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EVALUATION OF CSO TREATABILITY FOR THE CITY OF NIAGARA FALLS

FINAL REPORT

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NATIONAL WATER INSTITUTE
INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

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Preamble

One of the primary goals stated in the Stage II Remedial Action Plan report for the Niagara River Area of Concern was the reduction and virtual elimination of combined sewer overflows (CSOs). In this respect, the City of Niagara Falls has recognized the need to examine the environmental impact of CSO discharges on the aquatic environment, and assess the environmental benefit of new and innovative CSO treatment and pollution prevention technologies. For the effective design of a treatment process for CSOs, it is necessary to first understand the CSO characteristics with respect to chemical composition and settleability, with and without chemical additions. Environment Canada's National Water Research Institute (NWRI) has undertaken this study in support of the Great Lakes Action Plan (GLAP) and, specifically, to advance the process of delisting the Niagara River Area of Concern. This final study report summarizes the Institute's activities and results. Settleability of the samples was assessed by four methods, including three settling column-based methods and a newly proposed elutriation apparatus method (EAM). For practical design, the column-based methods and the EAM provided comparable data, although each method has unique merits and technical limitations. Treatability of dry-weather and CSO samples with chemical aids was assessed by jar testing. Data indicate that Niagara Falls CSOs may be well suited to chemically aided settling, with relatively inexpensive low dosages of coagulant. Chemical characterization of the samples indicates that the municipal sewage at this site is of relatively weak strength, with several statistically significant differences between the dry-weather and CSO water quality data. The results will be used by the study partners in the planning and set-up of a subsequent pilot-scale study, and eventual design of a full-scale CSO treatment facility.

Préambule

L'un des buts premiers énoncés dans le rapport sur la phase du Plan d'assainissement du secteur préoccupant de la rivière Niagara porte sur la réduction et l'élimination quasi totale des trop-pleins d'égout unitaires (TPEU). À cet égard, la ville de Niagara Falls admet qu'il est nécessaire d'examiner l'impact environnemental des rejets des TPEU sur le milieu aquatique et d'évaluer les avantages que représente l'application de nouvelles technologies novatrices de traitement des TPEU et de prévention de la pollution pour l'environnement. Pour mettre au point un procédé de traitement efficace des TPEU, il est nécessaire de commencer par bien comprendre leurs caractéristiques, en particulier leur composition chimique et leur décantabilité, avec ou sans addition de produits chimiques. L'Institut national de recherche sur les eaux (INRE) d'Environnement Canada a entrepris cette étude dans le cadre du Plan d'action des Grands Lacs (PAGL) et, spécialement, pour faire avancer le processus de retrait de la rivière Niagara de la liste des secteurs préoccupants. Le présent rapport final résume les activités et les résultats de l'Institut. La décantabilité des échantillons a été évaluée grâce à quatre méthodes : trois utilisaient des colonnes de décantation, et une nouvelle technique (appelée EAM) employait un appareil d'élutriation. Le traitement d'échantillons prélevés par temps sec et d'échantillons de TPEU, à l'aide d'adjuvants chimiques, a été évalué grâce à des essais de floculation. Les résultats montrent que les TPEU de Niagara Falls peuvent être traités efficacement par décantation assistée chimiquement, avec utilisation de faibles doses d'un coagulant, à un coût relativement bas. La caractérisation chimique des échantillons indique que les eaux d'égouts de cet endroit sont relativement peu concentrées et qu'il y a de nombreuses différences statistiquement significatives entre les données qualitatives des échantillons prélevés par temps sec et celles des échantillons de TPEU. Les résultats seront utilisés par les partenaires de l'étude pour la planification et l'élaboration d'une étude ultérieure à l'échelle pilote, et, peut-être, pour la conception d'une installation de traitement des TPEU à l'échelle réelle.

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1. Introduction

1.1 Background

In 1973, the International Joint Commission identified 43 Areas of Concern (AOCs) throughout the Great Lakes Basin where water quality impairment prevents full beneficial use of the local receiving waters. The Niagara River was identified as one of these AOCs. The City of Niagara Falls is located within the Niagara River AOC, and has been a very active partner in the development and implementation of a Remedial Action Plan (RAP) aimed at restoring the full beneficial use of the Niagara River. One of the primary goals stated in the Stage II RAP report for the Niagara River AOC was the reduction and virtual elimination of combined sewer overflows (CSOs). In this respect, the City has recognized the need to examine the environmental impact of CSO discharges on the aquatic environment, and assess the environmental benefit of new and innovative CSO treatment and pollution prevention technologies.

Specifically, the City has identified and wishes to fully evaluate the flow hydraulics, performance and pollutant removal efficiency of various physical screening /settling devices as well as the chemical coagulation technology for the high rate treatment of CSOs at a sewer outfall site. It is envisaged that these new satellite treatment technologies, if implemented successfully, could significantly reduce the cost of treatment of CSO discharges. As a preliminary requisite phase of the technology evaluation, it is imperative to first understand the City's CSO characteristics with respect to chemical composition and settleability, with and without chemical addition. Towards that end, the City has carried out a joint study with the National Water Research Institute (NWRI) to characterize the City's CSO, and to conduct a bench-scale treatability study of the CSO using polymer coagulation technology. This report summarizes the Institute's activities and study results.

2. Study Overview

2.1 Study Objectives

The purpose of the study component conducted by NWRI was to analyze the physical and chemical characteristics, as well as the treatability (including polymer coagulation/flocculation) of the CSOs and dry-weather flows (municipal sewage) sampled in Niagara Falls. Such data are essential for the planning and set-up of a subsequent pilot-scale study, and eventual design of a full-scale CSO treatment facility.

CSO settleability was to be investigated by means of well-established conventional "solids settling columns", under static conditions, and the elutriation apparatus method (EAM), which was recently developed at NWRI and measures the solids settling characteristics under dynamic flow conditions. It is expected that the flow field generated in the elutriation apparatus better reproduces the flow conditions in the actual clarifier than the conventional settling columns. Consequently, the results obtained by EAM should provide a more realistic prediction of solids settling in the full-scale facility.

In treatability studies, the EAM appears to be superior to the conventional jar-testing technique, again because of a better representation of actual flow conditions. This makes EAM particularly useful for on-line testing of the effectiveness of various types of coagulants/flocculants and their dosages in the improvement of solids settling under dynamic flow conditions.

2.2 Study Scope

The study scope was defined with respect to the settleability testing and coagulation / flocculation testing.

2.2.1 Settleability Tests

NWRI was requested to build and set-up four testing apparatuses – Aston, Brombach and EPA columns, and the NWRI elutriation apparatus and use them in assessing the settleability and treatability of Niagara Falls CSO samples. Samples were to be collected at the Niagara High Lift Station by city staff for 15 wet-weather events (overflows), and delivered to NWRI for testing.

All fifteen CSO samples were to be tested by all four methods, and the results of the three different column tests would be compared to, and cross-referenced against, those obtained by the elutriation apparatus method. These comparisons would ensure that the EAM results were valid and provide additional information not available from the conventional methods. Besides the settleability tests, all samples would be also analyzed for a number of water quality constituents, including total suspended solids (TSS), biochemical oxygen demand (BOD), nutrients, and trace metals.

2.2.2 Chemical Coagulation/Flocculation Tests.

Standard coagulation/flocculation jar tests would be performed on the collected CSO samples using various types of metal salts and polymers or a combination of both. Jar testing should help in selecting the most suitable coagulants/flocculants to be used for treating Niagara Falls CSOs and their optimum dosages.

3. Experimental Methods

3.1 Sample Collection and Preparation

The samples were collected by City of Niagara Falls staff. Wet-weather samples were collected at the High Lift Station using an American Sigma model 900 autosampler, activated when the wastewater plant inflow exceeded a level of 50 cm in the wet well. Several wet-weather samples were also collected at the Muddy Run and Central Pumping Station sites. Dry-weather grab samples were collected from the wet well, using a bucket to fill five 25-L carboys. Samples were transported without refrigeration to NWRI in Burlington (driving time approximately 60 minutes), where the samples were stored at 4°C in a dark walk-in refrigerator until tested. Samples were usually received on the day of the event.

Prior to testing, the carboys were emptied into a mixing drum and the sample was mixed/homogenized by continuous pumping through a ½-hp pump (300 L/min) for approximately 2.5 minutes and then divided into several 20-L carboys. The carboys were put into hot water baths to bring the sample temperature to that of the ambient air (20 ±2°C). At the

start of each test, a whole-water sample of the well-mixed sewage was collected and analyzed for TSS and other constituents, as discussed in section 3.4 below.

3.2 Settling Test Procedures

A number of different methods have been used in the past to characterize settleability of CSOs and wastewater (Michelbach and Wöhrle, 1993; Andoh and Smisson, 1996; Pisano, 1996; Rasmussen and Larsen, 1996). Several researchers have compared the traditional and alternative methods in order to determine which technique is the most suitable for assessing the treatability of wet-weather flows (Aiguier *et al.*, 1996 and 1998; Tyack *et al.*, 1996; O'Connor *et al.*, 2002). Since the testing methods for CSO characterization are not standardized, four such methods were included in this study. Three of the methods use settling columns, including the Aston column, the Brombach column and the U.S. EPA multi-port long column; the fourth one is a new elutriation method using an elutriation apparatus. The individual methods used are described below.

3.2.1 Aston Column

The Aston column was developed at Aston University, UK (Tyack *et al.*, 1993) with the objective of characterizing not only settling solids (sinkers), but also floating solids (floaters). The column used in this study is constructed of acrylic (2.2 m long and 5 cm ID), has a volume of approximately 5 L, and is supported by central gimbals allowing 180° rotation in the vertical plane to facilitate sampling of settled and floating solids (Fig. 3.1). At each end of the column, ball valves isolate terminal cells, which separate the sampling volume from the rest of the column.

A sewage aliquot of approximately 6 L is brought to the ambient lab air temperature (~20°C), thoroughly mixed and poured into the Aston column. With the outside valves closed, the column is rotated several times, the inside valves are exercised to purge trapped air, and sewage is topped-up as required to fill the column. The column remains undisturbed in the starting vertical position during a 3-hour initial settling period.

After the initial settling period, the two inside valves are closed, and water with floaters and sinkers collected during the initial period is removed from the outer cells A and B (see Fig. 3.1). The initial floaters (cell A) are saved for further analysis; the sinkers from cell B are thoroughly mixed and poured into the top cell A, the bottom cell B is filled with tap water, and the column is returned to the starting position. In sequence, the inside top valve (#2) and bottom inside valve (#3) are opened, releasing the re-introduced sinkers into the central column section for settling over a 2.5 hour period. At pre-selected times listed in Table 3.1, settled solids are collected. At the end of each sampling interval, valve 3 is closed (isolating cell B), and valve 4 is opened to collect the sample. The column is then inverted, cell B is refilled with tap water (of the ambient lab air temperature), the valves are exercised to purge entrained air, and the column is rotated back to its starting position. Valve 3 is then opened to capture settled sediment and stays open until the next sampling interval. At the end of the test, the final floaters, sinkers, and non-settled sample volumes are collected, and the apparatus is flushed. All samples (including the flush) are analyzed for TSS (APHA, 1998) and the results are used to check the mass balance of the test procedure.

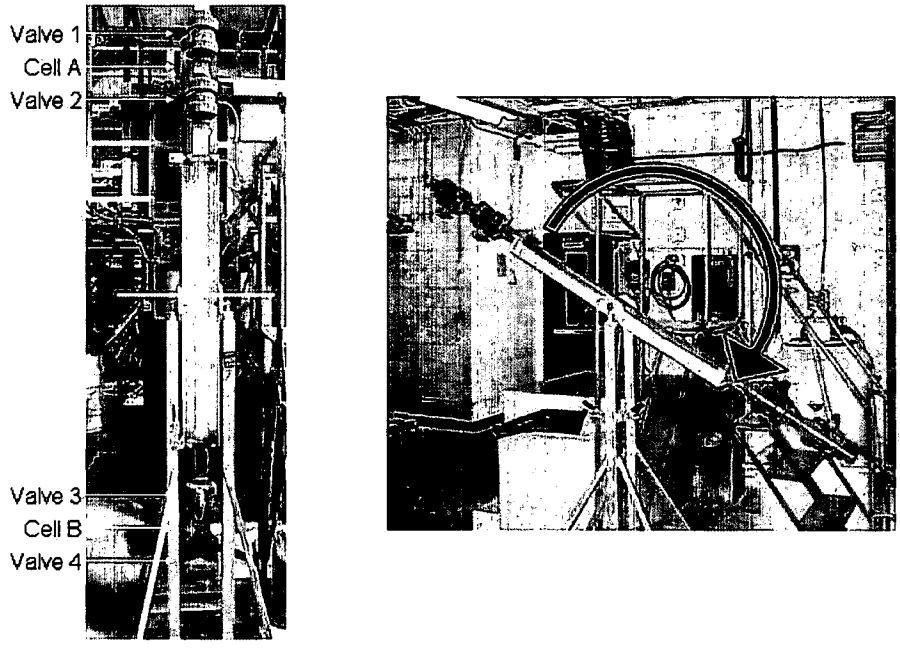

Fig. 3.1: Aston column: components and column rotation

Table 3.1: Sampling schedule for the Aston column

Sample #	Interval (min)
Mixed Raw	
Initial Floaters	0
1	1
2	3
3	5
4	10
5	20
6	30
7	40
8	60
9	90
10	120
11	150
Final Floaters	End of Test
Non-settling	End of Test
Flush	End of Test

3.2.2 Brombach Settling Column

The Brombach column (also known as the UFT, or Umwelt- und Fluid-Technik, column) has been used extensively in Germany to characterize the settleability of CSOs, and such data were used to design CSO storage tanks (Pisano and Brombach, 1996). The column consists of an upper reservoir (500 mL), with an offset sample delivery cylinder, a middle, transparent column section (approximately 5 cm ID x 49 cm), and an Imhoff cone (100 mL) attached to the column bottom. Samples are collected from the cone using a silicone tube with a pinch-clamp (Fig. 3.2).

In this procedure, a sewage sample is pre-settled in the column, the settled solids are collected, the column is drained and refilled with tap water, and the settled solids are reintroduced at the top of the column. Subsequently, samples are withdrawn from the bottom of the column at timed intervals and analyzed for total suspended solids.

The column is filled with 1 L of well mixed sewage at the ambient lab air temperature and allowed to settle for two hours. After this period, the settled sludge (solids) volume index (SVI) (mL/L) is determined (Fig. 3.2) as the volume of solids accumulated in the Imhoff cone (measured in mL) divided by the sample volume (1 L). The solids from the Imhoff cone are transferred to a small beaker and saved for further testing. The remaining wastewater in the

column (the non-settling fraction) is drained, sampled for TSS (as a component in the mass balance check), and the column is refilled with tap water at the ambient lab air temperature. The solids recovered from the Imhoff cone are mixed with tap water to obtain 75 mL of slurry, which is then poured into the offset sample delivery cylinder in the upper reservoir of the column. To initiate the second phase of the settling test, the sample delivery cylinder is slid sideways, until aligned with the top opening of the settling column, and the slurry is released from the cylinder into the settling column. Twenty-five milliliter samples are withdrawn from the Imhoff cone drain tube at the time intervals listed in Table 3.2. After each sample withdrawal, the upper water reservoir is replenished with an equivalent volume of tap water to maintain a constant hydraulic head in the column. The final non-settling volume and column flush are sampled and analyzed to verify mass balance for the test.

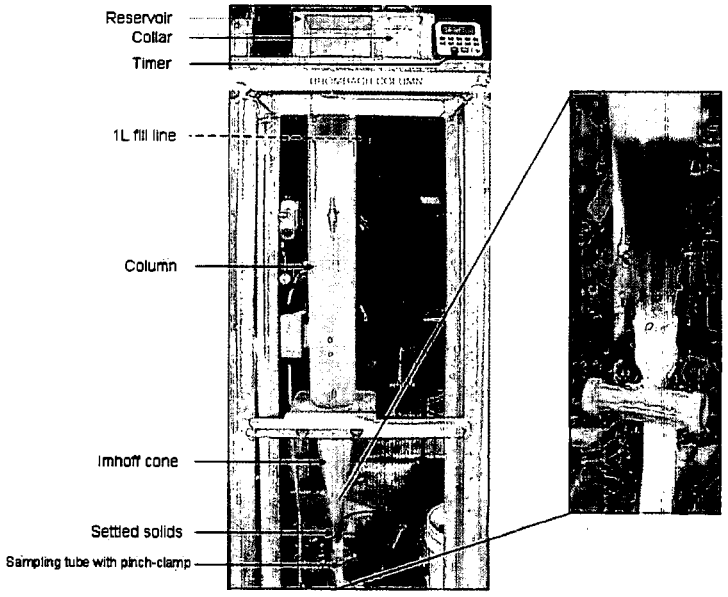

Fig. 3.2: Brombach column: overall view and a detailed view of the Imhoff cone

Table 3.2: Sampling schedule for the Brombach settling column

Sample #	Hours: minutes: seconds
Mixed Raw	
SVI	
Non-settling	
Initial flush	
1	0: 00: 07
2 (optional)	0: 00: 14
3	0: 00: 28
4	0: 00: 56
5	0: 01: 52
6	0: 03: 45
7	0: 07: 30
8	0: 15: 00
9	0: 30: 00
10	1: 00: 00
11	2: 00: 00
Final Non-settling	
Final flush	

3.2.3 U.S. Environmental Protection Agency (EPA) Settling Column

The U.S. EPA column is also known as the "long" column and was described in general terms by O'Connor *et al.* (2002). It is usually constructed of clear acrylic, in lengths ranging from 1.8 to 2.5 m, and fitted with evenly spaced side ports for sample withdrawal and a drain valve at the bottom. The column used at NWRI (Fig. 3.3) is 1.5 m long, 12.7 cm in diameter and has ports spaced at 25.3 cm.

