Characterization of the size distribution of contaminants in wastewater: treatment and reuse implications

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Wastewater treatment objectives and design specifications are typically defined in terms of nonspecific parameters such as biochemical oxygen demand (BOD) and suspended solids (SS). Yet the contaminants that must be removed from wastewater are complex mixtures of particulate and soluble constituents. Based on past studies, it is known that the treatability of wastewater depends strongly on the size distribution of the contaminants. Rates of sedimentation, mass transfer, adsorption, diffusion, and biochemical reaction are all influenced by particle size. Therefore, characterization of the size distribution of the contaminants in wastewater is important for developing a more fundamental understanding of the complex interactions that occur in the unit operations and treatment processes. Size distribution analyses of wastewater are also valuable for developing improved techniques for process selection and evaluation.

This paper discusses the types and sizes of the organic matter in wastewater and their relationship to treatment, techniques for characterizing particle size distributions in wastewater, the impacts of treatment on particle size distribution, and the implications of particle size in evaluating and designing treatment and reuse facilities.

SIZE RANGE OF ORGANIC MATTER IN WASTEWATER

Contaminants of interest in wastewater range in size from less than 0.001 to well over 100 μm. The material that comprises the BOD and SS of settled municipal wastewater is usually smaller than 50 μm. The size ranges of typical organic contaminants characteristic of settled municipal wastewater are presented in Figure 1. The fraction of organic material measured by the standard SS test[1] includes protozoa, algae, bacterial flocs and single cells, waste products, and other miscellaneous debris. Particulate matter smaller than 1.2 μm (the effective pore size of a glass fiber filter used for the SS test) is normally not detected by the standard SS test. However, some bacterial cells, cell fragments, viruses, and inorganic particles such as clays are in the size range from 0.1 to 1.2 μm.

Organic particulates smaller than 0.1 μm are typically cell fragments, viruses, macromolecules, and miscellaneous debris. The major groups of macromolecules in wastewater are polysaccharides, proteins, lipids, and nucleic acids. Because of difficulties associated with the measurement of molecular size, macromolecules are generally defined by apparent molecular mass. The approximate molecular mass range of macromolecules found in wastewater is between 10^3 to 10^6 atomic mass units (amu). As shown in Figure 1, a macromolecule with a molecular mass of approximately 10^6 amu corresponds to a particle size of about 0.01 μm. Compounds in the range from 10^3 to 10^6 amu include humic and fulvic acids which may be present in the water supply and in sewer inflows and infiltration. Wastewater compounds smaller than 10^3 amu include carbohydrates, amino acids, fatty acids, vitamins, and chlorophyll. Persistent chemical compounds such as DDT, PCB, and other toxic substances of public health significance are also low molecular mass compounds.

Incorporating particle size analysis into the design processes can result in innovative treatment facilities.

In some early studies, the contaminants in wastewater were separated into four size fractions by successive sedimentation, centrifugation, and filtration.[2,3,4] The fractions were classified by size range as settleable, supracolloidal, colloidal, or soluble. The size range and the organic content of each fraction are summarized in Table 1. An important conclusion from these early studies was that particles smaller than 1.0 μm can be degraded biochemically at a much more rapid rate than particles larger than 1.0 μm. Based on the biochemical oxidation rate results reported in Table 1, Balmat[2] suggested that one way to increase the capacity of biological treatment plants was to grind the larger particles in wastewater to a size of about 1.0 μm.

INTERRELATIONSHIPS BETWEEN CONTAMINANT SIZE RANGES AND WASTEWATER TREATMENT OPERATIONS AND PROCESSES

The effectiveness of specific treatment processes is influenced strongly by the size ranges of the contaminants in wastewater. Treatment processes modify the size distribution of the organic material in wastewater. By quantifying the organic material in wastewater in terms of size and studying the transformations that occur during treatment, it is possible to delineate the removal mechanisms operative in individual treatment pro-

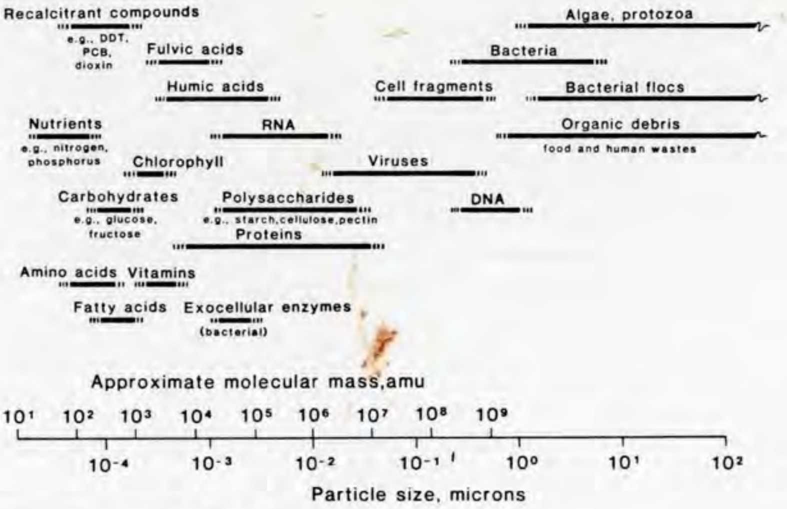

Figure 1—Typical organic constituents in settled municipal wastewater.

cesses. The approximate size range over which various physical, chemical, and biological treatment processes operate is presented in Figure 2.

Sedimentation. Sedimentation is effective for the removal of material larger than about 50 μm. Removal of particulate matter by sedimentation depends on the particle settling velocity which can be described by Stokes' law. Using typical design overflow rates of 32 to 48 $m^3/m^2 \cdot d$ for primary sedimentation tanks,[5] the minimum particle size that would be removed by primary sedimentation is about 54 to 67 μm, assuming that the average density of particulate matter in wastewater is 1.2 g/m^3 and the average wastewater temperature is 25°C.

Filtration. Mechanisms for removal of particulate matter by filtration include straining, impaction, interception, adhesion, and flocculation.[5,6] The efficiency of removal of particulate matter by filtration is roughly proportional to the square of the particle size.[6] In granular medium filtration of primary effluent, it has been shown that particles larger than about 3 μm are removed effectively.[7,8] Some smaller material is also removed by chance contact and adsorption to the filter medium.

