17) found that a significant component of the chlorination byproducts of a fulvic acid was identified as trichloroacetic acid (TCAA). The large prechlorination dose at Daytona may help explain why the

Table V. Carboxylic Acidities of Untreated Water Sources and Corresponding Treated Waters

water	site pH	carboxylic acidity, mequiv/g of hydrophobic NVTOC
Grasse River/untreated	7.1	8.0 ± 1.2
Grasse River/treated	6.4	22.4 ± 6.2
Floridan aquifer/untreated	7.0	6.4 ± 4.2
Floridan aquifer/treated	8.3	10.2 ± 5.2
Cobble Mtn Reservoir/untreated	6.1	12.0 ± 1.1
Cobble Mtn Reservoir/treated	5.9	9.0 ± 1.9
Colorado River/untreated	8.2	12.2 ± 2.6
Colorado river/treated	8.4	9.1 ± 2.9
fulvic acid/untreated	7.0	13.5 ± 1.4
fulvic acid/0.4 mg/L Al		14.7 ± 1.7
fulvic acid/4.0 mg/L Al		31.0 ± 5.6

hydrophilic content of the treated water comprises such an important component.

Carboxylic Acidity of Humic Substances. Humic substances contain acidic functional groups which impart a pH-related charge density. Carboxylic acidities determined for the hydrophobic material (i.e., operationally defined humic substances) present in the various untreated water sources and corresponding treated waters are summarized in Table V, as expressed in milliequivalents per gram of hydrophobic NVTOC. While the two principal acidic functional groups are carboxylic and phenolic hydroxyl, a decision was made in this research to highlight only the carboxylic acidity. The decision was based on the premise that phenolic hydroxyl groups are predominantly nonionized below a pH of 8.0 while carboxylic groups can be expected to be largely ionized at a pH of above 6.0. The charge density imparted by carboxylic functional groups is important in relation to removal mechanisms predicated on electrostatic attraction between negatively charged humic molecules and positively charged coagulants (aluminum hydrolysis species or cationic polyelectrolytes) used in conventional treatment and direct filtration.

Observed changes in carboxylic acidity between untreated vs. treated waters appeared to vary according to

type of water treatment. The direct filtration processes at Springfield and Las Vegas showed no significant differences when comparing carboxylic acidities before and after treatment. The relatively large alum dose used at the Canton conventional water treatment plant resulted in a treated water containing hydrophobic fractions with a much higher carboxylic acidity and hence higher charge density than the original water before treatment.

To further elucidate the effect of increasing alum dosages on carboxylic acidities, laboratory experiments (jar tests) were conducted with 10 mg/L of soil-derived fulvic acid solutions. Alum dosages of 0.4 mg/L as Al and 4.0 mg/L as Al were used to simulate chemical additions typically encountered in direct filtration and conventional treatment, respectively. It can be noted from Table V that increasing alum dosages resulted in increasingly higher carboxylic acidities associated with the residual hydrophobic fraction remaining after treatment.

The absolute value of carboxylic acidity reported for the fulvic acid at the higher alum dose is higher than any known natural water values reported in the literature. It is recognized that aluminum species can form complexes with the hydrophobic organic fraction and thus could possibly enter into the titration reactions. However, according to Vik et al. (4), residual aluminum concentrations in treated water are minimized when sufficient alum is added to achieve maximum humic substance removals in the optimum pH range. On the basis of laboratory jar tests, alum dosages larger than 4.0 mg/L Al for the fulvic acid solution did not result in improved NVTOC removals. Moreover, according to Thurman (19), acidifying the sample to pH 2 before application to the XAD-8 column should have minimized formation of humic substance–aluminum complexes. The relative trends exhibited by the fulvic acid data are considered pertinent, regardless of the absolute values of carboxylic acidity. Future studies examining the acidities remaining in solution after clarification by metal coagulant(s) should include analyses for residual metals in order to quantify their contribution.

Different types of humic molecules are characterized by different acidic group compositions: fulvic acids generally have a higher charge density than corresponding humic acids derived from the same source (20). As reflected by the predominance of lower molecular weight material in the Canton conventional treatment product water and the high carboxylic acidity of the hydrophobic material in this water, the lower molecular weight compounds present in the Grasse River possess a higher carboxylic acidity. The result is in agreement with others (21), who stated that the carboxyl content of humic substances appears to be inversely related to molecular weight. Therefore, it may be concluded that humic molecules with the highest content of acidic functional groups may be the most difficult to destabilize by aluminum coagulation dosages commonly employed in water treatment.

The data also suggest that lime softening appears to preferentially remove the lesser charged humic material. However, any conclusions drawn must be qualified by considering the potential effects of the large prechlorination dose employed at this treatment facility (13 mg/L). Additional research is needed to define the effects of prechlorination on humic substances characteristics such as carboxylic acidity and related effects on removal by water treatment processes.

Conclusions

The results of this research suggest that several important characteristics of dissolved aquatic organic matter, including molecular weight distribution, carboxylic acidity, and humic substances content, may affect removal by commonly employed water treatment processes. As a general rule, higher molecular weight matter proved to be more amenable to removal than lower molecular weight material, particularly that fraction with an apparent molecular weight of <500. Since in most cases THM reactivity or yield increased as a function of molecular weight (5), the most reactive THM precursors are preferentially removed in water treatment. It also appears that humic molecules with the highest carboxylic acidity and hence highest charge density are generally more difficult to remove by conventional treatment, direct filtration, or softening processes. Essentially, all of the various treatment processes studied preferentially removed hydrophobic over hydrophilic aquatic organic matter. Due to the use of different untreated water sources by the various processes investigated, it is difficult to accurately discern process-related from source-related differences.

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