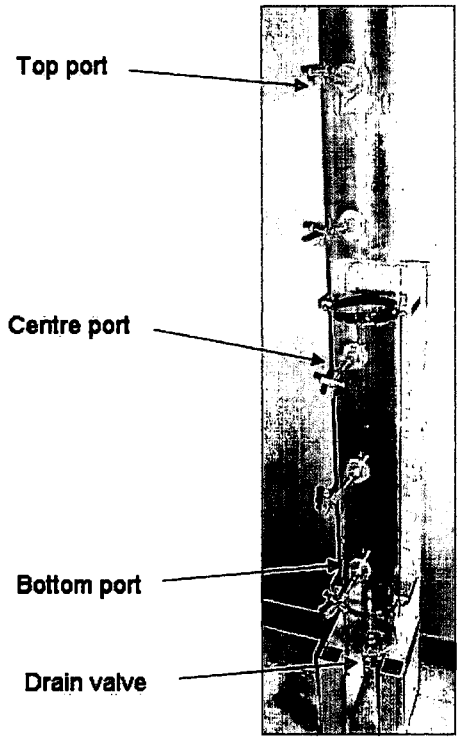

Fig. 3.3: U.S. EPA settling column

At the start of the test, a 20-L aliquot of sewage is brought to ambient lab air temperature and thoroughly mixed. The well mixed sample is then poured rapidly into the column, and a sub-sample is collected for determination of "raw" TSS. Sampling proceeds at timed intervals listed in Table 3.3, in a sequential fashion from the top to the bottom port. Before collecting each sample, the port is flushed by withdrawing 25 mL of sewage, which is discarded, but accounted for in mass balance calculations. A 25 to 50 mL sample is then collected from each port. As successive samples are withdrawn, the total depth of sewage in the column is reduced, which necessitates corrections of calculated settling rates for these changes. At the end of the two-hour test, the sewage remaining in the column is drained down to the lowest sampling port. The drained sewage is collected, mixed well, and sampled to determine the solids mass in the non-settled portion of the raw sample. The solids settled in the column are collected below the bottom sampling port and removed through the bottom drain. The column is flushed with tap water to account for solids adhered to the column walls in the mass balance.

Table 3.3: Schedule of sampling intervals and sample volumes for the U.S. EPA settling column

Sample #	Minutes	Volume (mL)
Mixed Raw		
1	2	25
2	4	25
3	8	30
4	16	30
5	30	30
6	60	50
7	120	50
Non-settling	End of test	
Settled	End of test	
Flush	End of test	

3.2.4 Elutriation Apparatus

An experimental elutriation apparatus method (EAM) has been included in this battery of settleability tests to provide an alternative approach to conventional static settling column tests. In EAM, the particles are exposed to dynamic interaction while settling, and this more accurately reflects the type of settling which would occur in a conventional full-size flow-through settling basin. The method was adapted from a water elutriation process which was originally proposed by Walling and Woodward (1993) to measure particle size distribution of riverine suspended sediment. The original apparatus developed by Walling and Woodward (1993) consisted of four cylinders with diameters 25 mm, 50 mm, 100 mm and 200 mm, and arranged sequentially in the ascending order of their diameters. The river water was drawn through these cylinders by a pump, which was placed at the downstream side of the cylinders. The river water was routed through these cylinders in such as way that it entered the cylinders near the bottom and exited near the top. Such an arrangement allowed the river sediment that has settling velocity higher than the upward velocity of the water to settle in a particular cylinder. Since the diameters of the cylinders were progressively increasing, sediment with different settling velocities settled in different cylinders. By measuring the amount of sediment in each cylinder, the settling velocity distribution was deduced.

Krishnappan *et al.* (2004) used such a system and developed a protocol for measuring the settling velocity distribution of CSO solids. The elutriation apparatus method used for the Niagara Falls samples is based on this protocol. The apparatus consists of eight cylinders (instead of four used

by Walling and Woodward, 1993) to provide higher resolution of settling velocity distributions (first seven columns) and to trap the floatable material (8^{th} cylinder). The configuration of the apparatus is shown in Fig. 3.4.

Columns 1 through 8 are filled with distilled water at the start of the experiment. The internal diameters of settling columns 1 through 8 are: 25, 34, 49, 70, 105, 143, 197 and 197 mm. In the present test procedure, CSO samples are split into two 25 L carboys (a total of 50 L of sample is eluted) and mixed by impellers. A Y-connector combines the delivery lines from the two carboys, so that their streams become completely mixed prior to entering the first column. This configuration was designed to duplicate the effect of an online mixing process such as polymer addition, which is often used to improve settleability of CSOs. As the CSO sample enters the column at the bottom, it begins to rise towards the outflow tube located at the top of the column. Particles or flocs with settling velocities greater than the upward flow velocity are retained within the column, and particles with settling velocities smaller than the upward flow velocity are carried through into the next column. As the upward flow velocities in each successive column become progressively slower, finer and finer solids settle. Finally, column 8 at the downstream end of the apparatus can be used to collect floatable materials by having reversed flow field, in a downward direction (Fig. 3.5). Floatable materials are retained in the top portion of the column, and all other materials with settling velocities smaller than those collected in column 7 will pass through to the effluent carboys. Alternatively, if operated in the upward flow direction, column 8 acts to effectively 'lengthen' column 7, allowing more efficient capture of the solids with low settling velocities. For the first two dry-weather samples, July 7 and August 28, 2003, the elutriation apparatus was operated in floatables collection mode, but for all other samples, the flow was reversed and solids collected in columns 7 and 8 were considered as a single fraction. The masses of solids collected in each column (and effluent carboys) are determined using a conventional TSS analysis (APHA, 1998).

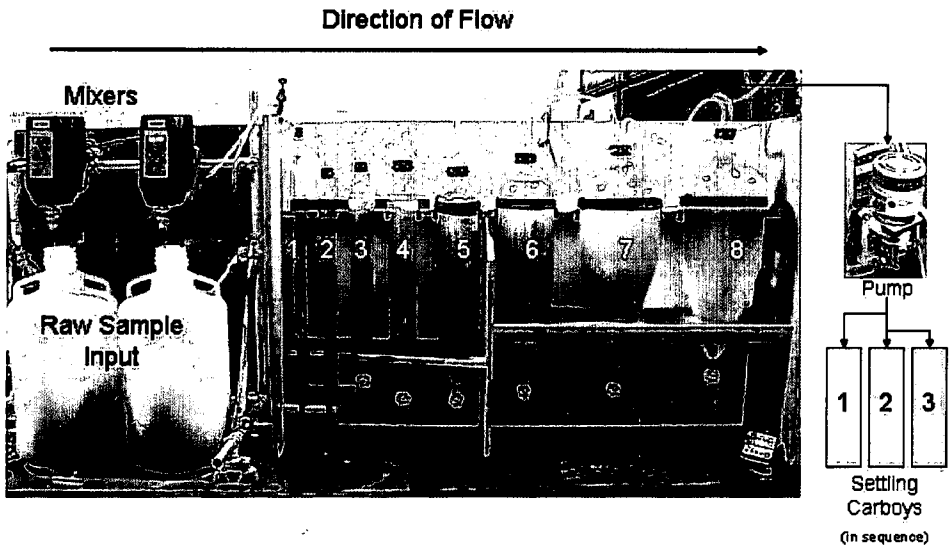

Fig. 3.4: Elutriation apparatus configuration

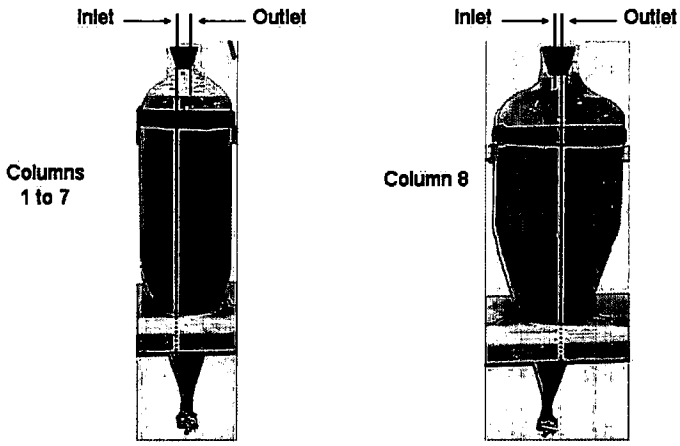

Fig. 3.5: Elutriation apparatus flow arrangements: upward flow in columns 1-7 and downward flow in column 8

3.3 Jar tests

Many contaminants, including metals, bacteria, viruses, and many organic micropollutants, have an affinity for particulates. The addition of coagulants and flocculants during primary treatment of wastewater aids in the removal of suspended solids, and therefore in the removal of associated contaminants (Odegaard, 1988).

Most suspended solids have negatively charged surfaces under normal conditions of water and wastewater treatment. Removal by chemically assisted sedimentation typically progresses through the following steps: destabilization of colloids (coagulation), aggregation of destabilized particles (flocculation), and sedimentation. Coagulants often destabilize suspended solids through neutralization of surface charge; common coagulants include inorganic salts, such as alum or ferric chloride, and polyelectrolytes (polymers) with high charge and low molecular weight. Alternatively, a flocculant may be added to aid the aggregation process by bridging, or adsorbing to multiple particles at one time. Typical flocculants are long-chain (high molecular weight) polymers with a low degree of charge. While anionic and nonionic polyelectrolytes are commonly used as flocculant aids in conjunction with inorganic coagulants, the polymers used as primary coagulants and flocculants in water and wastewater treatment are typically cationic (Amirtharajah and O'Melia, 1990). Advantages of polymeric flocculants over inorganic chemical treatments have been reported to include: lower dosage requirements; reduced sludge volumes; reduced need for pH adjustment; and the formation of flocs that are relatively resistant to shear forces (Hennis *et al.,* 2001; Bolto *et al.,* 1996). However, polymer costs may be higher than those of many inorganics, and highly coloured water may not be effectively treated by polymers alone (Bolto *et al.,* 1996).

Alum was used as supplied by the manufacturer (Eaglebrook, 57 g/L as Al). The polymer flocculant chosen for the present tests was a high molecular weight, low cationic charge polyacrylamide, Zetag 7873 (CIBA Specialty Chemicals) that has previously been shown to be successful in stormwater and CSO treatment studies (e.g. Wood *et al.*, 2004; Marsalek *et al.*, 2004; Li *et al.,* 2003). As suggested by the supplier, the polymer was applied as a dilute solution. Each week, a 1% stock solution of Zetag 7873 polymer in distilled water was prepared; the stock solution can be stored for up to 5 days. Each test day, a 0.15% feed solution of polymer in distilled water was prepared.

Conventional jar tests typically incorporate a rapid mixing period for efficient coagulant dispersal, a slow mixing period for improved floc formation and growth, and 30 to 60 minutes of quiescent settling. It has been shown (Young *et al.,* 2000; Li *et al.,* 2003) that slow mixing does not greatly improve TSS removal during polymer coagulation, so this step was only applied for

alum-dosed experiments in this study. A somewhat modified jar test procedure was followed in an effort to better reflect rapid treatment conditions, although it must be recognized that results from batch testing of small volumes may not necessarily be directly applicable to continuous flow, full-scale conditions. A simple jar test can, however, indicate the optimal conditions of treatment, and the maximum contaminant removals that can be expected under those conditions. The use of modified jar tests for evaluation of coagulants and flocculants complement the results of the standard suite of settling columns in identifying solutions to address the MOE F-5-5 requirements at the Niagara Falls sewage treatment plant.

The jar test apparatus used was a 6-2L square jar manifold with flat-blade impellers (Phipps and Bird, PB 700 jar tester) (Fig. 3.6). Immediately before testing, a 10-L subsample (enough for one test) was removed from the cold room and warmed in a water bath for 30 minutes, or until the temperature reached 20 (± 2) °C. Each jar was filled with 1.5 L of sample. The jar test procedure included coagulant / flocculant dosing using a serological pipette for polymer or a micropipette for alum, a 2-minute rapid mix at 100 rpm, a 15-minute slow mix at 30 rpm (for alum only), and 20 minutes of quiescent settling. Dosages applied ranged from 0 to 10 mg / L as polymer or Al, as appropriate. After the settling period, samples were collected through the sampling tap of each jar for analysis of TSS, temperature, and pH.

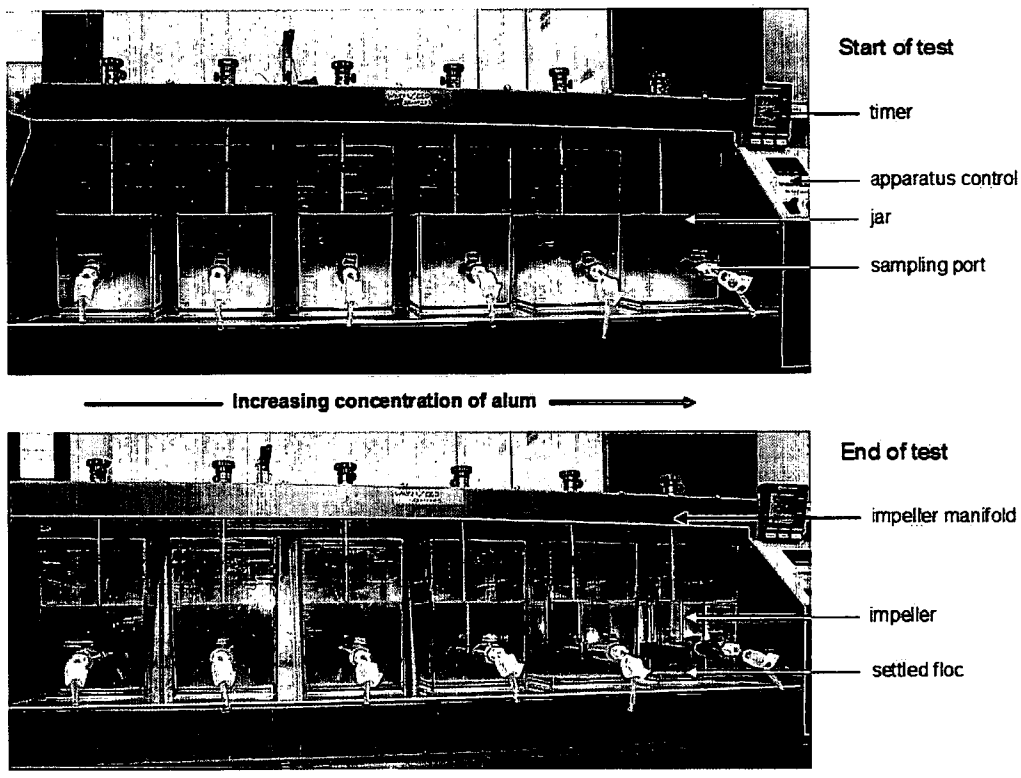

Fig. 3.6: Jar testing apparatus set-up.

3.4 Analytical methods

Analyses for total suspended solids (TSS) and volatile suspended solids (VSS) were performed in accordance with *Standard Methods for the Examination of Water and Wastewater, 20th edition* (APHA, 1998).

Analyses for total organic carbon (TOC), dissolved organic carbon (DOC), chemical oxygen demand (COD), 5-day total biochemical oxygen demand (BOD), ammonia (NH_3), total Kjeldahl nitrogen (TKN), total phosphorus (TP), chloride, and dissolved and total metals (cadmium, copper, nickel, lead, and zinc) were performed by the Wastewater Technology Centre Analytical Laboratory from June 2003 to August 2004, and by PSC Analytical Services after that time. Both are CAEAL-certified laboratories.

3.5 QA/QC

All samples received were stored in a 4°C walk-in refrigerator until tested. All column/apparatus tests were conducted on the same day (exceptions noted in Table 4.1) to minimize potential chemistry and particulate changes that may occur on storage. Prior to testing, each raw sample was warmed to ambient temperature (± 2°C). A 'raw' sewage subsample was removed for each apparatus, to check the uniformity of the samples among column tests via TSS analyses.

Samples were thoroughly mixed before any analyses were performed (including TSS and temperature measurement, or sub-sampling for analytical chemistry submissions). All column volumes were measured and subsamples retained for TSS analysis, including raw samples, unsettled volumes remaining after sampling, flush volumes containing solids that previously adhered to column walls, and 'wasted' volumes, for calculating solids mass balances. Final temperatures of unsettled samples were checked to determine whether temperatures had changed significantly during the tests.

Only a single replicate of total suspended solids were analyzed for each column sample collected, due to limited sample volume. Where large volumes of sample were present (e.g. EPA and Aston columns unsettled fractions, and before/after raw elutriation volumes), duplicate subsamples were analyzed. Analytical chemistry performed by the third-party laboratories included suitable duplicate samples, spiked samples, and percentage recovery for reference samples.

4. Samples Tested

Between June 9th, 2003 and January 28th, 2005 a total of 19 wet-weather samples (including 3 from the Central Pump Station, and 1 from Muddy Run) and 12 dry-weather samples were tested by NWRI. Samples were generally subjected to testing within seven days of receipt at NWRI; dates are listed in Table 4.1.

Table 4.1: Descriptions of wet-weather and dry-weather samples received by NWRI

	Event Date	Weather	Sampling location	Test dates		
				Columns	Jar Test	Elutriation
1	09-Jun-03	Wet	HLS	10-Jun-03	12-Jun-03	15-Jul-03
2	11-Jul-03	Wet	HLS	14-Jul-03	17-Jul-03	N/A
3	15-Jul-03	Wet	HLS	16-Jul-03	18-Jul-03	03-Dec-03
4	05-Aug-03	Wet	HLS	07-Aug-03	08-Aug-03	19-Dec-03
5	19-Nov-03	Wet	HLS	24-Nov-03	25-Nov-03	24-Nov-03
6	11-Dec-03	Wet	HLS	12-Dec-03	12-Dec-03	12-Dec-03
7	02-Mar-04	Wet	HLS	04-Mar-04	04-Mar-04	04-Mar-04
8	06-Mar-04	Wet	HLS	10-Mar-04	10-Mar-04	10-Mar-04
9	20-Mar-04	Wet	HLS	23-Mar-04	23-Mar-04	23-Mar-04
10	18-Apr-04	Wet	HLS	20-Apr-04	i.v.	i.v.
11	21-Apr-04	Wet	HLS	23-Apr-04	24-Apr-04	i.v.
12	02-May-04	Wet	HLS	06-May-04	i.v.	i.v.
13	09-May-04	Wet	HLS	11-May-04	11-May-04	11-May-04
14	02-Jul-04	Wet	MR	05-Jul-04	05-Jul-04	i.v.
15	07-Jul-04	Wet	CPS	12-Jul-04	16-Jul-04	i.v.
16	14-Jul-04	Wet	HLS	19-Jul-04	19-Jul-04	19-Jul-04
17	14-Jul-04	Wet	CPS	20-Jul-04	21-Jul-04	20-Jul-04
18	27-Jul-04	Wet	HLS	29-Jul-04	03-Aug-04	29-Jul-04
19	05-Nov-04	Wet	CPS	12-Nov-04	10-Nov-04	12-Nov-04
1	16-Jun-03	Dry	HLS	inc. data	24-Jun-03	inc. data
2	05-Sep-03	Dry	HLS	09-Sep-03	09-Sep-03	17-Dec-03
3	09-Oct-03	Dry	HLS	10-Oct-03	10-Oct-03	10-Oct-03
4	10-Nov-03	Dry	HLS	12-Nov-03	12-Nov-03	13-Nov-03
5	12-Feb-04	Dry	HLS	13-Feb-04	13-Feb-04	13-Feb-04
6	29-Mar-04	Dry	HLS	30-Mar-04	30-Mar-04	30-Mar-04
7	19-Apr-04	Dry	HLS	23-Apr-04	23-Apr-04	23-Apr-04
8	03-Jun-04	Dry	HLS	07-Jun-04	07-Jun-04	07-Jun-04
9	12-Jul-04	Dry	HLS	14-Jul-04	14-Jul-04	14-Jul-04
10	07-Sep-04	Dry	HLS	10-Sep-04	10-Sep-04	10-Sep-04
11	25-Jan-05	Dry	HLS	27-Jan-05	26-Jan-05	27-Jan-05
12	28-Jan-05	Dry	HLS	01-Feb-05	04-Feb-05	01-Feb-05

Note: HLS – High Lift Station; MR – Muddy Run; CPS – Central Pumping Station; i.v. – insufficient volume; inc. data = incomplete data set.