Coagulation/flocculation. The effectiveness of coagulation/flocculation processes depends on the nature of the chemicals that are used, the effectiveness of the initial mixing operation, and the number of collisions between particles brought about by differential internal fluid shear and by differential settling velocities. All of these mechanisms are related to particle size. The effectiveness of interparticle collisions for promoting particle aggregation is roughly proportional to the cube of the particle size.[9] Chemical coagulation/flocculation processes can be used to aggregate wastewater constituents in the size range from less than 0.1 to about 10 μm.

Biological treatment. During biological treatment, particle size distributions in wastewater change as a result of new cell synthesis, flocculation, adsorption, enzymatic breakdown of macromolecules, and biochemical oxidation. The size ranges of organic material in wastewater play a key role in biological treatment processes. Particulate matter, polymers, and macromolecules cannot be transported across bacterial membranes, but may be adsorbed to biofilm surfaces or entrapped in microbial flocs and thereby removed from solution. Proteolytic, lipolytic, and cellulolytic enzymes, synthesized within bacterial cells, hydrolyze adsorbed macromolecules into smaller subunits that can be transported across the cell membrane and metabolized. Molecules with a molecular mass of less than 10^3 amu can be taken up by bacteria.[10] The biodegradability of low molecular mass compounds is governed by their molecular structure. Many of these compounds, such as humic acids and refractory organic compounds, are stable under normal treatment conditions because of kinetic limitations. The reason that the activated sludge process is so widely accepted is that it can effectively treat wastewater contaminants in all size ranges (see Figure 2).

Table 1—Composition of organic materials in wastewater.[a]

	Classification			
Item	Soluble	Colloidal	Supracolloidal	Settleable
Size range (μm)	<0.08	0.08–1.0	1–100	>100
COD (% of total)	25	15	26	34
TOC (% of total)	31	14	24	31
Organic constituents (% of total solids)				
Grease	12	51	24	19
Protein	4	25	45	25
Carbohydrates	58	7	11	24
Biochemical oxidation rate, k, d^{-1} (base 10)	0.39	0.22	0.09	0.08

[a] Adapted in part from References 2, 3, 4.

TECHNIQUES FOR PARTICLE SIZE CHARACTERIZATION

Particle sizes and distributions in wastewater can be measured by electronic particle counters, light scattering devices, light

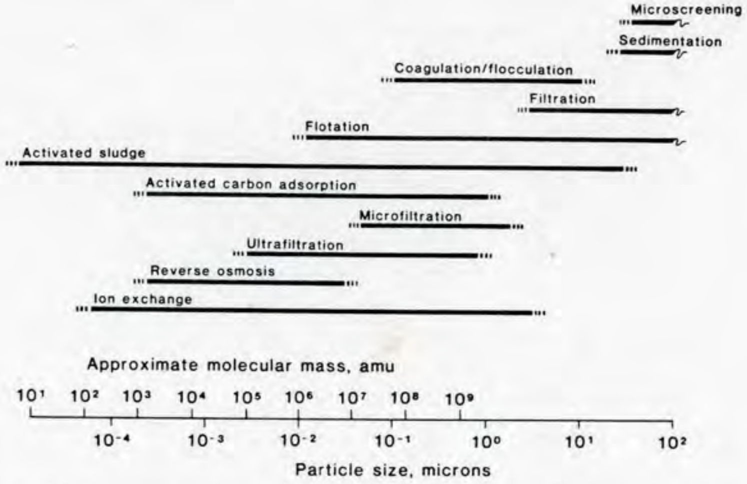

Figure 2—Size ranges over which various wastewater treatment unit operations and processes are effective.

microscopy, scanning electron microscopy (SEM), centrifugation, gradient sedimentation, serial filtration, field flow fractionation, and gel filtration chromatography. The size range over which each of these analytical techniques can be used is shown in Figure 3.

To quantify the range of sizes of particulate matter in wastewater, SEM analyses were performed on samples of primary effluent from a number of wastewater treatment plants. Typical electron micrographs of the particulate matter in settled municipal wastewater are presented in Figure 4. As shown in the figure, the shapes of particles in wastewater are irregular. Therefore, it is both difficult and impractical to define particle size by a single linear dimension or on the basis of an equivalent spherical diameter. Based on the results of the SEM evaluations of particle sizes, it was concluded that several methods were necessary to characterize the particle sizes in wastewater. Further, from a review of the size ranges of organic matter in wastewater (see Figure 1), and the available analytical techniques (see Figure 3), it was concluded that the contaminants in wastewater could be separated into two size categories: larger than 0.1 μm, and smaller than 0.1 μm.

Characteristics of particulate matter larger than 0.1 μm. Particulate matter larger than 0.1 μm in settled wastewater was characterized by serial filtration, and steric field flow fractionation (FFF). SEM was used to quantify individual particle sizes.

Serial filtration. A series of polycarbonate membrane filters[11] with pore sizes of 12, 8, 5, 3, 1, and 0.1 μm are used to obtain the mass distribution of filtrable solids. A comparison of the pore structure of the polycarbonate membrane filters used in this study with that of the glass fiber filter used for Method 209c as specified in "Standard Methods,"[1] is shown in Figure 5. The serial filtration technique was selected because a wide range of particle sizes can be evaluated, and chemical and biochemical analyses can be performed on the various size

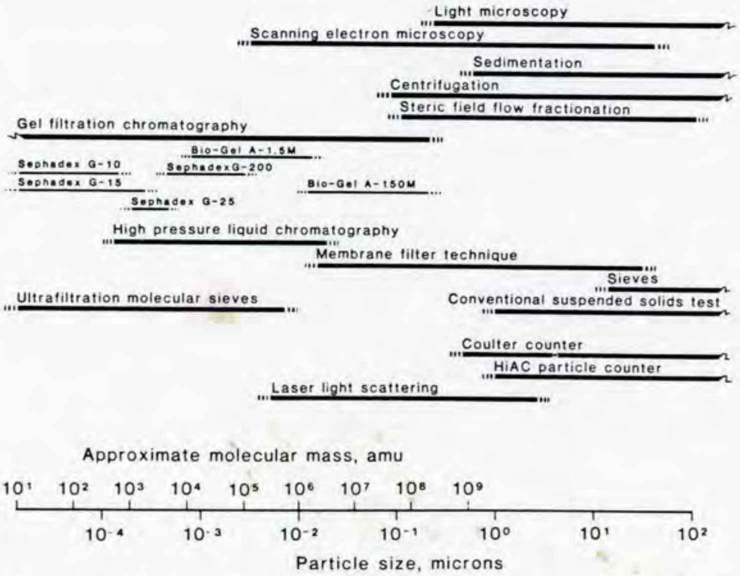

Figure 3—Analytical techniques used for identification of the size of wastewater contaminants smaller than 100 μm.

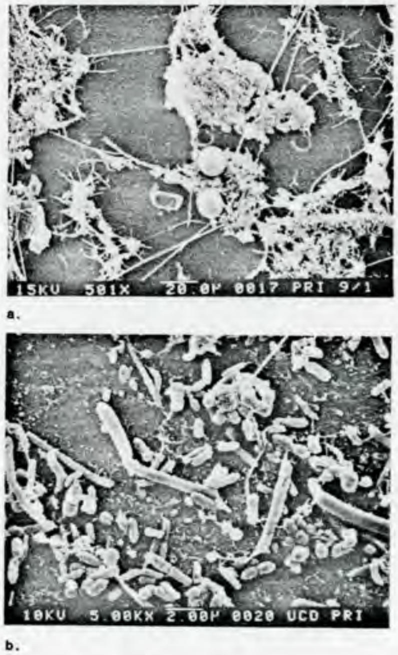

Figure 4—Micrographs of settled municipal wastewater from the University of California, Davis Wastewater Plant, September 1982. a) Filtrable solids retained on a membrane filter with a nominal pore size of 8 µm. b) Filtrable solids retained on a membrane filter with a nominal pore size of 0.1 µm (prefiltered through a membrane filter with a nominal pore size of 8.0 µm). Length of the bars in the captions correspond to 20 and 2 µm respectively.

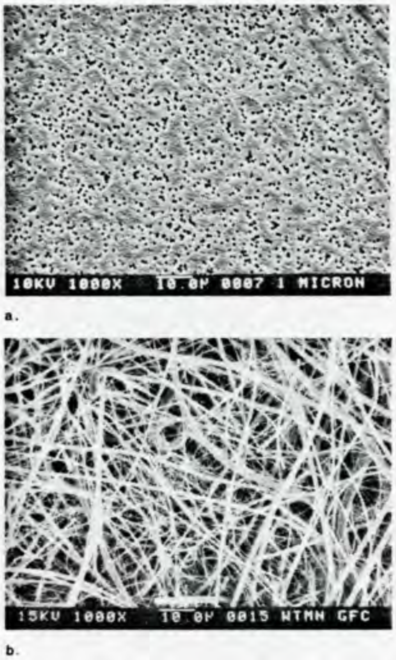

Figure 5—Micrographs of two laboratory filters used for the measurement of suspended solids in wastewater. a) Polycarbonate membrane filter with a nominal pore size of 1.0 µm. b) Glass fiber filter with a nominal pore size of 1.2 µm.

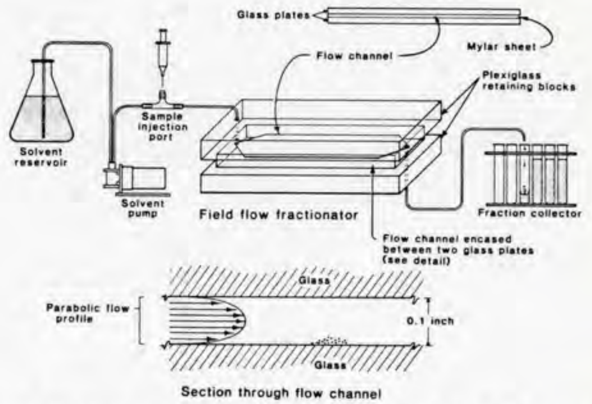

Figure 6—Schematic of field flow fractionator used for the separation of particles in wastewater.

fractions. Also, the equipment requirements for sample analysis by this technique are minimal and are readily available at most laboratories and treatment plants.

Steric FFF. In steric FFF, the sample suspension is injected into a shallow rectangular channel contained between two glass plates (see Figure 6). Following a quiescent sedimentation elution buffer is pumped through the channel to transport the particles. Because flow in the channel is laminar, the particles are separated by size in the flow streamlines.[12] The separated particles are collected for further chemical, biochemical, or microscopic analysis. A diagram of the velocity profile in the channel and the differential migration of particles is also shown in Figure 6. As would be expected, the physical properties of the particles, such as size, shape, and density, control the separation of particles. Therefore, the particles are separated into size ranges based on particle dynamics in a fluid flow field.

The steric FFF technique was selected because the entire spectrum of particle sizes larger than 0.1 µm can be analyzed. The FFF technique was calibrated by fractionating samples of wastewater and analyzing the size of the particles in each fraction by SEM. The SEM analysis was used to measure the size of particles and to evaluate the nature of the particles in each size range. By relating the particle size in each fraction to the elution volume, a calibration curve was developed. The

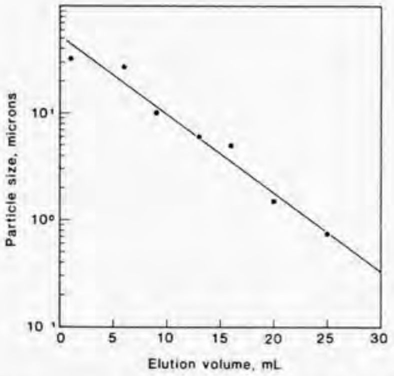

Figure 7—Calibration curve for determination of the size of wastewater contaminants separated with field flow fractionation (FFF).

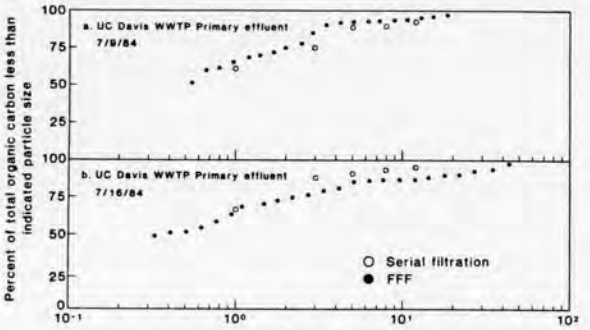

Figure 8—Comparison of the cumulative distribution of total organic carbon (TOC) in primary effluent using serial filtration and field flow fractionator (FFF) techniques.

Table 2—Chromatographic gels used for determination of apparent molecular mass distributions of organic constituents in wastewater.

Gel type	Name	Separation range, amu
Dextran	Sephadex G-200	1 000–600 000
Agarose	BioGel A-1.5 M	10 000–1 500 000
Agarose	BioGel A-150 M	10^6–1.50×10^8

calibration curve for separation of wastewater particles is presented in Figure 7. The various size fractions were analyzed for total organic carbon (TOC) to obtain the distribution of organic material in each sample and to provide a common basis for sample comparison.