5. Results and Discussion

Presentation of results starts with data on CSO settleability (Section 5.1), followed by jar testing (i.e., settleability with chemical additions, Section 5.2), and CSO chemical characterization (Section 5.3).

5.1 CSO Settleability Results

CSO settleability has been assessed using four methods, including three columns (Aston, Brombach and EPA) and the elutriation apparatus. Test results are presented in the same order.

5.1.1 Analysis of data collected using the Aston Column

a) Mass balance calculation:

Let the original mass of the particles in the raw sample used in the Aston column be M_R, and the masses of the sinkers and floaters collected after the initial three hour period be M_S and M_F respectively. The masses of samples collected at different sampling times during the settling experiment are denoted by the symbol, M_i, where (i=1, 2 ...11). Let the mass of the floaters collected at the end of the settling experiment be M_{FE}, and the mass of the non-settled fraction in the column at the end of the test be M_{NS}. The mass collected during the flushing operation is denoted by M_{flush}. Using these symbols, the total mass of particles measured at different stages of the operation was calculated as:

$$\text{Total mass of particles measured } (M_M) = M_S + M_F + \sum M_i + M_{FE} + M_{NS} + M_{flush} \quad (1)$$

The above mass was compared with the original raw sample mass M_R, and a mass balance error (MBE) as a percentage was calculated as follows:

$$MBE = \frac{M_M - M_R}{M_R} \times 100 \quad (2)$$

b) Calculation of settling velocity distribution:

The settling velocity distribution was calculated using M_i values as follows:

M_i collected at T_i gives the mass of the particles that have settling velocity in the range between L/T_i (where L is the length of the column), and L/T_{i-1}. Expressing M_i as a percentage of M_M, a cumulative percentage of particles that have a settling velocity less than a certain value can be calculated as shown in Table 5.1.

Table 5.1: Calculation of settling velocity distribution using Aston column data

Settling velocity, SV_i, in mm/s	**% of particles with settling velocity less than corresponding SV_i**
L/T_1	100 - (% of mass collected at T_1)
L/T_2	Above value - (% of mass collected at T_2)
.	.
.	.
L/T_{11}	Above value – (% of mass collected at T_{11})
$-L/T_{11}$	Above value – $(M_{NS}/ M_M)*100$
$-L/T_{10}$	Above value – $(M_{FE}/ M_M)*100$
$-L/T_1$	Above value – $(M_F/ M_M)*100$

A typical settling velocity distribution measured using the Aston column is shown in Fig. 5.1.

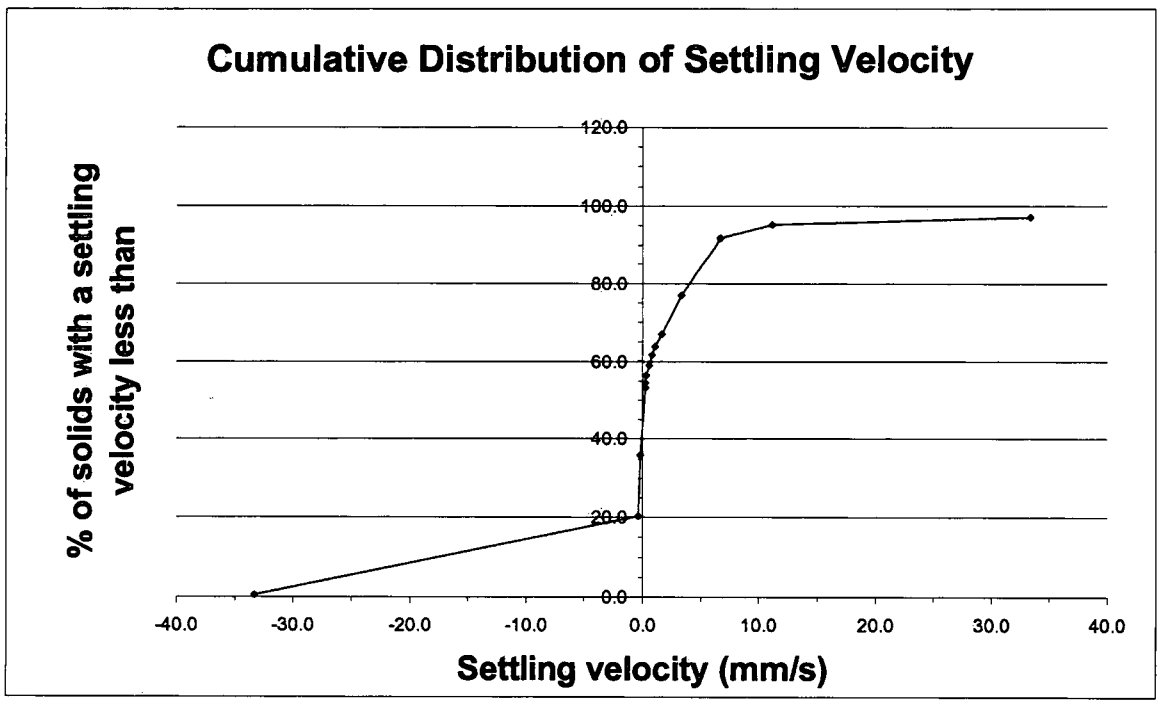

Fig. 5.1: A typical settling velocity distribution measured using the Aston column.

5.1.2 Analysis of data collected using the Brombach settling column

a) Mass balance calculation:

Let the masses of initially non-settled, initial column flush, final non-settled and final column flush be denoted by M_{NS1}, M_{flush1}, M_{NS2}, M_{flush2} respectively. Let the masses of sampled particles be M_i (i=1,10), and the mass of particles in the original raw sample be M_R. Using these symbols, the total mass of particles measured at different stages of the Brombach column use was calculated as:

$$\text{Total mass of measured particles } (M_M) = M_{NS1} + M_{flush1} + \sum M_i + M_{NS2} + M_{flush2} \qquad (3)$$

The above mass was compared with the original raw sample mass M_R, and a mass balance error (MBE) was calculated using Equation 2.

b) Calculation of settling velocity distribution:

The procedure used to calculate settling velocity distributions using data from the Brombach column is similar to the one used for the Aston column data. Table 5.2 gives the details.

Table 5.2: Calculation of settling velocity distribution for Brombach column data

Settling velocity, SV_i, in mm/s	**% of particles with settling velocity less than corresponding SV_i**
L/T_1	100 - (% of mass collected at T_1)
L/T_2	Above value - (% of mass collected at T_2)
. .	. .
L/T_{10}	Above value – (% of mass collected at T_{11})

A typical settling velocity distribution measured using the Brombach column is shown in Fig. 5.2.

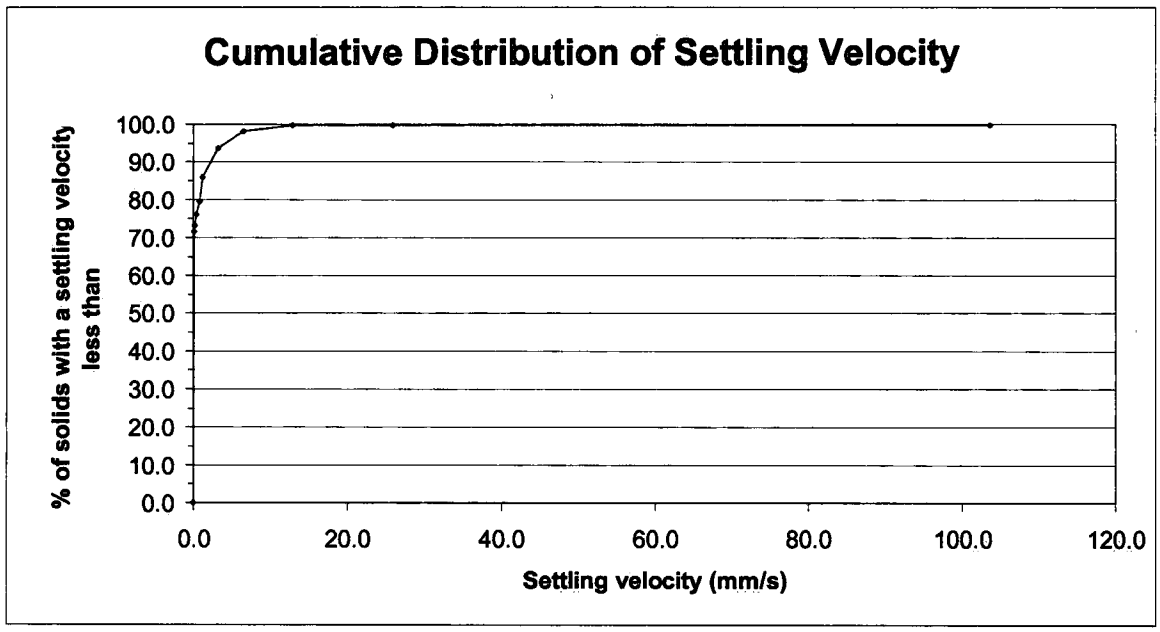

Fig. 5.2: A typical settling velocity distribution measured using the Brombach column.

5.1.3 Analysis of data collected using the U.S. EPA settling column

a) Mass balance calculation:

Let the mass of the raw sample used in the U.S. EPA column be M_R, and the masses of non-settled, settled and the flush portions of the particles be M_{NS}, M_S, and M_{flush} respectively. The masses of the solids collected during sampling are denoted as $M_{i,j}$ (i=top, middle and bottom ports and j=1-7, and this includes the mass wasted from each port when sampling). The total mass of particles measured during the operation of the column is denoted as M_M, and is given as follows:

$$M_M = M_{NS} + M_S + M_{flush} + \sum M_{i,j} \tag{4}$$

Using M_M and M_R, an error in mass balance for this method was calculated according to Equation 2.

b) Calculation of settling velocity distribution:

Samples collected at the top, middle and bottom sampling ports give the concentration of solids at different time intervals at these three locations. Knowing the distances from the free surface

to these sampling locations and the sampling times, three different settling velocities can be calculated and the masses of solids exceeding these three settling velocities can be computed by knowing the concentrations of solids in three overlapping portions of the column. In calculating the concentrations of the solids in different portions of the column, average values were computed using the measured concentrations at different elevations. The settling velocity and the percentage of mass of particles that have settling velocities less than the specified value were sorted and plotted into a cumulative settling velocity distribution. A typical distribution measured using the U.S. EPA column is shown in Fig. 5.3. The points are the measured data and the line represents an analytical expression that gives the best fit to the data.

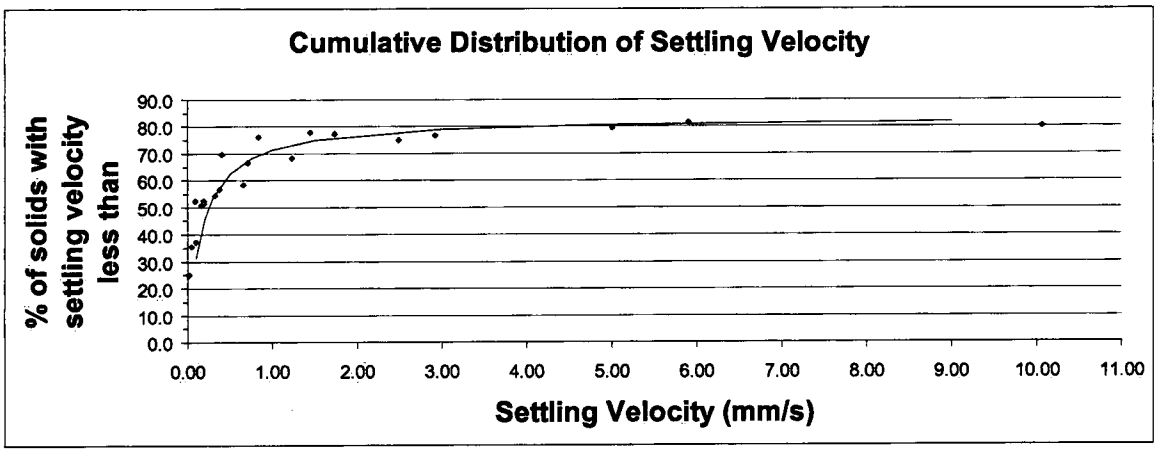

Fig. 5.3: A typical settling velocity distribution measured using the U.S. EPA settling column.

5.1.4 Analysis of data collected using the elutriation apparatus

a) Mass balance calculation:

The masses of particles in the two raw sample input carboys were measured before and after the operation of the elutriation apparatus. The difference gives the mass of particles routed through the apparatus during the test. This mass was then compared with the masses collected in all eight columns and three collecting flasks. From this comparison, a mass balance error was computed.

b) Calculation of settling velocity distribution:

From the value of the flow rate through the apparatus, the flow velocities in individual columns can be computed. Particles collected in a particular column have settling velocities larger than the flow velocity in that column. Therefore, knowing the settling velocities in all the columns, and the masses of particles collected in these columns, a cumulative settling velocity distribution was calculated. A typical distribution measured using the elutriation apparatus is shown in Fig. 5.4.

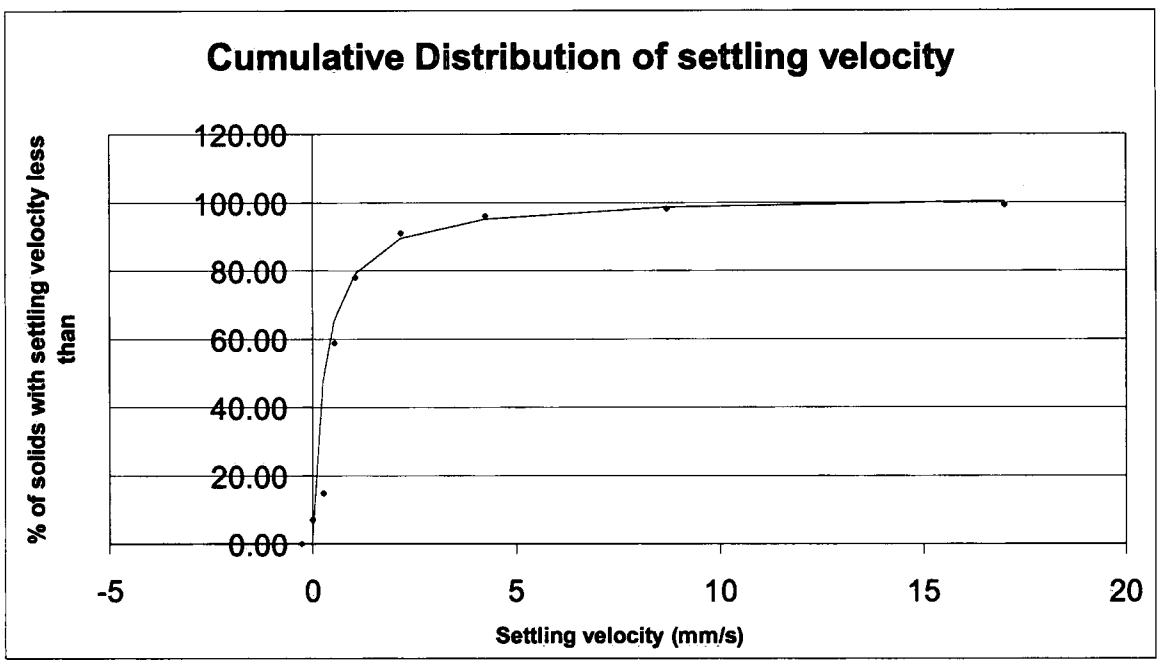

Fig. 5.4: A typical settling velocity distribution measured using the elutriation apparatus.

5.1.5 Comparison of settleability results

Table 5.3 compares characteristics of the four methods employed in this study for assessment of solids settling.

Table 5.3: Comparison of four settleability assessment methods used in the Niagara Falls study

Method	Method Characteristics				
	Sample volume (L)	**Flow conditions during test**	**Measurement of sinkers**	**Measurement of floatables**	**Chemical additions**
Aston column	5	Quiescent	Yes	Yes	No
Brombach column	1	Quiescent	Yes	No	No
Elutriation apparatus	50	Dynamic	Yes	Yes (with limitations)	Yes
U.S. EPA column	20	Quiescent	Yes	No	No

a) Comparison of mass balance errors

The mass balance errors were calculated for all the tests and are summarized in Table 5.4 shown below. In this table, the samples were identified with their event date, shown in the first column of Table 4.1. The overall mass balance errors range from + 46 percent to -60 percent. However, in the majority of tests, the mass balance error is much smaller than these extreme values. Based on the standard deviations, the U.S. EPA column has the largest mass balance error (with the standard deviation of the percent error of 14.9). The Aston column, Brombach column and elutriation apparatus had similar mass balance errors, with the standard deviation of percent errors of 11.0, 10.8 and 12.2, respectively.

Table 5.4: Summary of mass balance errors in percentage

Sample	Aston column	Brombach column	U.S. EPA column	Elutriation apparatus
09-Jun-03	-0.48	25.18	2.45	-12.12
11-Jul-03	1.95	1.61	-3.77	N/A
15-Jul-03	0.98	2.26	-6.26	10.04
05-Aug-03	2.29	0.99	-6.85	-36.14
19-Nov-03	-17.61	-22.1	-9.1	45.69 *
11-Dec-03	-8.28	-8.8	-9.2	3.08
02-Mar-04	-4.04	-9.03	-21.76	9.75
06-Mar-04	13.23	-11.06	2.62	-18.61
20-Mar-04	13.56	-3.14	-12.1	-21.58
18-Apr-04	-16.74	-16.29	-1.55	N/A
21-Apr-04	0.41	-8.75	22.4	N/A
02-May-04	-1.33	-11.57	-7.63	N/A
09-May-04	1.03	8.91	-9.61	-5.73
02-Jul-04 (MR)	-25.87	-10.15	-5.06	N/A
07-Jul-04 (CPS)	-20.38	-3.25	-59.81	N/A
14-Jul-04	-7.89	4.55	-16.29	3.25
14-Jul-04 (CPS)	3.37	1.71	8.88	2.42
27-Jul-04	-26.46	-0.02	-7.38	-2.06
05-Nov-04 (CPS)	-18.50	5.19	-7.09	-33.76
05-Sep-03	7.24	9.32	-9.8	-16.8
09-Oct-03	0.92	-14.07	-7.26	-16.32
10-Nov-03	-5.35	2.9	3.04	-7.36
12-Feb-04	-2.34	-3.74	-15.91	-3.72
29-Mar-04	-6.83	11.51	33.34	-9.85
19-Apr-04	2.11	26.92	-7.88	-6.47
03-Jun-04	-10.26	-3.06	-11.9	-4.35
12-Jul-04	4.3	-6.64	1.93	-1.00
07-Sep-04	-6.73	-5.54	-7.52	-15.64
25-Jan-05	18.09	1.04	1.99	2.12
28-Jan-05	-0.15	5.77	0.62	1.2
Mean	-3.66	-0.98	-5.55	-7.81
Standard Deviation	11.0	10.8	14.9	12.2

* This value was rejected as an outlier due to an elutriation method variation on this date (19-Nov-03).

b) Comparison of settling velocity distributions obtained by various methods

To compare the settling velocity distributions from all four methods, the distributions were fitted to an analytical expression of the form shown below:

$$y = \frac{\frac{1}{\alpha}x}{\frac{\beta}{\alpha}x + 1} \tag{5}$$

where y is the ordinate representing the percent of the particles by weight that have settling velocity less than a prescribed value (percent slower), and x is the abscissa representing the settling velocity. The values of α and β were adjusted until the equation 5 matched the measured values reasonably well. Typical matching that was achieved for all four methods can be seen in Fig. 5.5 to 5.8.

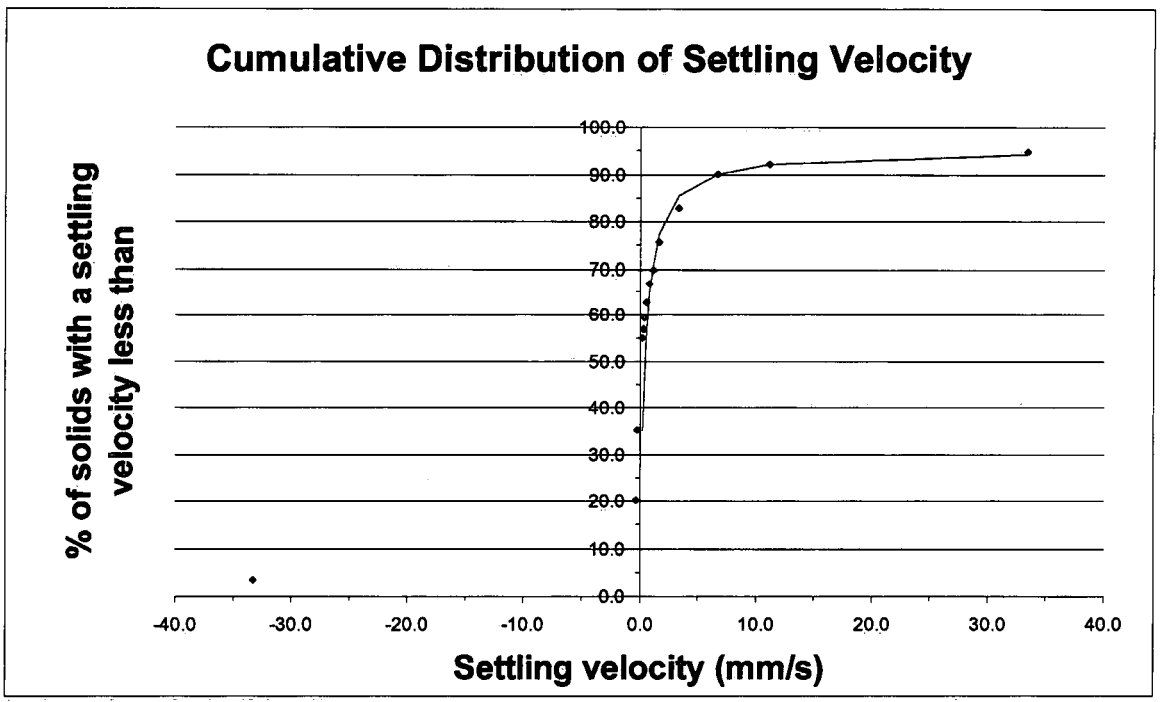

Fig. 5.5: Typical match between equation 5 and measured data using the Aston Column.

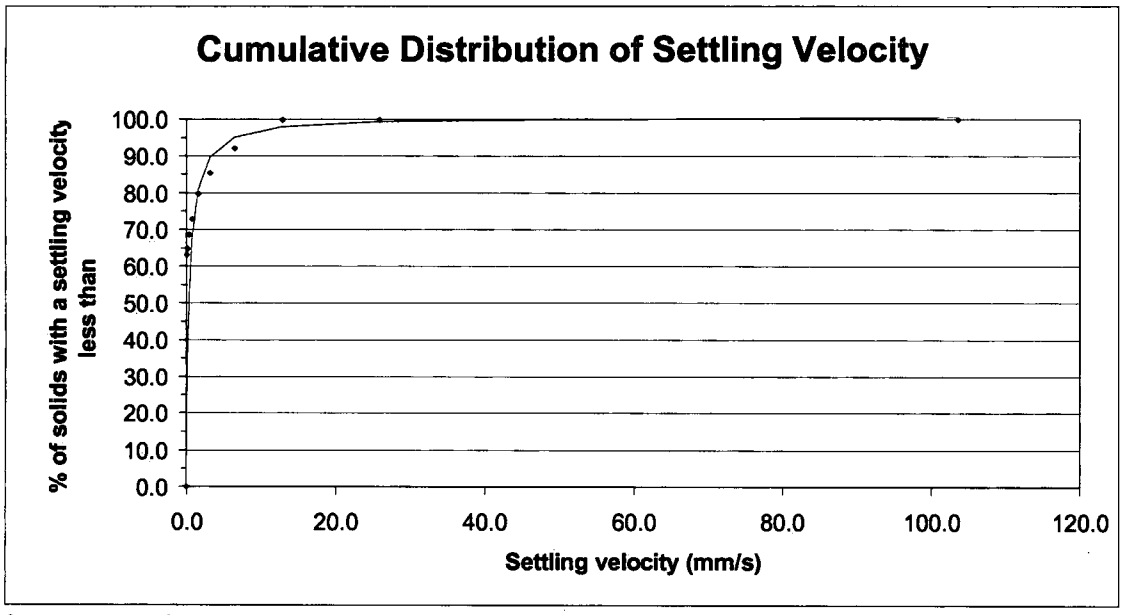

Fig. 5.6: Typical match between equation 5 and measured data using the Brombach column.

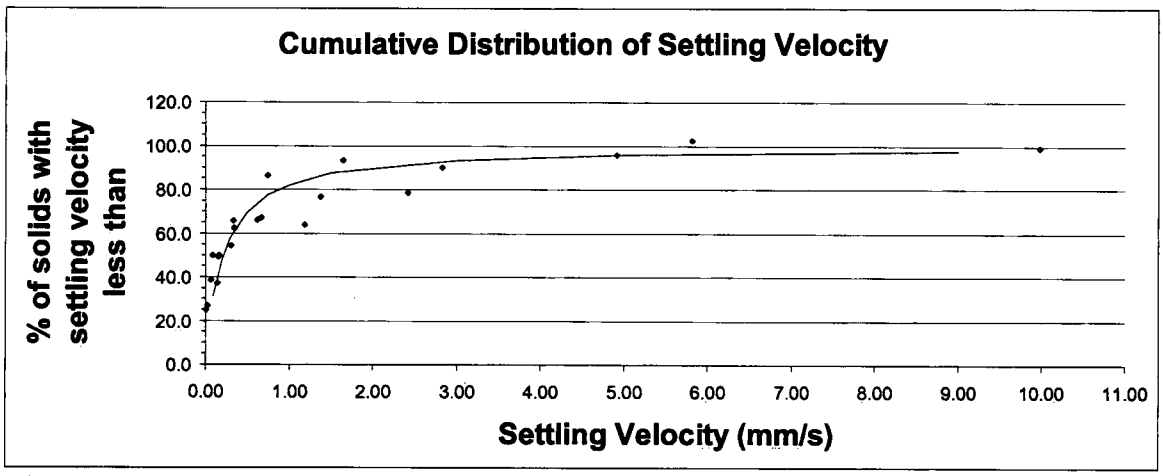

Fig. 5.7: Typical match between equation 5 and measured data using the U.S. EPA column.

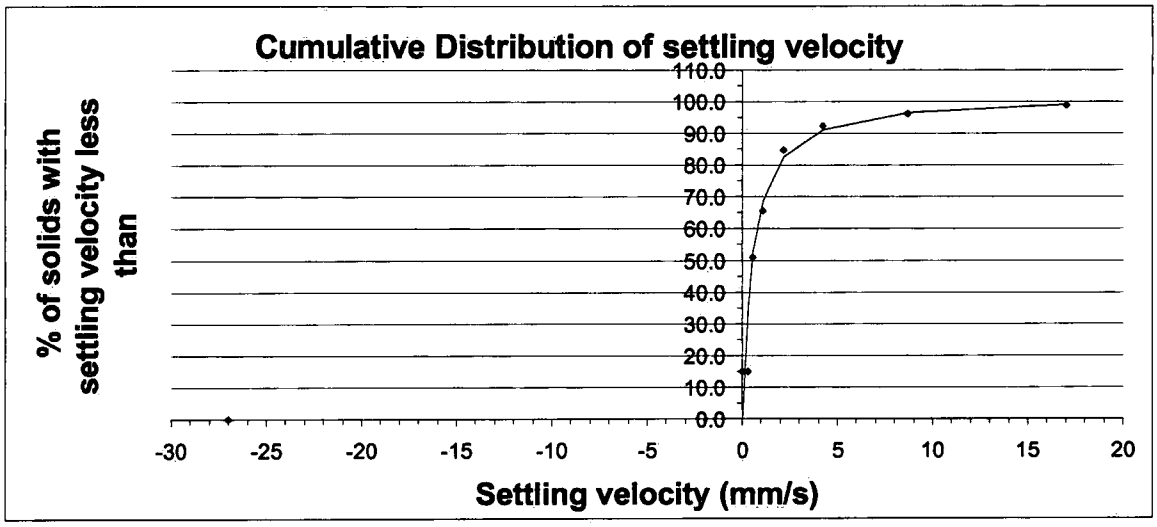

Fig. 5.8: Typical match between equation 5 and measured data using the elutriation apparatus.

The values of α, β that gave the best fit of Equation 5 to measured data from all four methods and for all samples are listed in Table 5.5 below:

Table 5.5: Summary of α, β values for all four measuring methods and for all samples

Sample	Aston Column		Brombach Column		US EPA Column		Elutriation apparatus	
	α	β	α	β	α	β	α	β
9-Jun-03	0.0070	0.0105	0.0030	0.0100	0.0020	0.0097	0.0065	0.0096
11-Jul-03	0.0050	0.0107	0.0018	0.0100	0.0010	0.0100	-	-
15-Jul-03	0.0070	0.0100	0.0035	0.0099	0.0018	0.0110	0.0030	0.0098
05-Aug-03	0.0040	0.0103	0.0035	0.0100	0.0020	0.0122	0.0043	0.0098
19-Nov-03	0.0040	0.0103	0.0035	0.0099	0.0040	0.0180	0.0017	0.0100
11-Dec-03	0.0025	0.0103	0.0035	0.0100	0.0020	0.0100	0.0048	0.0098
02-Mar-04	0.0035	0.0103	0.0023	0.0100	0.0030	0.0150	0.0070	0.0096
6-Mar-04	0.0040	0.0103	0.0005	0.0100	0.0050	0.0160	0.0030	0.0099
20-Mar-04	0.0040	0.0103	0.0030	0.0100	0.0030	0.0110	0.0060	0.0098
18-Apr-04	0.0080	0.0100	0.0100	0.0100	0.0050	0.0100	-	-
21-Apr-04	0.0040	0.0105	0.0020	0.0100	0.0020	0.0122	-	-
2-May-04	0.0040	0.0103	0.0019	0.0100	0.0020	0.0120	-	-
9-May-04	0.0040	0.0103	0.0020	0.0100	0.0040	0.0122	0.0043	0.0098
2-Jul-04 (MR)	0.0060	0.0100	0.0100	0.0098	0.0003	0.0100	-	-
7-Jul-04 (CPS)	0.0090	0.0098	0.0060	0.0099	0.0030	0.0240	-	-
14-Jul-04	0.0040	0.0100	0.0100	0.0100	0.0040	0.0140	0.0150	0.0094
14-Jul-04 (CPS)	0.0030	0.0103	0.0030	0.0100	0.0006	0.0100	0.0050	0.0098
27-Jul-04	0.0045	0.0100	0.0035	0.0100	0.0030	0.0100	0.0060	0.0098
5-Nov-04 (CPS)	0.0045	0.0100	0.0025	0.0100	0.0020	0.0122	0.0043	0.0098

Sample	Aston Column		Brombach Column		US EPA Column		Elutriation apparatus	
	α	β	α	β	α	β	α	β
05-Sep-03	0.0030	0.0102	0.0003	0.0100	0.0040	0.0100	0.0043	0.0098
09-Oct-03	0.0035	0.0102	0.0040	0.0100	0.0020	0.0105	0.0032	0.0098
10-Nov-03	0.0015	0.0103	0.0020	0.0100	0.0014	0.0126	0.0043	0.0098
12-Feb-04	0.0040	0.0103	0.0018	0.0100	0.0030	0.0150	0.0030	0.0098
29-Mar-04	0.0020	0.0103	0.0015	0.0100	0.0005	0.0100	0.0030	0.0098
19-Apr-04	0.0025	0.0103	0.0015	0.0100	0.0020	0.0110	0.0035	0.0098
03-Jun-04	0.0400	0.0103	0.0035	0.0100	0.0004	0.0099	0.0045	0.0098
12-Jul-04	0.0040	0.0100	0.0060	0.0100	0.0020	0.0122	0.0060	0.0098
07-Sep-04	0.0040	0.0105	0.0035	0.0100	0.0020	0.0110	0.0060	0.0098
25-Jan-05	0.0030	0.0100	0.0019	0.0100	0.0020	0.0100	0.0043	0.0098
28-Jan-05	0.0030	0.0102	0.0020	0.0100	0.0015	0.0100	0.0060	0.0098

The values of α and β listed in the above table were used in Equation 5 to evaluate the cumulative settling velocity distributions for all the samples; these distributions are shown in Figs. 5.9 to 5.38.

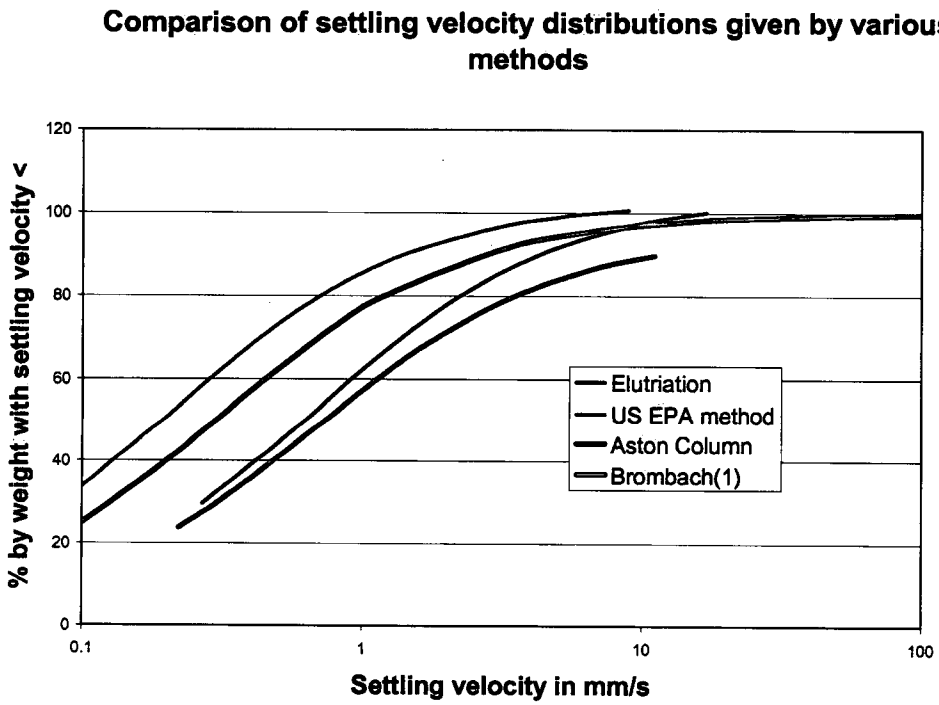

Fig. 5.9: Comparison of settling velocity distributions given by various methods for the wet-weather sample: June 9, 2003.