Comparison of results. To compare the results obtained by the two analytical techniques, samples of primary effluent were analyzed. Serial filtration methods were used to determine the distribution of TOC associated with the filtrable solids in primary effluent. Parallel studies were performed using the steric FFF technique to obtain the distribution of TOC associated with the particulate matter larger than 0.1 μm in primary effluent. By using the serial filtration technique to determine the filtrable solids distribution, selected particle size ranges were evaluated, while the continuum of particle sizes was analyzed using the steric FFF technique. A comparison of the results obtained using these two techniques to characterize the size distribution of organic contaminants larger than 0.1 μm in two different samples of primary effluent is presented in Figure 8. As shown, the results from the serial filtration and steric FFF techniques are essentially the same. Based on the results of a number of studies in which the two techniques were compared, it was concluded that the serial filtration technique is a reliable method for modeling the size distribution of particles in wastewater larger than 0.1 μm. An advantage of the serial filtration technique is that the necessary filtration equipment is readily available to every laboratory.

Characteristics of organic material smaller than 0.1 μm. Limited information is available regarding the size distribution of wastewater contaminants smaller than 0.1 μm. Gel filtration chromatography was selected as an analytical technique for this study because of the wide size range of organic macromolecules that can be analyzed (see Figure 3). In gel filtration chromatography, a concentrated sample is applied to a column of chromatographic medium. A phosphate buffer is pumped through the column and the components of the sample are separated by molecular size (see Figure 9). The porosity and composition of the medium control the elution pattern of the sample. Large molecules cannot penetrate the interstices of the medium and remain in the bulk fluid. Smaller molecules with higher diffusivities will be retarded by the gel medium.[13] By using a combination of gel filtration media, an apparent molecular mass distribution of the sample can be obtained. Because a large variety of molecular shapes exist in solution, it is impossible to obtain an exact molecular mass distribution. However, under fixed experimental conditions, similar molecules may be assumed to have similar elution profiles.

Typical gel types and their applicable molecular mass sepa-

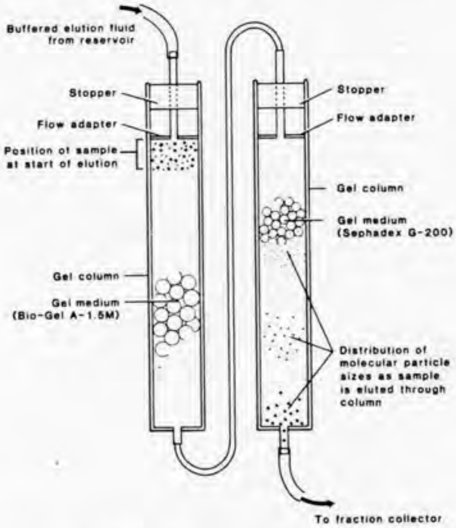

Figure 9—Schematic of chromatographic gel columns used for the separation of wastewater constituents smaller than 0.1 μm.

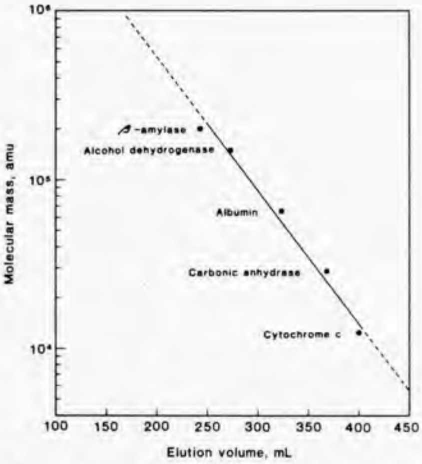

Figure 10—Calibration curve developed using standard protein compounds for the two column series of chromatograph gels shown in Figure 9 (Bio Gel A-1.5 and Sephadex G-200).

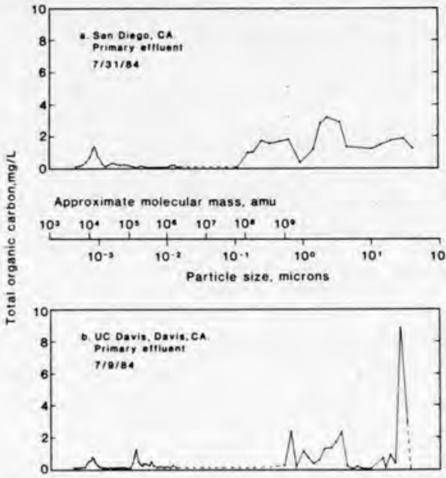

Figure 11—Size distributions of the organic constituents in primary effluent from two locations. a) San Diego, Calif. b) University of California, Davis.

ration ranges are shown in Figure 3. Agarose and dextran gels (see Table 2) were used as the chromatographic media[14] to evaluate the apparent molecular mass distribution of the organic material smaller than 0.1 µm. Two chromatography columns, each with an inside diameter of 25 mm and a length of 0.50 m, were used (see Figure 9). The columns, operated in series, were calibrated using a mixture of five protein standards with molecular mass from 12 400 to 200 000 amu. The calibration curve for the two-column series is shown in Figure 10. Because the concentration of organic contaminants smaller than 0.1 µm is typically very low, wastewater samples were concentrated 50 to 100 times by lyophilization.

WASTEWATER PARTICLE SIZE CHARACTERIZATION STUDIES

A variety of wastewater samples from a number of different treatment plants and individual treatment operations and processes were characterized in terms of size. As an introduction to the sizes of the contaminants in wastewater the results of these studies are presented below.

Primary wastewater effluents. To characterize the size distribution of organic contaminants in settled wastewater, samples from a number of wastewater treatment plants were analyzed. The particulate matter was evaluated using serial filtration to obtain the mass distribution of filtrable solids. Steric FFF was used to obtain a distribution of organic carbon associated with the particulate matter. By using SEM analyses and image analyzing techniques, the nature of the particles eluted in each size fraction and the average particle dimensions were evaluated. Material smaller than 0.1 µm was characterized with gel filtration chromatography.

The size distributions of the organic material in primary effluent from two locations are shown in Figure 11. For the samples shown, approximately 63 to 70% of the organic

Table 3—Percent of organic matter in primary effluent associated with constituents smaller than and larger than 0.1 µm.[a]

Sample location	Date	Parameter measured	Total organic concentration, mg/L	Percent of total organic matter	
				<0.1 µm	≥0.1 µm
Davis, Calif.	6/4/84	TOC	69.6	32.6	67.4
	6/5/84	TOC	60.8	29.6	70.4
Las Vegas, Nev.	8/3/83[b]	COD	102	64.7	35.3
	8/3/83[b]	COD	125	65.7	34.4
	8/4/83	COD	95	35.8	64.2
Orange County, Calif.	12/9/82	COD	251	69.3	30.7
	12/9/82	COD	305	64.3	35.7
	12/16/82	COD	348	62.1	37.9
	12/16/82	COD	356	49.5	50.5
	12/17/82	COD	350	49.2	50.8
San Diego, Calif.	7/31/84	TOC	76.5	30.0	70.0
University of California, Davis	9/28/82	COD	247	43.3	56.7
	10/13/82	COD	296	42.3	57.7
	10/21/82	COD	321	51.5	48.5
	10/29/82	COD	418	29.9	70.1
	11/10/82	COD	272	15.5	84.5
	2/17/83	TOC	61.0	27.9	72.1
	6/29/84	TOC	62.8	33.4	66.6
	6/5/84	TOC	28.5	36.9	63.1
	7/9/84	TOC	34.3	51.3	48.7
	7/16/84	TOC	29.2	37.0	63.0

[a] Determined by filtering sample through a polycarbonate membrane filter with a nominal pore size of 0.1 µm.

[b] Chemical coagulants added prior to primary sedimentation.

material measured by the TOC test is associated with particles larger than 0.1 μm. The remaining organic material is distributed over the entire analytical size range of molecular mass. The size range of organic material present in primary effluents is influenced by many factors including the length and condition of the wastewater transmission system, whether influent pumping or grit removal is used, and the design and operation of the primary clarifier. In long, flat sewer lines, much of the large molecular mass material is broken down in size by hydraulic shear forces, solubilization, and enzymatic hydrolysis so that more of the total organic material is present in the lower molecular mass fraction. Additional data on the distribution of organic matter in primary effluents from five different treatment plants are reported in Table 3. In the samples analyzed, from 30 to 85% of the organic material is associated with particles larger than 0.1 μm.

Virtually no organic matter was detected in the size range between 0.01 and 0.1 μm in any of the samples evaluated. The absence of material in this size range was verified by gel filtration chromatography studies specific for the separation of organic material in the corresponding molecular mass range from 10^6 to 1.5×10^8 amu. Based on these results, it seems that the 0.1 μm size selected initially is a valid separation point, not only for analytical purposes, but also for differentiating between the major groups of organic contaminants in wastewater. Thus, the use of a filter with a pore size of 0.1 μm seems to have a more rational basis than the use of a glass fiber filter (effective pore size 1.2 μm) for characterizing the suspended material in wastewater.

Apparent molecular mass distributions of constituents smaller than 0.1 μm in primary effluents from three different locations are shown in Figure 12. In all cases, a significant peak in the distribution occurred in the molecular mass range less than 20 000 amu. This peak is probably composed of humic and fulvic acids and other organic compounds that are difficult to treat (see Figure 1). Further work to identify the composition of the material associated with the low molecular mass peak is planned.

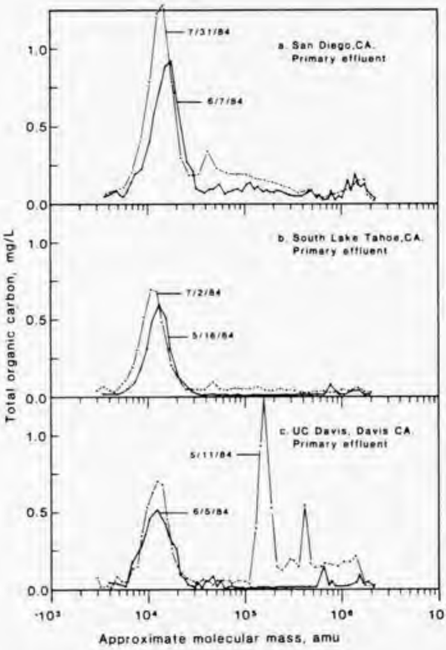

Figure 12—Comparison of the size distributions of organic constituents smaller than 0.1 μm in primary effluent from three locations. a) San Diego, Calif. b) South Lake Tahoe, Calif. c) University of California, Davis.

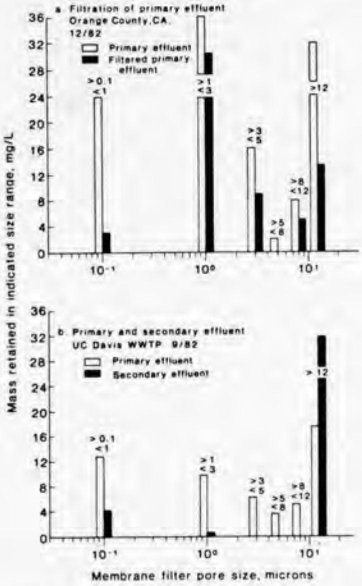

Figure 13—Distributions of filtrable solids in wastewater. a) Primary and filtered primary effluent, Orange County, Calif. (12/82). b) Primary and secondary effluent, University of California, Davis (9/82).

Primary, filtered primary, and secondary effluents. The size range of organic contaminants removed by pulsed-bed filtration and by secondary treatment processes was evaluated by analyzing samples of primary effluent, filtered primary effluent, and secondary effluent. Filtrable solids distributions of the particles larger than 0.1 μm in primary effluent before and after treatment by pulsed-bed filtration are shown in Figure 13a. Filtrable solids distributions of primary and secondary effluents are shown in Figure 13b. The distributions of organic contaminants smaller than 0.1 μm in wastewater samples from two locations and the alteration of the distributions with treatment are shown in Figure 14. The effect of pulsed-bed filtration (see subsequent discussion) is that some of the large molecular mass material has been removed. Following secondary treatment, the same molecular mass fractions are present, but the concentration of organics in each size range is considerably reduced. It is interesting to note that conventional biological treatment processes do not completely remove the compounds associated with the concentration peak that occurs around 20 000 amu.

Phosphorus in wastewater. Inorganic contaminants such as phosphorus are often associated with solid particles. Identification of the size range of particles with which phosphorus is associated can be useful in the selection of treatment options for phosphorus removal. Data on the distribution of phosphorus and its alteration during treatment are presented in Table 4. As reported in Table 4, the majority of the phosphorus in the treatment plant influent is associated with the filtrable solids.