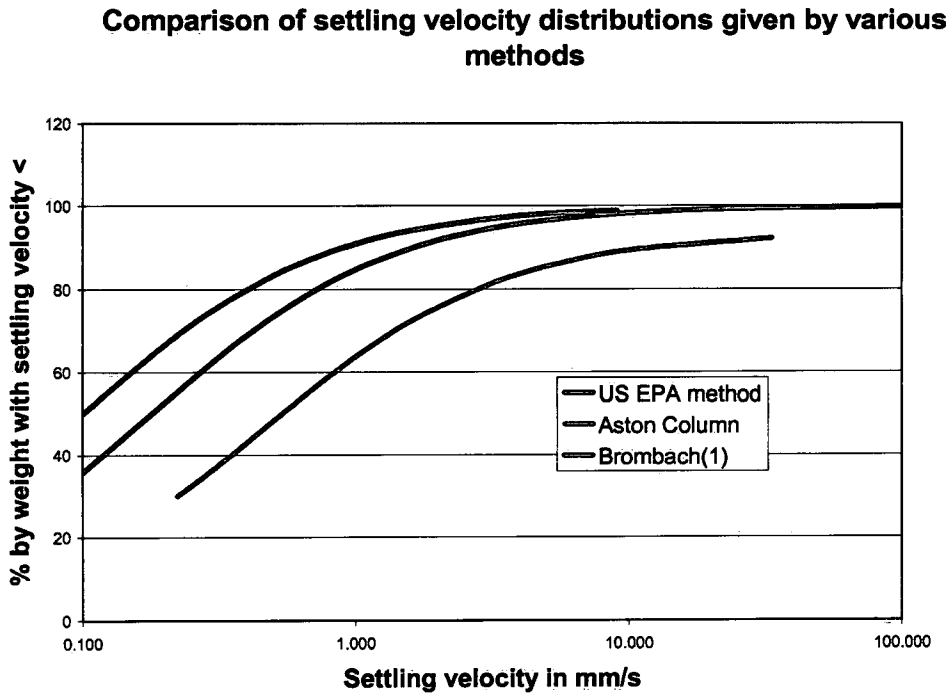

Fig. 5.10: Comparison of settling velocity distributions given by various methods for the wet-weather sample: July 11, 2003.

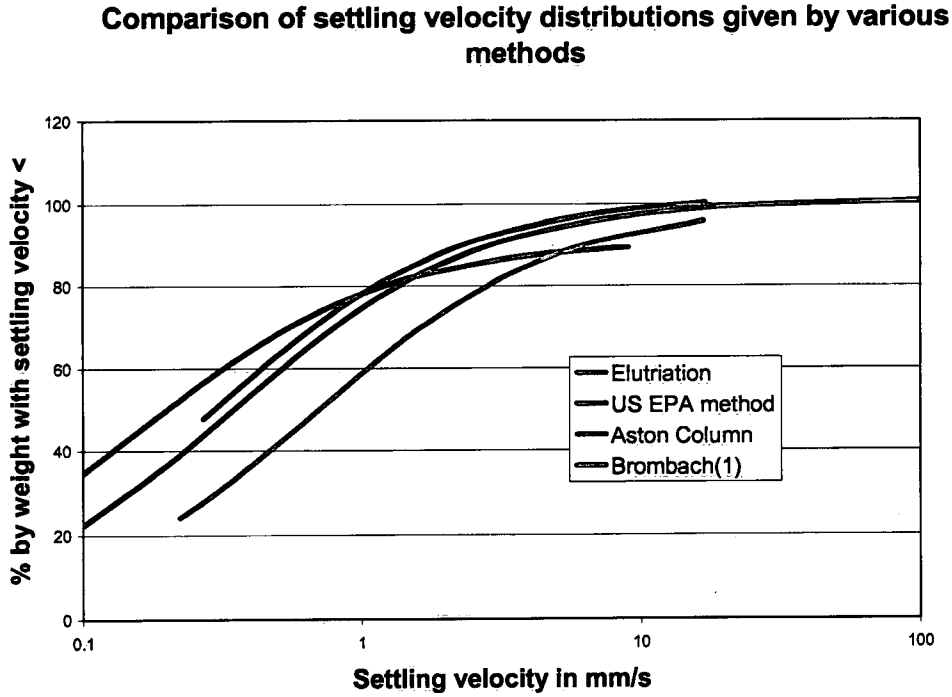

Fig. 5.11: Comparison of settling velocity distributions given by various methods for the wet-weather sample: July 15, 2003.

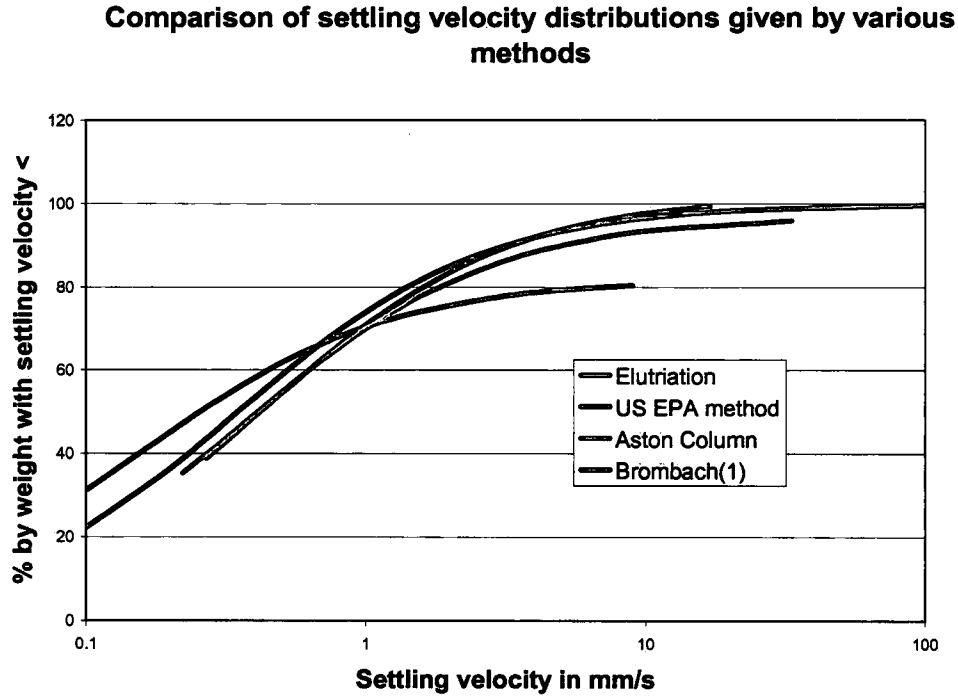

Fig. 5.12: Comparison of settling velocity distributions given by various methods for the wet-weather sample: August 5, 2003.

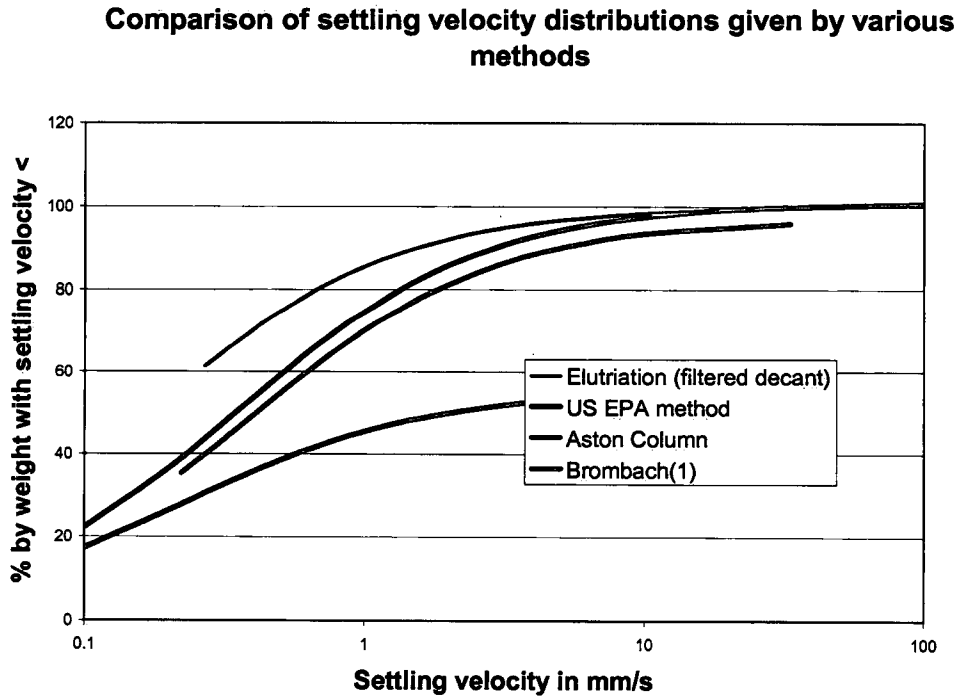

Fig. 5.13: Comparison of settling velocity distributions given by various methods for the wet-weather sample: November 19, 2003.

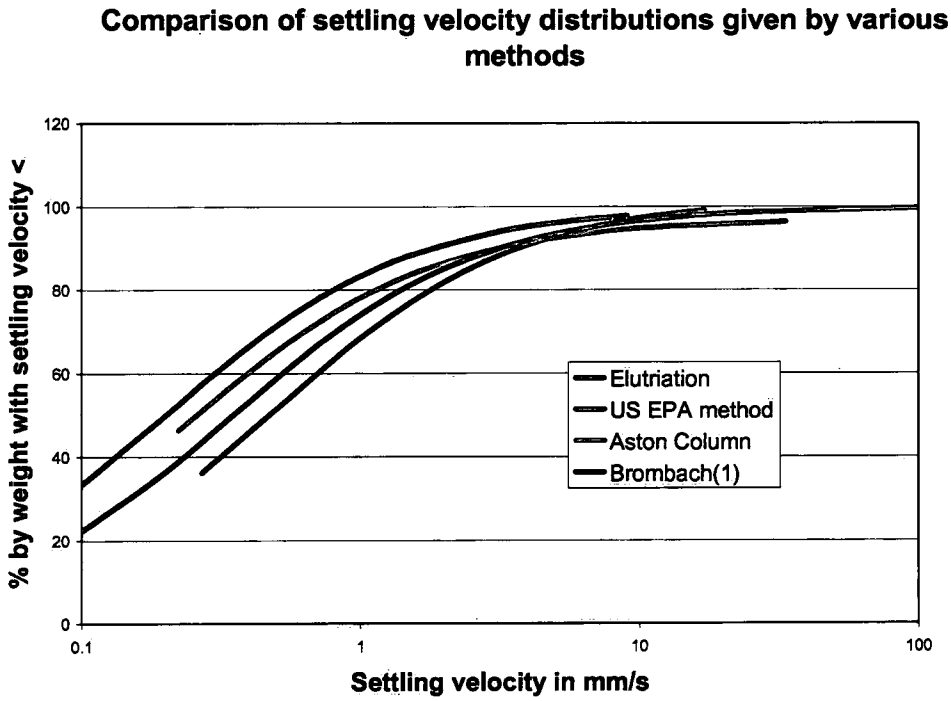

Fig. 5.14: Comparison of settling velocity distributions given by various methods for the wet-weather sample: December 11, 2003.

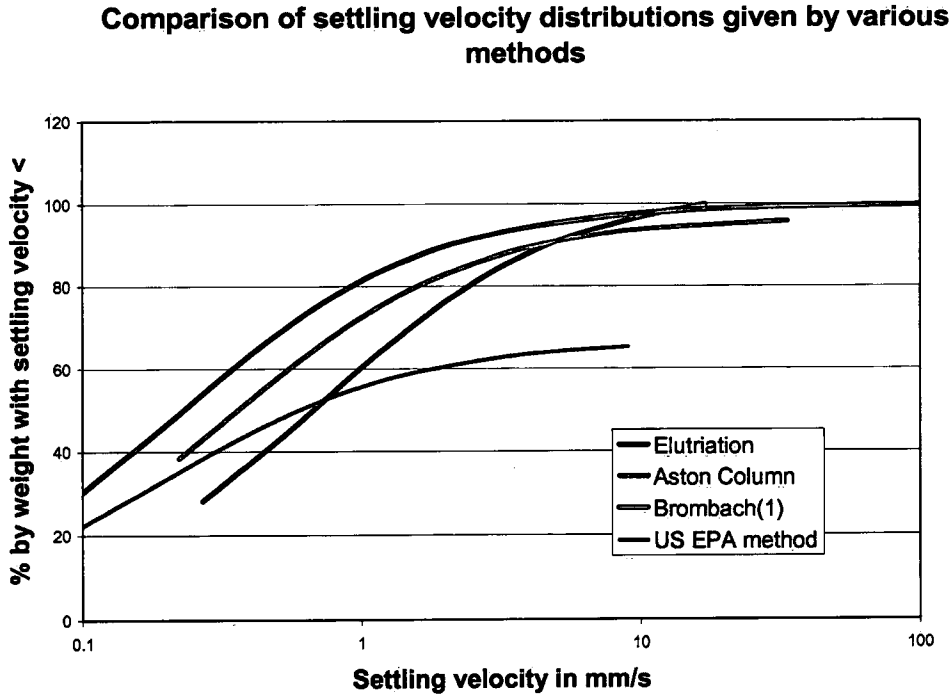

Fig. 5.15: Comparison of settling velocity distributions given by various methods for the wet-weather sample: March 2, 2004.

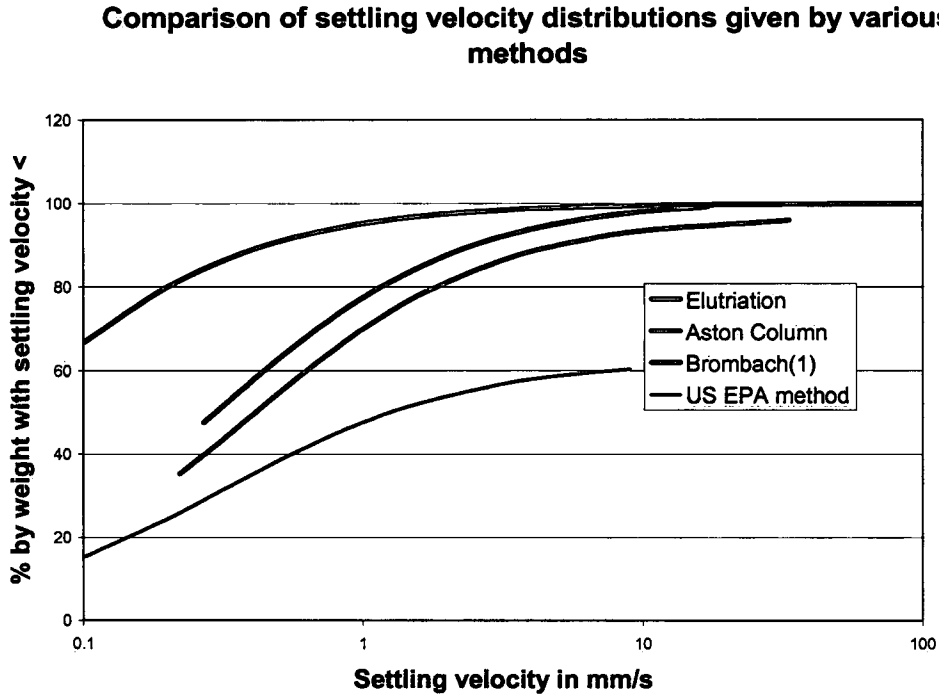

Fig. 5.16: Comparison of settling velocity distributions given by various methods for the wet-weather sample: March 6, 2004.

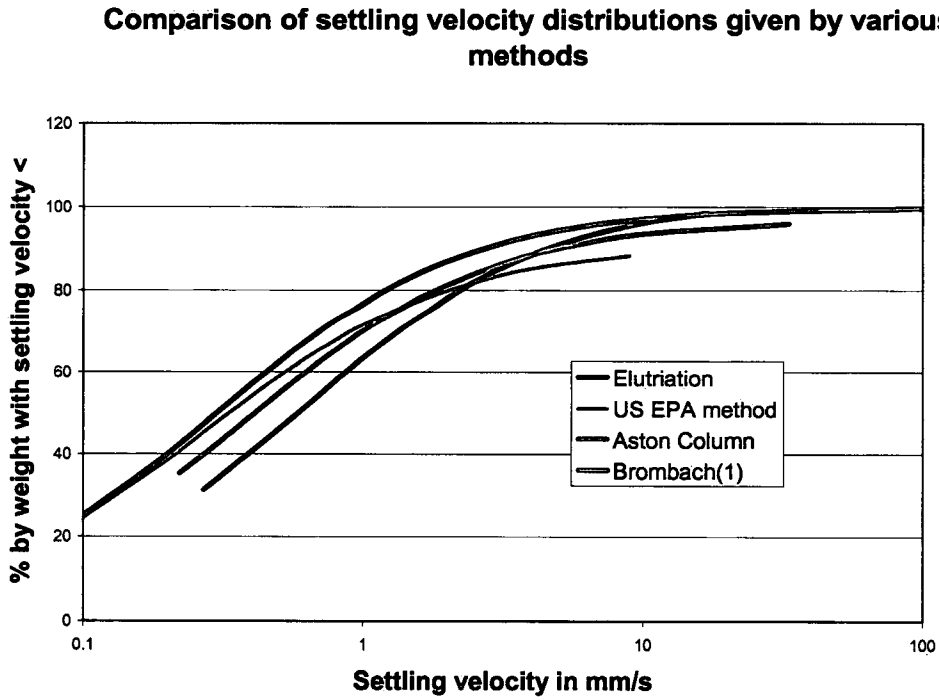

Fig. 5.17: Comparison of settling velocity distributions given by various methods for the wet-weather sample: March 20, 2004.

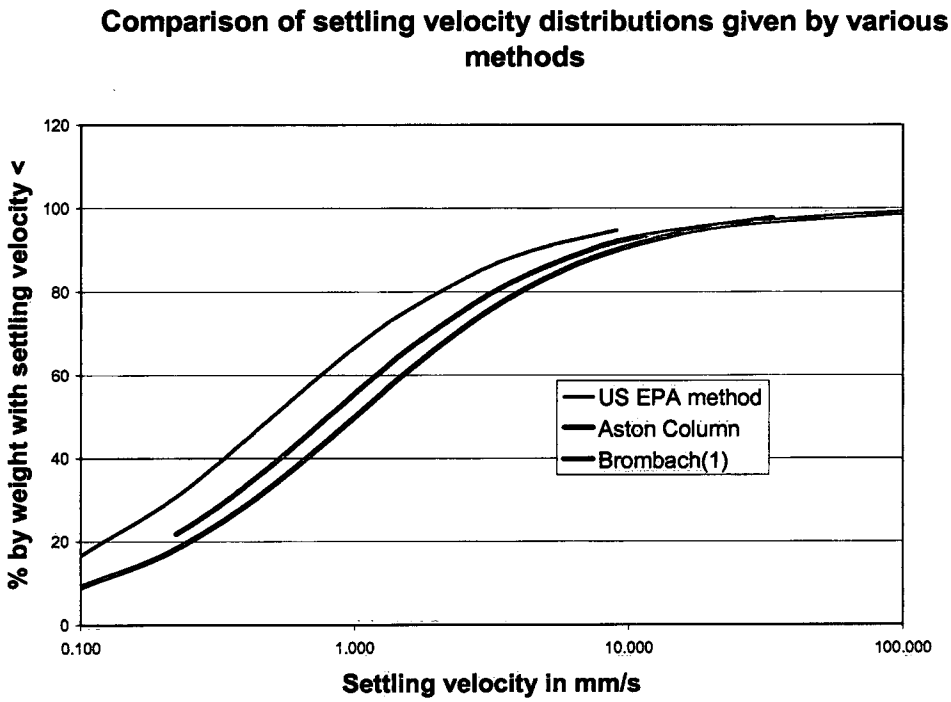

Fig. 5.18: Comparison of settling velocity distributions given by various methods for the wet-weather sample: April 18, 2004.

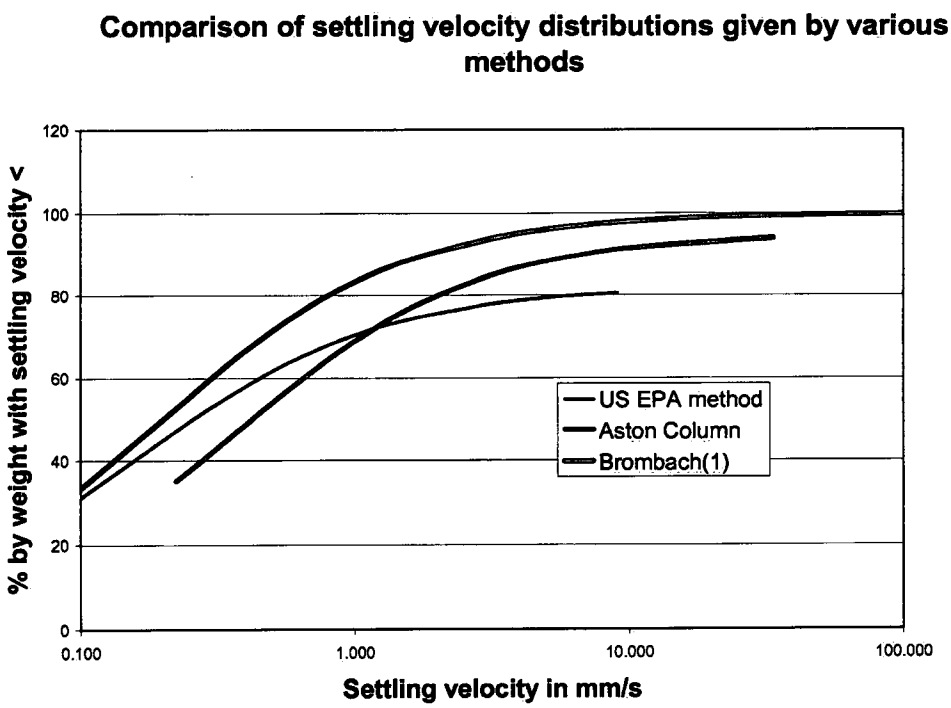

Fig. 5.19: Comparison of settling velocity distributions given by various methods for the wet-weather sample: April 21, 2004.

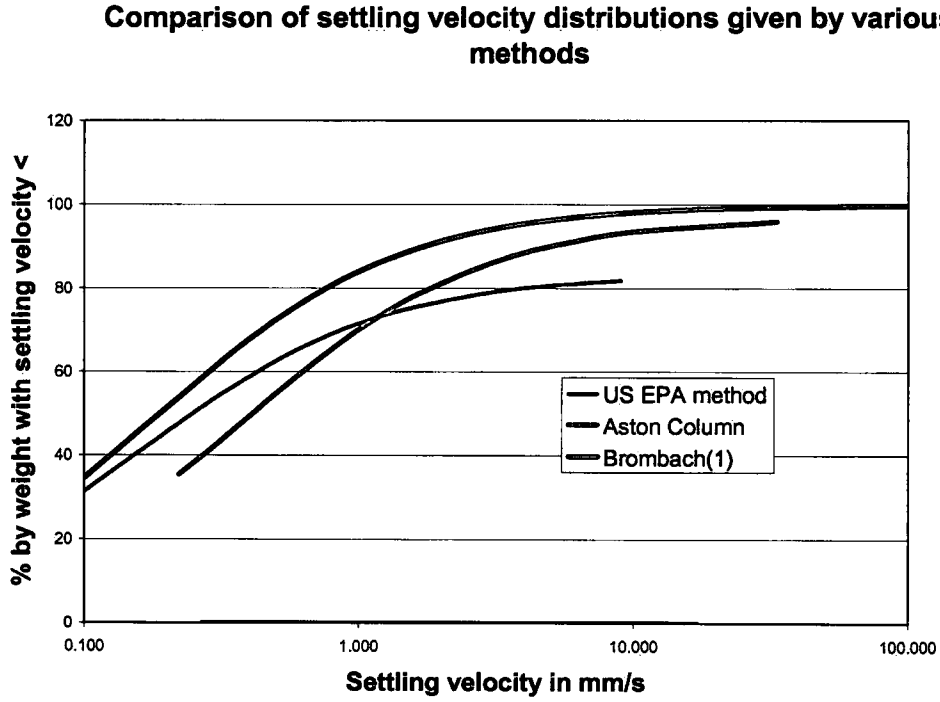

Fig. 5.20: Comparison of settling velocity distributions given by various methods for the wet-weather sample: May 2, 2004.

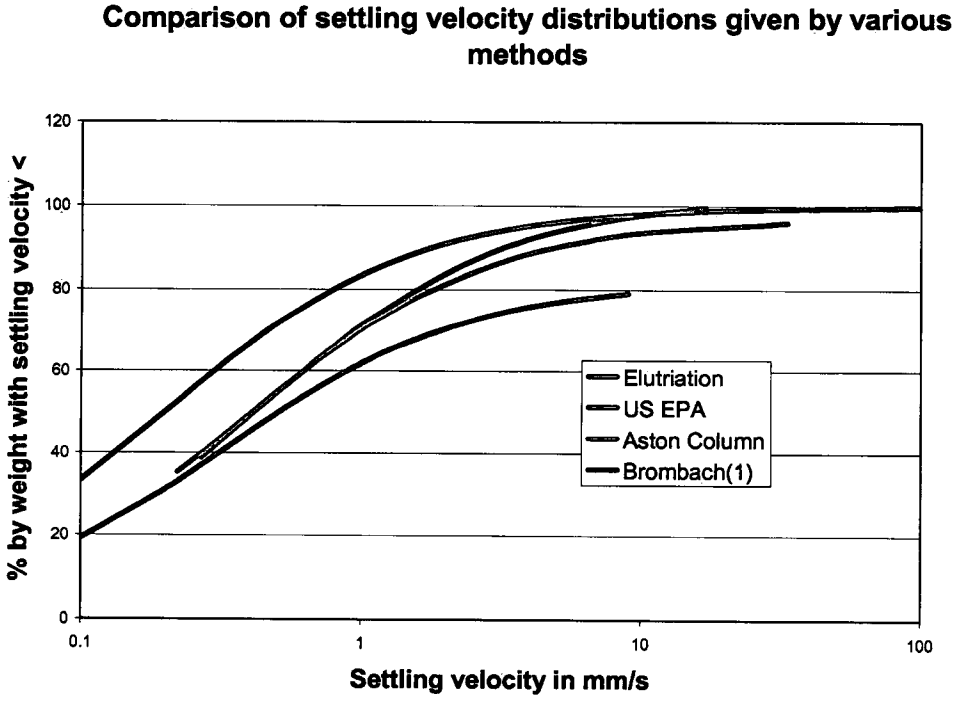

Fig. 5.21: Comparison of settling velocity distributions given by various methods for the wet-weather sample: May 9, 2004.

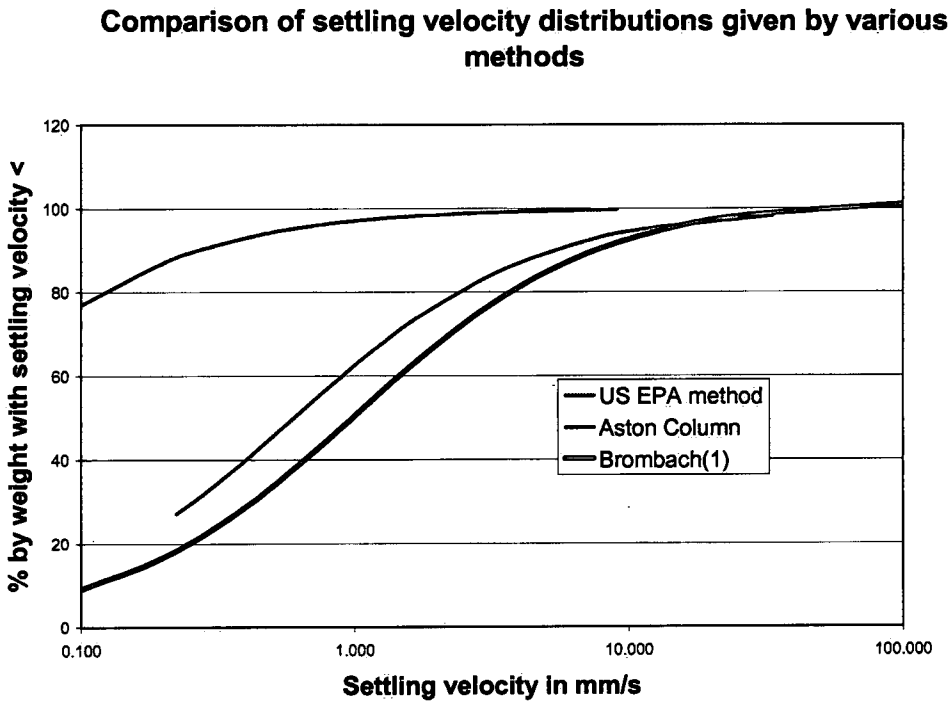

Fig. 5.22: Comparison of settling velocity distributions given by various methods for the wet-weather sample: July 2, 2004 (Muddy Run).

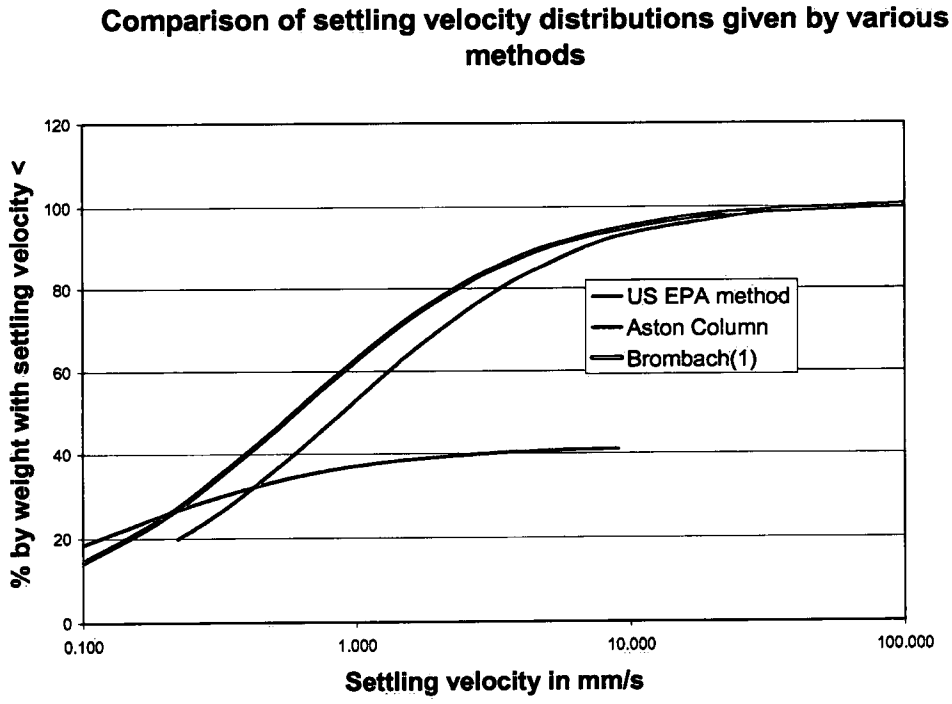

Fig. 5.23: Comparison of settling velocity distributions given by various methods for the wet-weather sample: July 7, 2004 (Central Pumping Station).

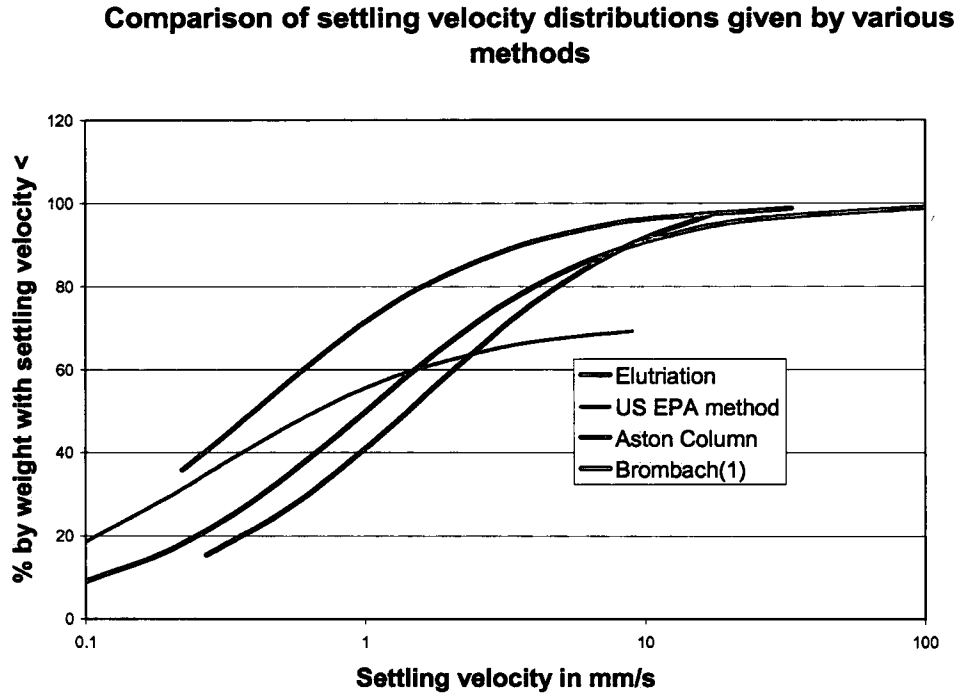

Fig. 5.24: Comparison of settling velocity distributions given by various methods for the wet-weather sample: July 14, 2004.

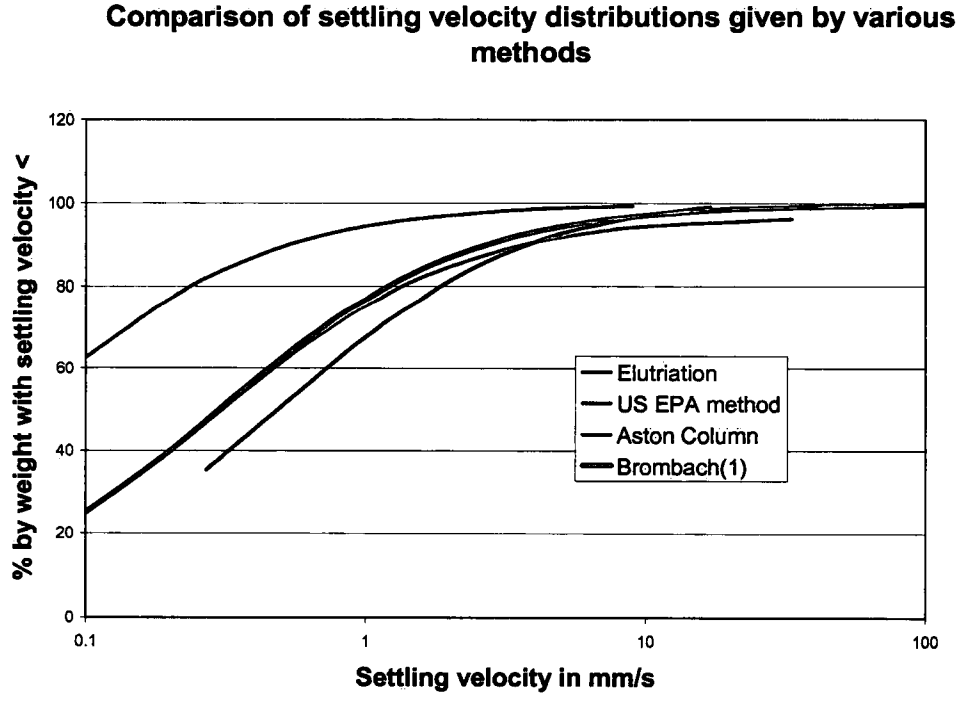

Fig. 5.25: Comparison of settling velocity distributions given by various methods for the wet-weather sample: July 14, 2004 (Central Pumping Station).