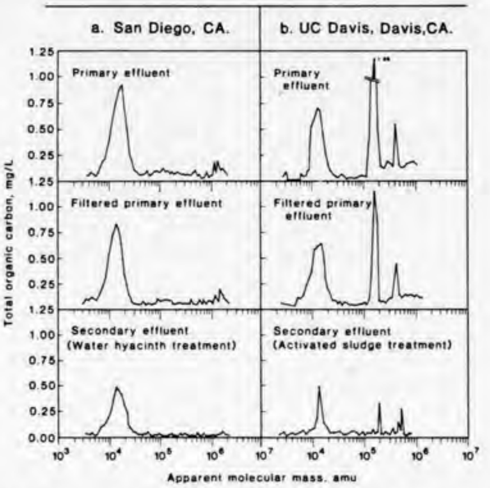

Figure 14—Comparison of the effectiveness of treatment processes for the removal of organic constituents in wastewater with an apparent molecular mass of less than 10^7 amu. a) San Diego, Calif. b) University of California, Davis.

Following biological treatment, most of the phosphorus is present in the soluble fraction (less than 0.1 μm).

PARTICLE SIZE/TREATMENT PROCESS INTERACTIONS

Particle size characterizations were also made to assess the performance of several unit operations and processes. The principal objective of these studies was to determine how particle sizes were altered during treatment and the effects of the altered wastewater on treatment performance.

Pulsed-bed filtration of primary effluent. The effectiveness of pulsed-bed filtration of primary effluent for removal of suspended solids and BOD is well documented.[7,8] A comparison of the filtrable solids distribution of primary effluent before and after pulsed-bed filtration is shown in Figure 13a. In effect, by removing the larger particles and modifying the particle size distribution, the pulsed-bed filter can be used to accomplish the same objective of size reduction that Balmat suggested.[2] An added benefit of primary effluent filtration is the concomitant reduction in the concentration of organic matter applied to subsequent treatment processes. By removing the particles that are larger and more difficult to treat, the efficiency of subsequent treatment processes can be enhanced, especially where adsorption is an important mechanism such as in activated sludge, trickling filter, and powdered activated carbon treatment processes.

Tower trickling filter. Prior to biological treatment by tower trickling filters, pulsed-bed filtration of primary effluent was used to remove the large, less readily degraded material in primary effluent. The influence of the altered particle size distribution of filtrable solids on process loading rates was evaluated.[8,15,16] Because of the altered particle size distribution in the filtered wastewater, effective treatment was possible at process loading rates much higher than for conventional trickling filter operation without recirculation. Data on the performance of tower trickling filter treatment of filtered primary effluent at various hydraulic loading rates are presented

Table 4—Typical data on the distribution of phosphorus associated with filtrable solids in untreated and treated wastewater.[a]

Sample			Concentration mg/L	Percent of phosphorus retained in size range[b]				
Location	Date	Time		<0.1	>0.1 < 1.0	>1.0 < 3.0	>3.0 < 5.0	>5.0
Influent	8/3/83	8:30 a.m.[c]	3.62	35.9	4.9	31.5	3.3	24.3
	8/3/83	2:00 p.m.[c]	8.16	14.9	0.5	18.6	13.0	52.9
Primary	8/3/83	9:45 a.m.[c]	2.23	52.9	9.4	8.5	3.1	26.0
	8/3/83	2:30 p.m.[c]	1.42	54.2	19.7	14.8	7.7	3.5
	8/4/83	8:30 a.m.[d]	2.38	17.2	54.6	0.8	6.3	21.0
	8/4/83	12:30 p.m.[d]	4.70	15.7	67.0	5.3	3.4	8.5
Trickling filter	8/3/83	10:15 a.m.[c]	0.79	79.7	12.6	1.3	10.1	
	8/3/83	2:30 p.m.[c]	0.75	68.0	14.7	17.3[e]		
	8/4/83	9:00 a.m.[d]	2.22	53.1	10.8	0.9	35.1[f]	
	8/4/83	1:00 p.m.[d]	3.64	78.6	12.4	0.5[g]	[h]	8.5
Secondary effluent	8/3/83	11:00 a.m.[c]	0.70	82.8	8.6	4.3	4.3	
	8/3/83	2:30 p.m.[c]	0.74	71.6	13.5	1.4	13.5[d]	
	8/4/83	9:00 a.m.[d]	0.38	38.7	29.9	26.1	5.3[d]	
	8/4/83	1:00 p.m.[d]	2.66	6.8	6.4	15.4[g]	[h]	71.4

[a] Based on grab samples obtained from the Las Vegas, Nev. WWTP.

[b] Wastewater samples were fractionated by serial filtration technique.

[c] Chemical coagulants added to influent.

[d] Chemical addition after trickling filter.

[e] Percent of P > 1.0 μm.

[f] Percent of P > 3.0 μm.

[g] Percent of P > 1.0 and <5.0.

[h] Not measured.

in Table 5. For comparison, a high rate trickling filter is typically designed to operate at a hydraulic loading rates between 10 and 40 $m^3/m^2 \cdot d$. As shown in the table, effective removal of BOD and SS is possible even at the highest hydraulic loading rate, 160 $m^3/m^2 \cdot d$.

The significance of the altered particle size distribution applied to the biological tower trickling filters can be appreciated by considering what happens when unfiltered primary effluent is applied. In the treatment of unfiltered primary effluent, both enzymatic hydrolysis in the liquid stream and recirculation pumping are important factors in reducing the size of the larger particles for more efficient removal by adsorption. By using filtration to remove the larger particles, the remaining material can be treated efficiently without recirculation.

Coagulation/flocculation processes. The principal objective of chemical coagulation/flocculation is to aggregate small particles into larger particles that can be removed effectively by physical means such as sedimentation and/or filtration. The effect of coagulation/flocculation on the size distribution of the particles in wastewater at two different locations is considered below.

The effect of adding chemical coagulants on the size distribution of particles larger than 0.1 μm in primary effluent was tested at the Las Vegas, Nev. wastewater treatment plant. The filtrable solids distribution of primary effluent without and with chemical addition was evaluated. A Parshall flume was used for rapid mixing of alum before primary sedimentation. A comparison of the distribution of filtrable solids in primary effluent under both conditions is presented in Figure 15a. Chemical addition modified the size distribution by aggregation and improved the performance of primary sedimentation.

The key to effective coagulation/flocculation of small particles in both water and wastewater is proper management of both the initial mixing step, where chemicals are introduced, and the subsequent flocculation step. Wilson[17,18] demonstrated that more effective flocculation can be achieved with a sheet mixer and a decayed gradient flocculator than with conventional mixing and flocculating equipment. A pilot-scale sheet mixer coupled to a three size step pipeline flocculator was used to study the flocculation of filtered primary effluent.[19] The distribution of filtrable solids in filtered primary effluent before and after coagulation/flocculation using alum as a coagulant is shown in Figure 15b. The sheet mixer and pipeline flocculator promote more effective particle aggregation, especially in the particle sizes smaller than 1.0 μm. It is interesting to note that particles smaller than 1.0 μm are not measured effectively by either the SS test or optical techniques, such as turbidity measurements, typically used to monitor and study coagulation/flocculation processes. By using size distribution analyses for the evaluation of process performance, the transformations that occur during treatment can be assessed more reliably. Particle size distributions are fundamentally important in the effectiveness of water treatment processes.[20]

Table 5—Typical performance data for tower trickling filters treating filtered primary effluent.[a]

Item	Hydraulic loading rate in $m^3/m^2 \cdot d$ 40	60	80	120	160
Filtered primary effluent, mg/L[b]					
SS[c]	23	32	24	34	26
BOD, total	54	76	76	71	49
BOD, filtered[d]	37	59	52	55	38
Trickling filter effluent, mg/L[e]					
SS[c]	17	22	30	36	28
BOD, total	20	32	30	31	25
BOD, filtered[d]	12	19	15	13	13

[a] References 8, 15.

[b] Primary effluent treated by pulsed-bed filtration.

[c] Determined using a filter with pore size ≈ 1.2 μm as specified in "Standard Methods."[1]

[d] Determined on a sample filtered through a 1.2-μm filter.

[e] Effluent from tower trickling filter with sedimentation.

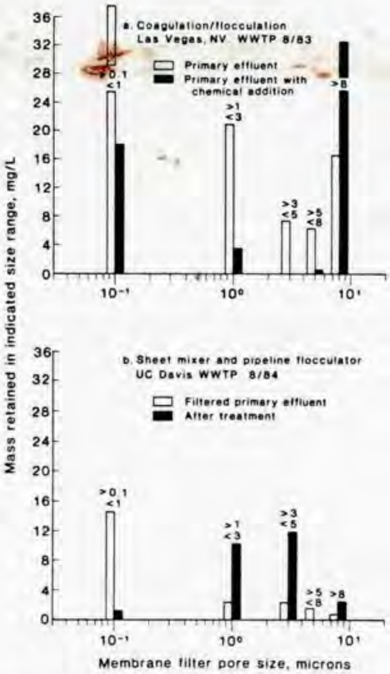

Figure 15—The influence of coagulation/flocculation processes on the mass distribution of filtrable solids in wastewater. a) Comparison of primary effluent without and with chemical addition. b) Comparison of filtered primary effluent before and after treatment with a sheet mixer and a three-stage pipeline flocculator.

Two-stage filtration. The technical feasibility of treating filtered primary effluent with coagulation/flocculation followed by a second stage pulsed-bed filter has been demonstrated.[21,22,23] Typical performance data from the operation of a two-stage pulsed-bed filtration system with and without chemical addition are reported in Table 6. Using alum as a coagulant, a cationic polymer, and an aspirator-type mixing device between filtration steps, the effluent consistently met secondary requirements. With further optimization of the coagulation/flocculation process to enhance flocculation of particles less than 1.0 μm, even better performance is anticipated.[24] Clearly, particle size management is fundamentally important in the performance of two-stage filtration.

Table 6—Typical performance data for the operation of two-stage pulsed-bed filtration without and with chemical addition between filtration steps.[a]

Sample data	SS mg/L			BOD mg/L		
	Primary effluent	After first-stage filtration[b]	After second-stage filtration	Primary effluent	After first-stage filtration[b]	After second-stage filtration
Without chemical addition						
7/23/81[c]	88.1	20.0	10.2	74	36	35
7/24/81[c]	56.5	19.5	12.0	105	45	35
7/31/81[c]	79.6	18.2	16.3	62	30	22
10/7/81[d]	89.4	39.3	29.7	85	71	54
With chemical addition[e]						
8/5/81[c]	54.5	21.5	9.9	84	42	23
10/9/81[d]	51.0	24.6	6.1	56	31	16
10/12/81[d]	69.4	27.3	13.0	75	45	18
10/14/81[d]	66.4	27.7	8.4	89	53	19

[a] Adapted from Reference 21.

[b] First-stage filter operated with a sand size of 0.45 mm.

[c] Second-stage filter operated with a sand size of 0.45 mm.

[d] Second-stage filter operated with a sand size of 0.35 mm.

[e] Coagulant chemical dosages were 10 mg/L alum and 3.5 mg/L polymer.

The application of two-stage filtration using the pulsed-bed filter for reclamation of municipal wastewater has been investigated recently in Orange County, Calif. The results of a 15-month study indicate that two-stage filtration could be used effectively as a pretreatment process for reverse osmosis demineralization of wastewater.[23]

Anaerobic digestion of wastewater. The anaerobic digestability of two types of wastewater sludges were evaluated using completely mixed, pilot-scale anaerobic digestors operated at 35°C and a solids retention time of 10 days. Process performance was monitored by testing for total and volatile solids, pH, alkalinity, chemical oxygen demand (COD), volatile acids, and gas production.[25] To gain insight into the treatability of different particle size fractions a modified size distribution analysis was performed. Typical data on the anaerobic digestability of various size fractions are presented in Table 7. Solids larger than 100 μm were essentially untreated. The material between 1.2 and 100 μm and the material smaller than 1.2 μm was effectively treated. Because enzymatic hydrolysis is primarily a surface phenomenon, the rate at which particles can be hydrolyzed to a size small enough for bacterial uptake is related directly to the available surface area. Thus, smaller material is degraded more readily. Degradation of the larger material is limited by the system kinetics. Future studies are planned to explore the degradability of primary solids that are mechanically pretreated to reduce the size of the larger particles.

ENGINEERING IMPLICATIONS

Characterization of the contaminants in wastewater by size distribution has significant implications for wastewater treatment and reuse. Based on the results presented in this paper, it is clear that a number of operations and processes can be used to manipulate the size distribution of particles in wastewater and that subsequent treatment can be enhanced through such particle size management. This has important implications related to wastewater treatment and wastewater reclamation and reuse.