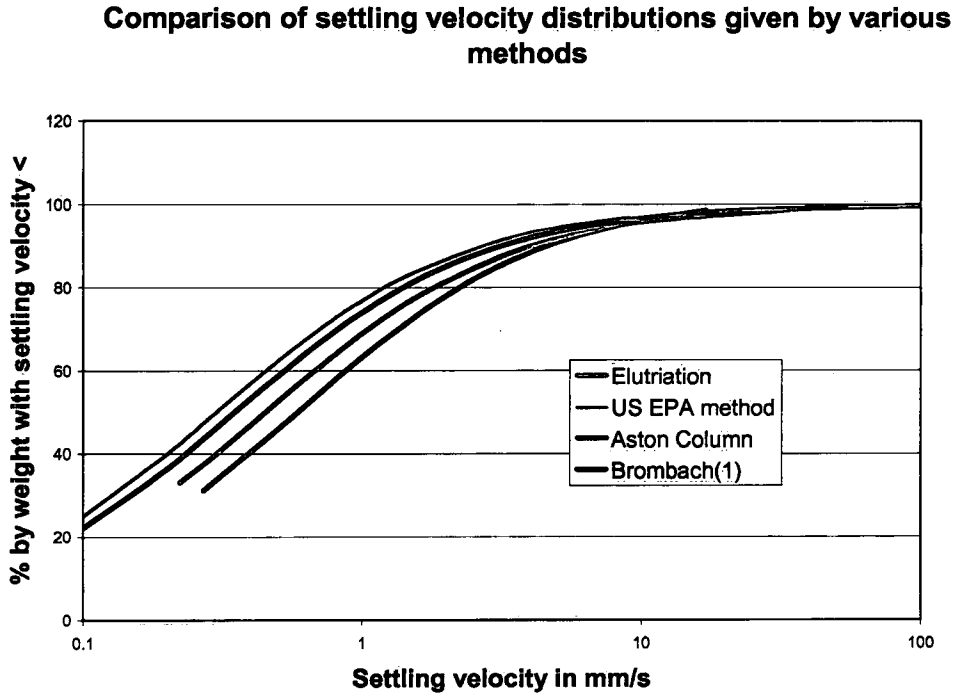

Fig. 5.26: Comparison of settling velocity distributions given by various methods for the wet-weather sample: July 27, 2004.

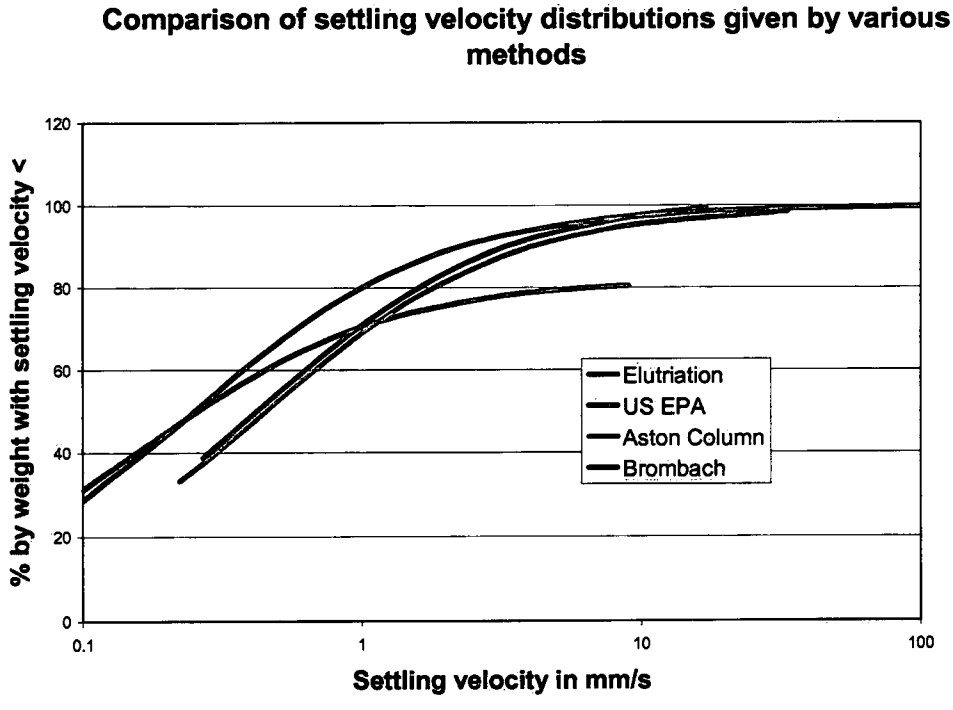

Fig. 5.27: Comparison of settling velocity distributions given by various methods for the wet-weather sample: November 5, 2004 (Central Pumping Station).

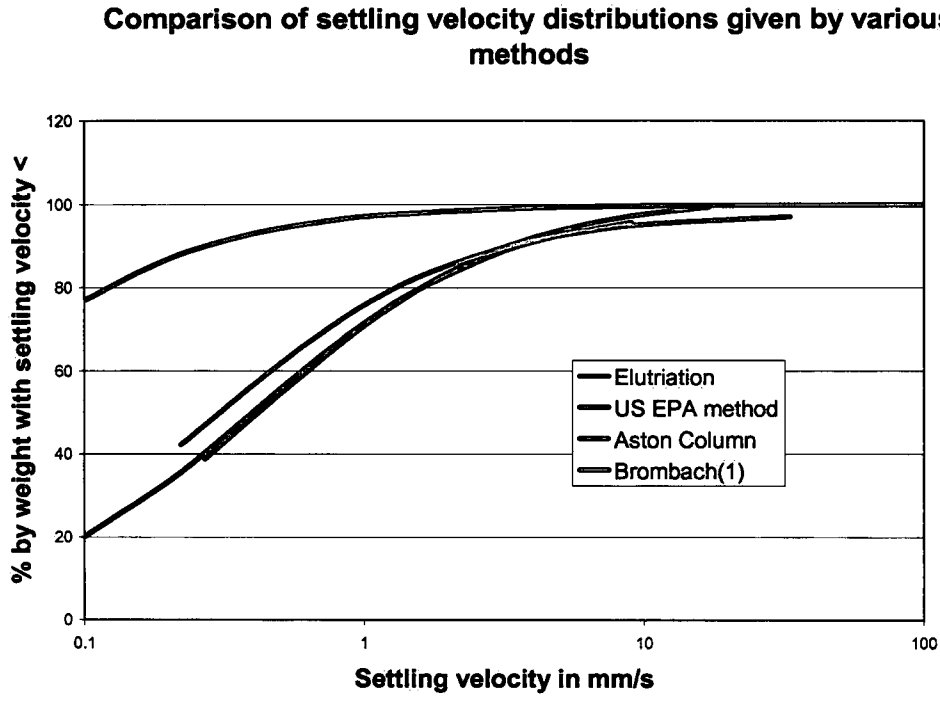

Fig. 5.28: Comparison of settling velocity distributions given by various methods for the dry-weather sample: September 5, 2003.

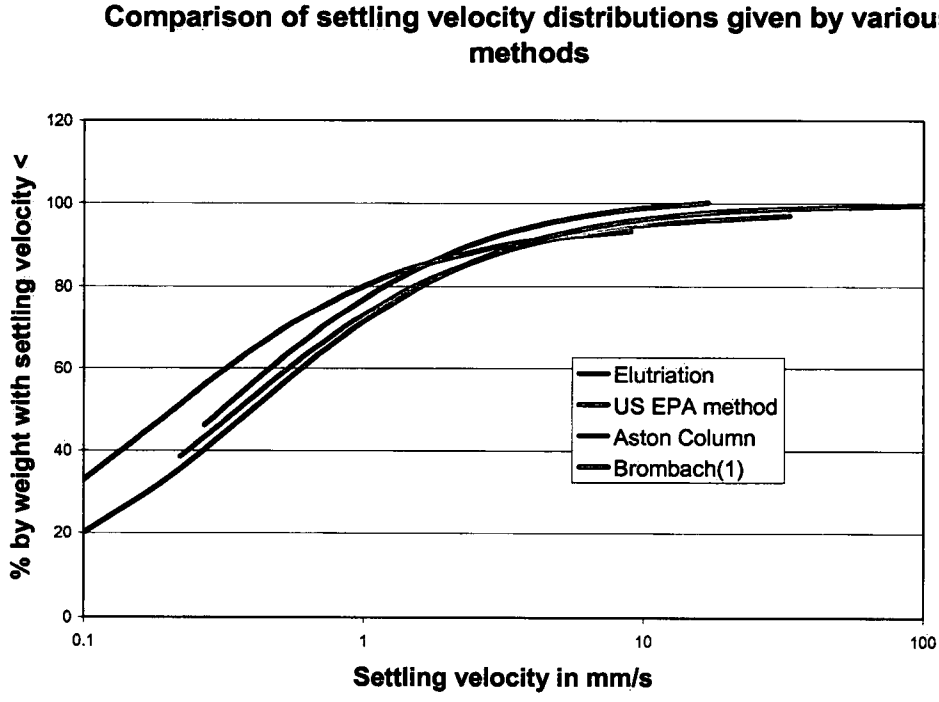

Fig. 5.29: Comparison of settling velocity distributions given by various methods for the dry-weather sample: October 9, 2003.

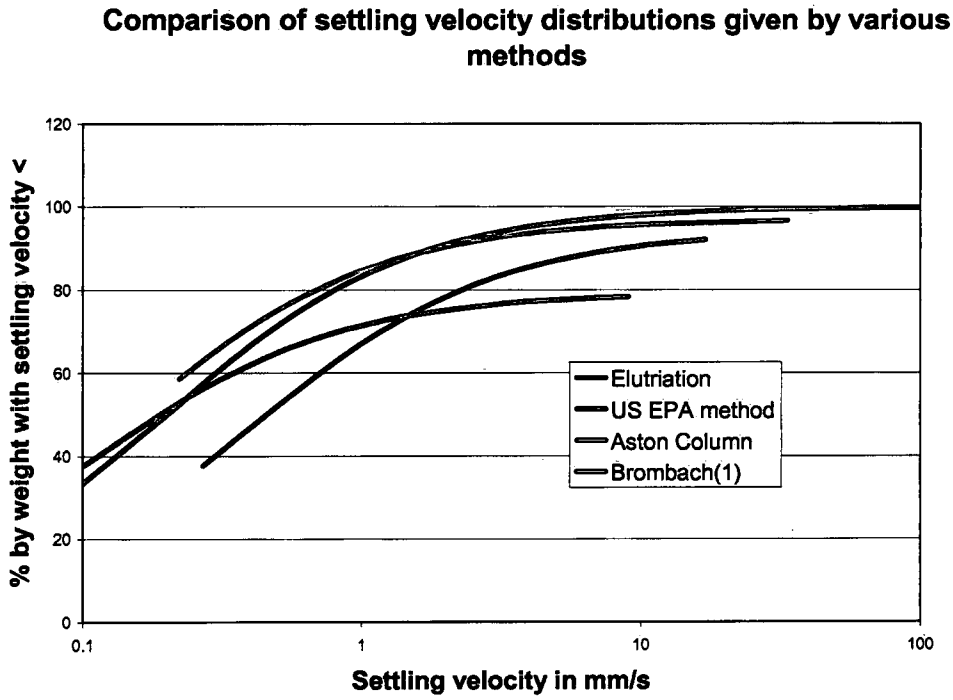

Fig. 5.30: Comparison of settling velocity distributions given by various methods for the dry-weather sample: November 10, 2003.

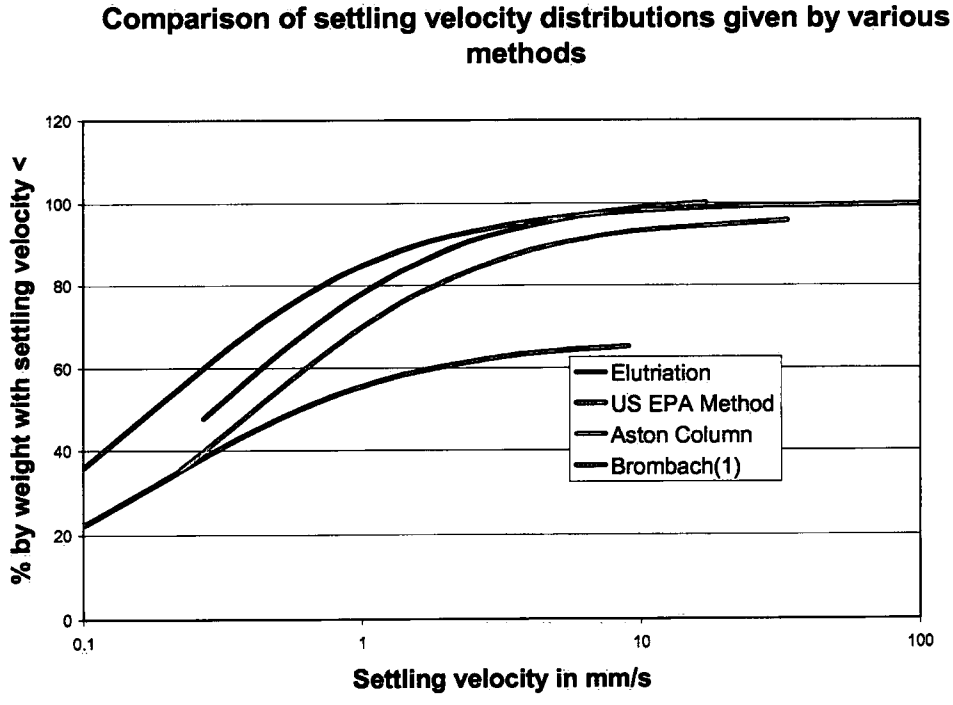

Fig. 5.31: Comparison of settling velocity distributions given by various methods for the dry-weather sample: February 12, 2004.

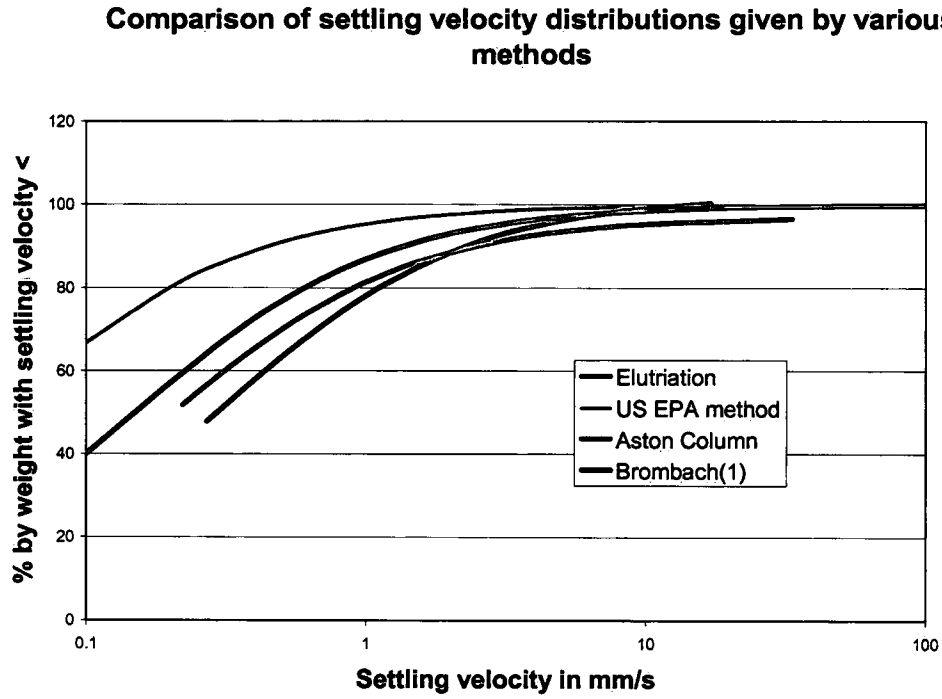

Fig. 5.32: Comparison of settling velocity distributions given by various methods for the dry-weather sample: March 29, 2004.

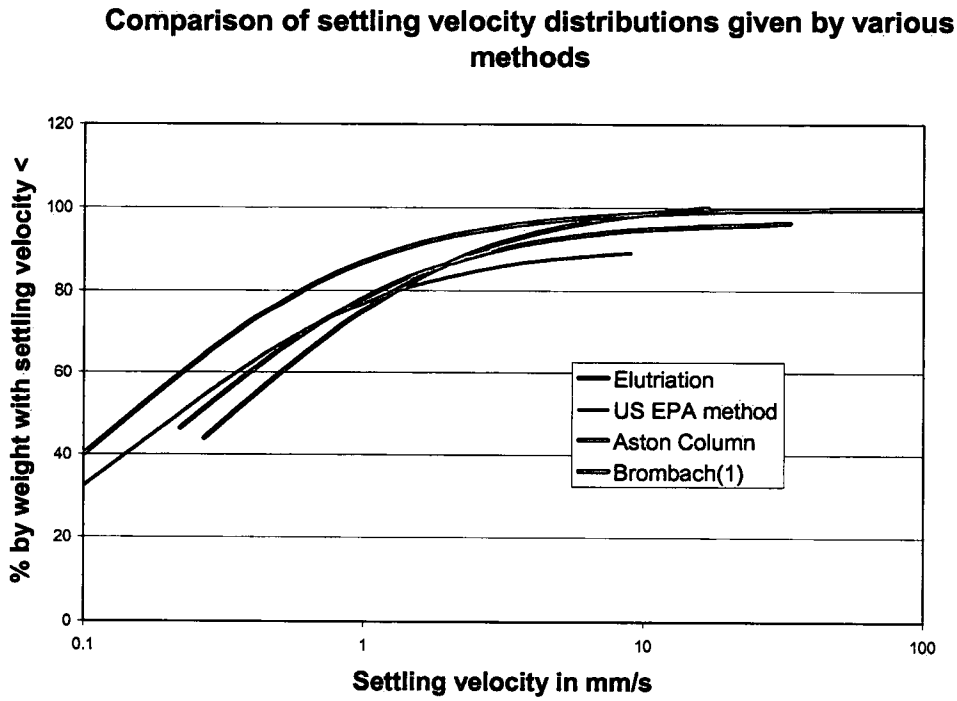

Fig. 5.33: Comparison of settling velocity distributions given by various methods for the dry-weather sample: April 19, 2004.