Wastewater treatment. By characterizing the size spectrum of the organic contaminants in wastewater, the transformations and fate of various size fractions can be assessed. Approximately 30 to 85% of the organic contaminants in municipal wastewater are associated with the particulate matter larger than about 0.1 μm. By using physical/chemical treatment processes to remove or break up the large material, biological treatment or activated carbon adsorption can more efficiently remove the smaller organics. In some cases, water quality objectives can be met by physical/chemical treatment alone, without biological treatment. Separation and removal of the particulate fractions early in the treatment train may preclude the need for costly solids processing facilities following biological treatment.

Based on the experimental results reported in the literature

Table 7—Size ranges of solids in wastewater sludges before and after treatment by anaerobic digestion.[a]

Sludge	Size range, μm		
	<1.2	1.2–100	>100
Untreated, mg/L			
Primary	8 830	4 460	11 710
Backwash	4 330	5 850	14 820
Digested, mg/L			
Primary	1 150	1 570	10 620
Backwash	1 370	670	12 570

[a] Adapted from Reference 25.

and the findings of this study, it is suggested that the concept of particle size management be incorporated into the design of wastewater treatment systems. Use of nonspecific parameters such as BOD and SS to monitor the removal of contaminants during treatment implies that the nature of the organic material is unchanged and only the concentration of the contaminants is altered. Clearly, this assumption is not correct. The nature of the BOD and SS that remains after secondary treatment is quite different from that in untreated wastewater. Process selection based on size distribution analyses can result in the use of innovative treatment alternatives. With appropriate treatment technologies, the particle size distribution can be tailored to optimize contaminant removal. Sedimentation, pulsed-bed filtration, two-stage filtration, coagulation/flocculation, activated carbon, and reverse osmosis are all processes that can be used for efficient particle size management.

The concept of particle size management can be incorporated into a wastewater treatment system design as follows. First, the applicable water quality objectives must be defined. The next step is to characterize the wastewater in terms of organic content (BOD, TOC, and so on), solids content (SS), and the fraction of the contaminants associated with particulate matter larger than 0.1 μm. As demonstrated by this study, wastewater can be characterized effectively by separating the contaminants into two size categories based on a size of 0.1 μm. If a significant amount (more than 30%) of the organic contaminants are associated with material larger than 0.1 μm, further size characterization studies should be performed to identify the size ranges of the particulate matter. The next step is to assess the physical/chemical and biological treatability of the various particle sizes. Then, treatment operations and processes should be selected that are appropriate for removing or altering the size range of the contaminants of concern or for treating the wastewater as received. Final process selection should be based on cost-effectiveness. Examples of treatment process flowsheets that might result from the application of this design approach are illustrated in Figures 16a through 16d. The flowsheets presented in Figure 16 are suitable for treatment of wastewater that contains a significant fraction of particulate organic matter and are not intended for treatment of wastewater predominantly composed of soluble matter.

Wastewater reclamation and reuse. For wastewater reclamation and reuse, the interactions among unit operations and processes are particularly important. The nature of the material remaining after each treatment process influences the effectiveness of subsequent treatment, especially disinfection.[24] By using size distribution analyses, the appropriateness of particular treatment technologies for a given wastewater can be evaluated more thoroughly. The work of Rigby *et al.*[23] is an excellent example of such an application in the field of wastewater reclamation.

One of the major areas of concern in wastewater reclamation is the removal of pathogenic bacteria and viruses. Solid material in wastewater tends to shield bacteria and virus particles and therefore should be removed in upstream processes to ensure adequate disinfection. If the solids are removed prior to disinfection, the chlorine requirements would be reduced considerably.

Because of uncertainties associated with health risk assessment of pathogens in reclaimed wastewater, improvements in wastewater treatment technology based on particle size management are warranted.[24] By effective characterization of the wastewater prior to design of reclamation facilities, treatment processes appropriate for contaminant removal can be selected, thereby avoiding redundant and expensive treatment that may result from the current practice of adding an entire water treatment plant onto a wastewater treatment plant. Examples of alternative flowsheets for meeting wastewater reclamation objectives without the use of biological treatment are given in Figures 16e and 16f.

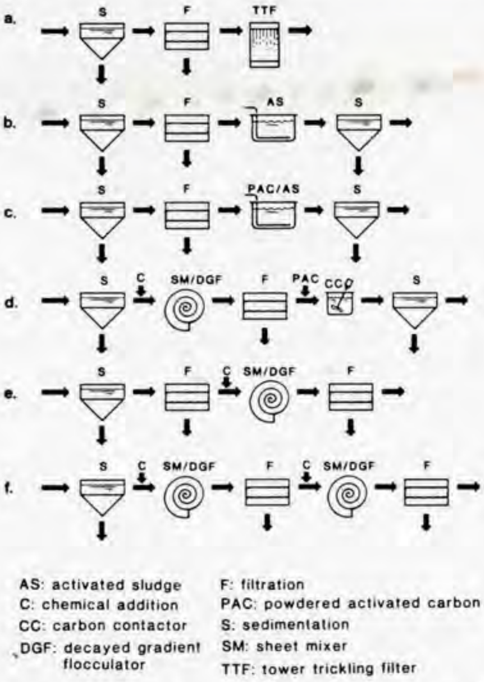

Figure 16—Flowsheets for treatment and reuse applications developed based on the concept of particle size management.

SUMMARY AND CONCLUSIONS

- The organic contaminants in municipal wastewater can be effectively classified as either greater than or less than 0.1 μm.
- The size of the organic particulate matter in settled municipal wastewater ranges from about 0.1 to 50 μm. The molecular size of organic contaminants smaller than 0.1 μm ranges from less than 10^3 to about 10^7 amu.
- The percentage of organic material larger than 0.1 μm in settled municipal wastewater ranges from 30 to 85%. The specific percentage will depend on the nature of the community, the length and flow regime in the sewers, whether influent pumping or grit removal is used, and on the design and operating characteristics of the primary sedimentation facilities.
- The predominant removal mechanisms of most processes for treatment of wastewater contaminants are related to particle size.
- There is no reason to accept wastewater as it arrives at the treatment plant. Appropriate technologies can be used to tailor the size distribution of contaminants to meet specific treatment objectives. The incorporation of size distribution

analyses into the design process will result in the development of more innovative and cost-effective treatment facilities for wastewater treatment and reuse.

- In the future, the selection, design, and operation of wastewater treatment facilities can be improved by using a design procedure that incorporates the concept of particle size management.

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