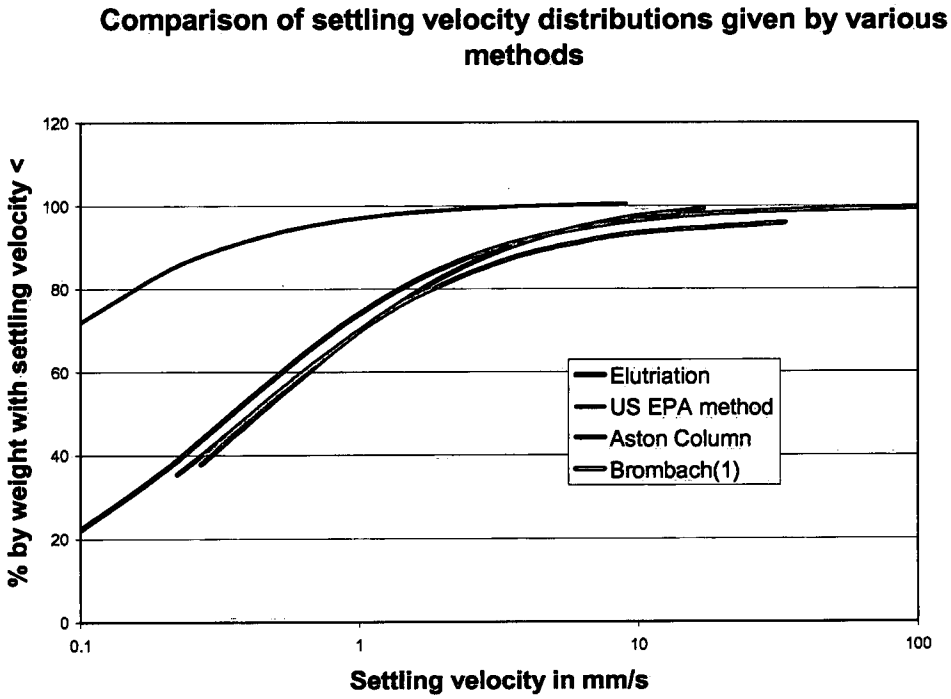

Fig. 5.34: Comparison of settling velocity distributions given by various methods for the dry-weather sample: June 3, 2004.

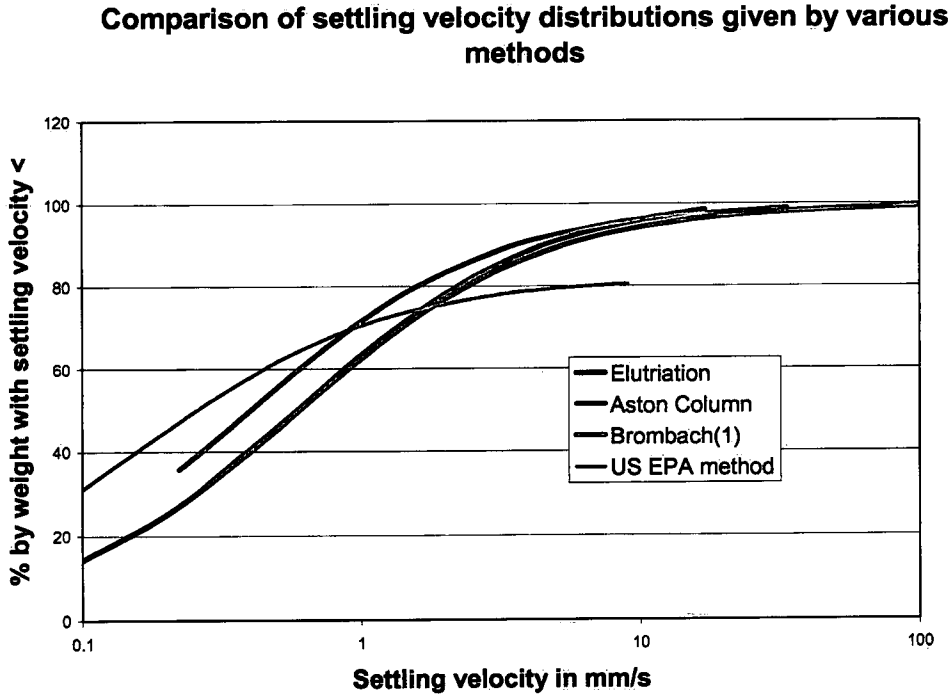

Fig. 5.35: Comparison of settling velocity distributions given by various methods for the dry-weather sample: July 12, 2004.

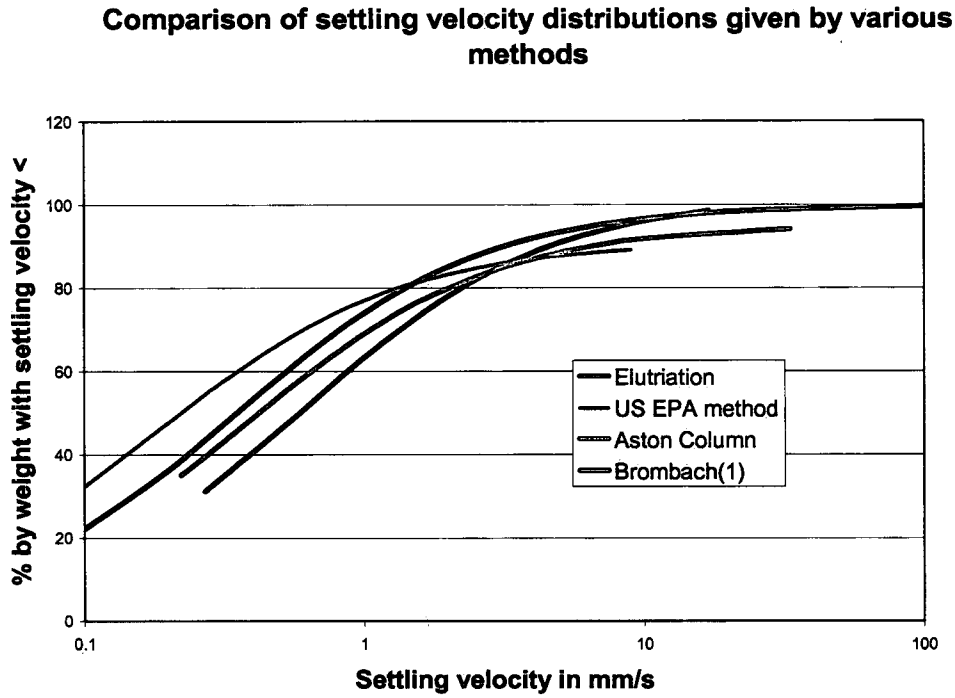

Fig. 5.36: Comparison of settling velocity distributions given by various methods for the dry-weather sample: September 7, 2004.

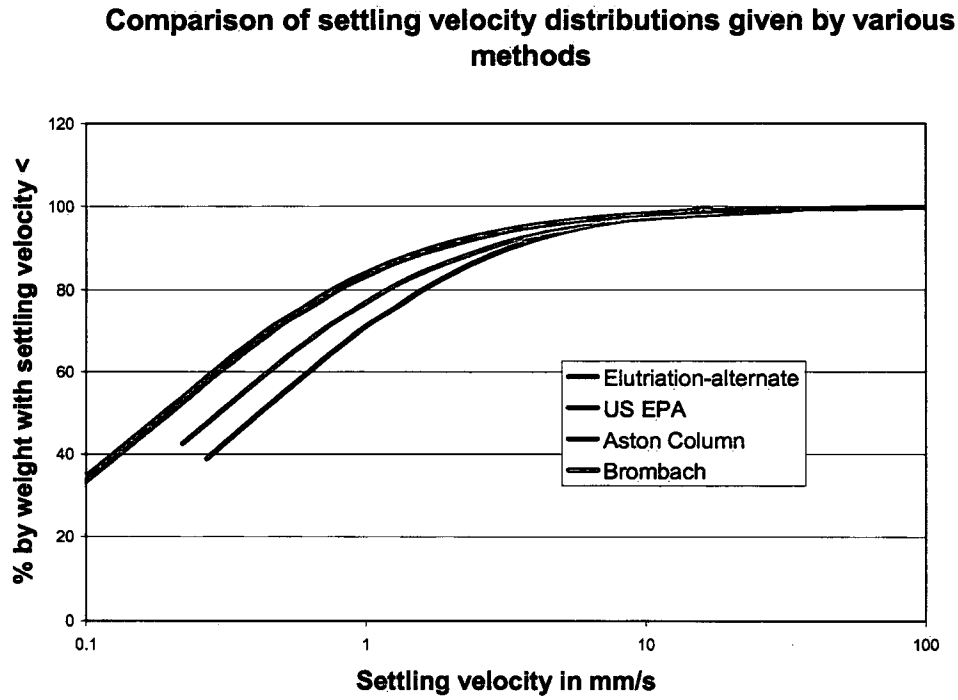

Fig. 5.37: Comparison of settling velocity distributions given by various methods for the dry-weather sample: January 25, 2005.

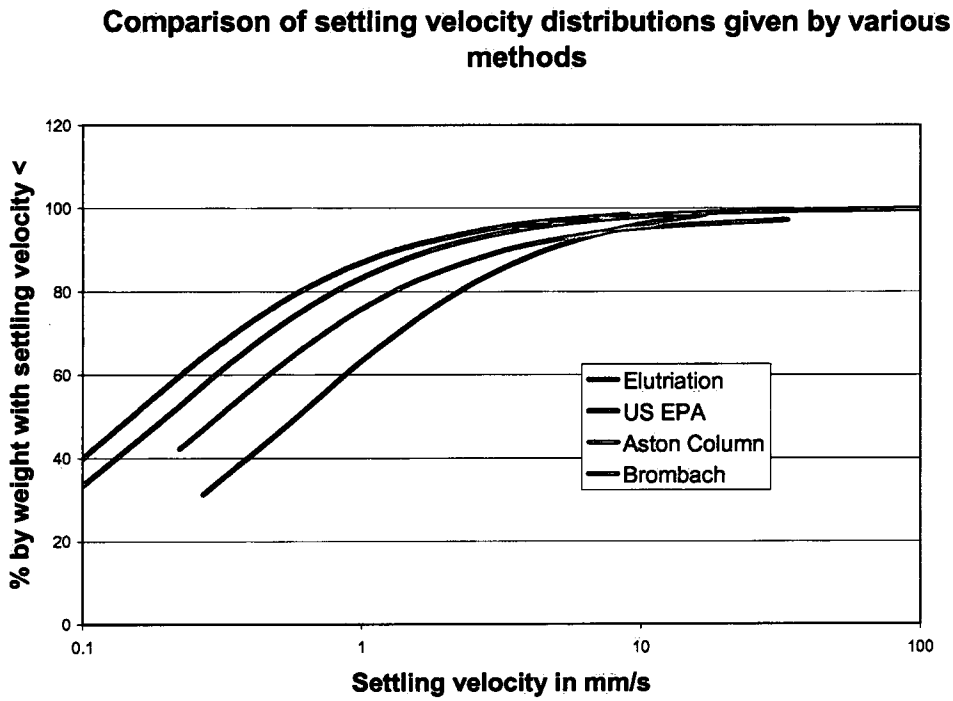

Fig. 5.38: Comparison of settling velocity distributions given by various methods for the dry-weather sample: January 28, 2005.

From the above figures, we can see that the there are large differences in the settling velocity distributions given by the various methods. In general, the U.S. EPA method gives flatter distributions for some of the samples. The shape of the distributions given by the other three methods is fairly similar for most of the samples tested.

Transposing equation 5 to express the settling velocity (x) in terms of percent by weight of solids with settling velocity less than a specified value (percent slower, y), we get:

$$x = -\frac{y}{\frac{\beta}{\alpha}y - \frac{1}{\alpha}} \tag{6}$$

From this equation, a relationship between the surface loading rate and the percent removal can be established as the settling velocity gives a measure of the surface loading rate, and the percent of solids with settling velocity less than a specified value can be related to percent retained and hence to percent removal. Using Equation 6, the surface loading rate in m/hr was calculated for different removal rates for all the samples as shown in Figs. 5.39 to 5.68.

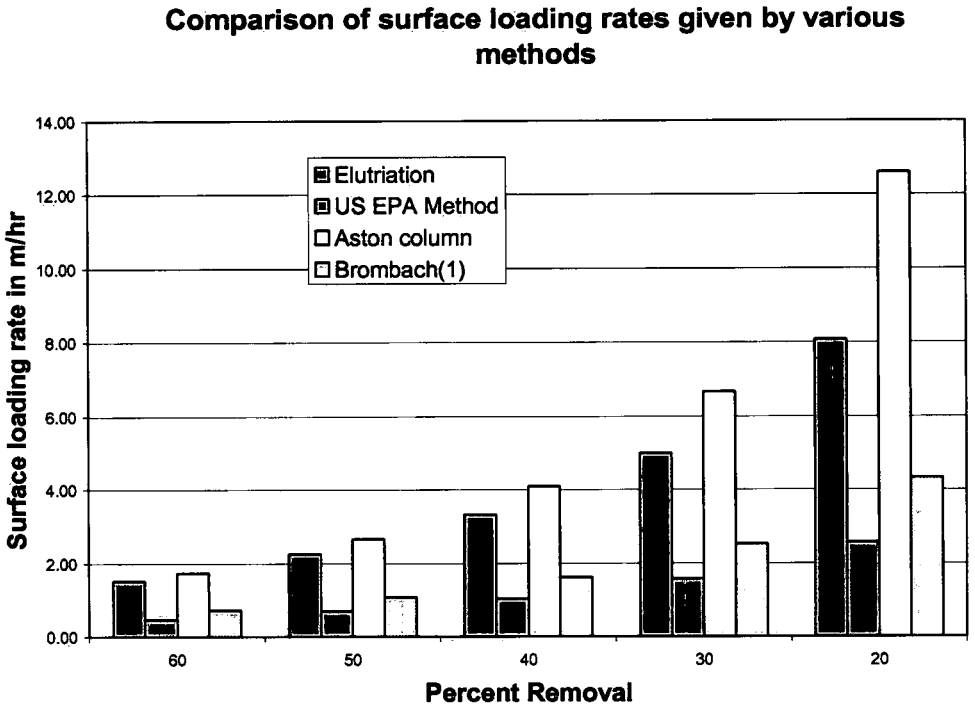

Fig. 5.39: Comparison of surface loading rates given by various methods for the wet-weather sample: June 9, 2003.

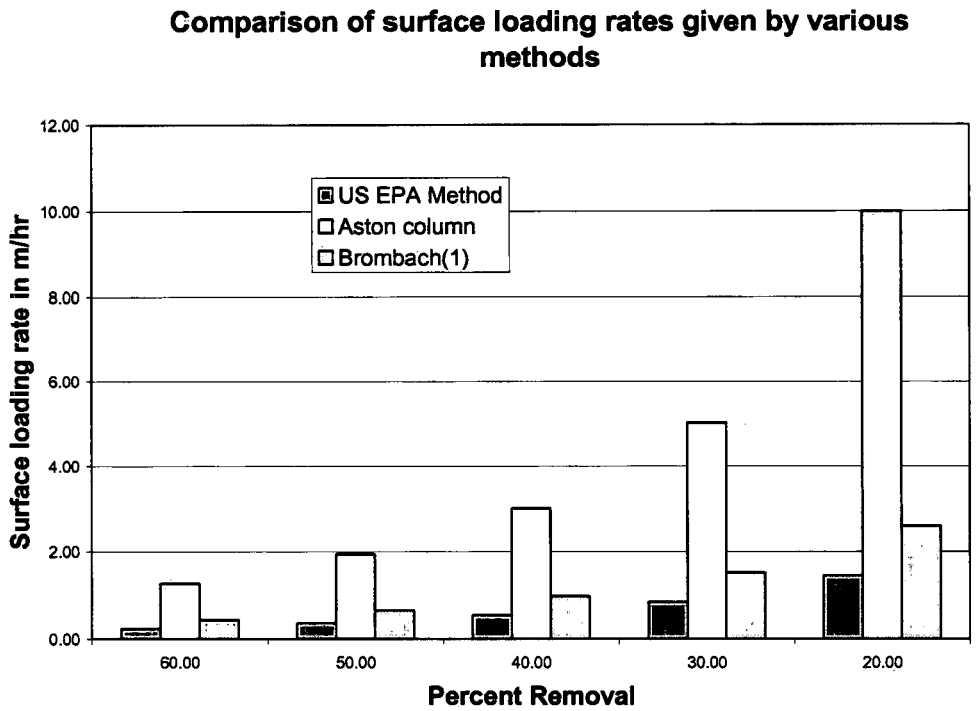

Fig. 5.40: Comparison of surface loading rates given by various methods for the wet-weather sample: July 11, 2003.

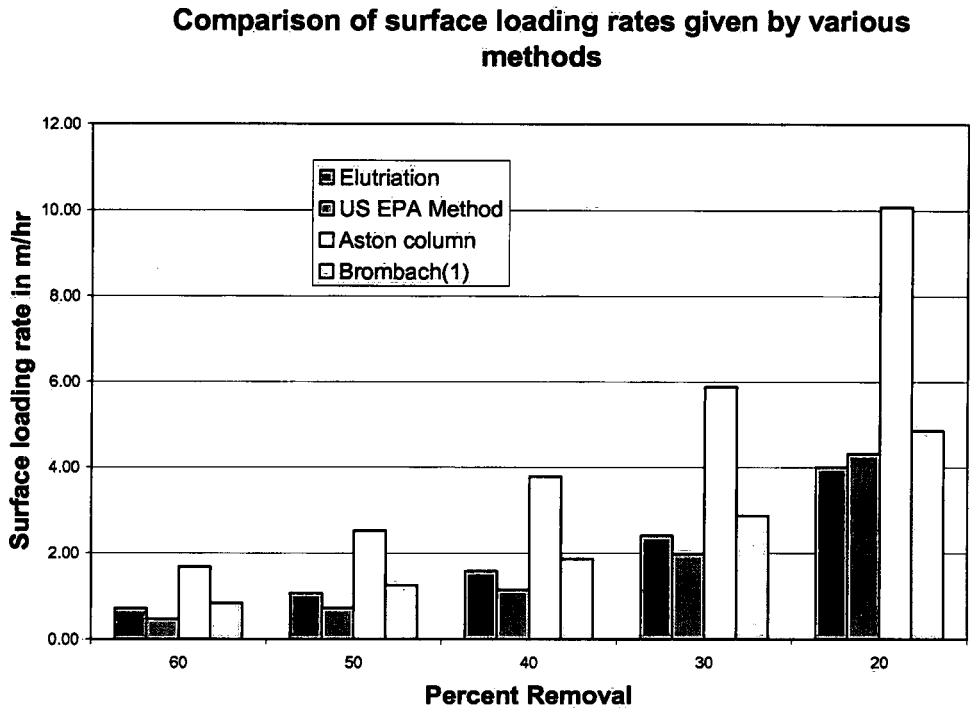

Fig. 5.41: Comparison of surface loading rates given by various methods for the wet-weather sample: July 15, 2003.

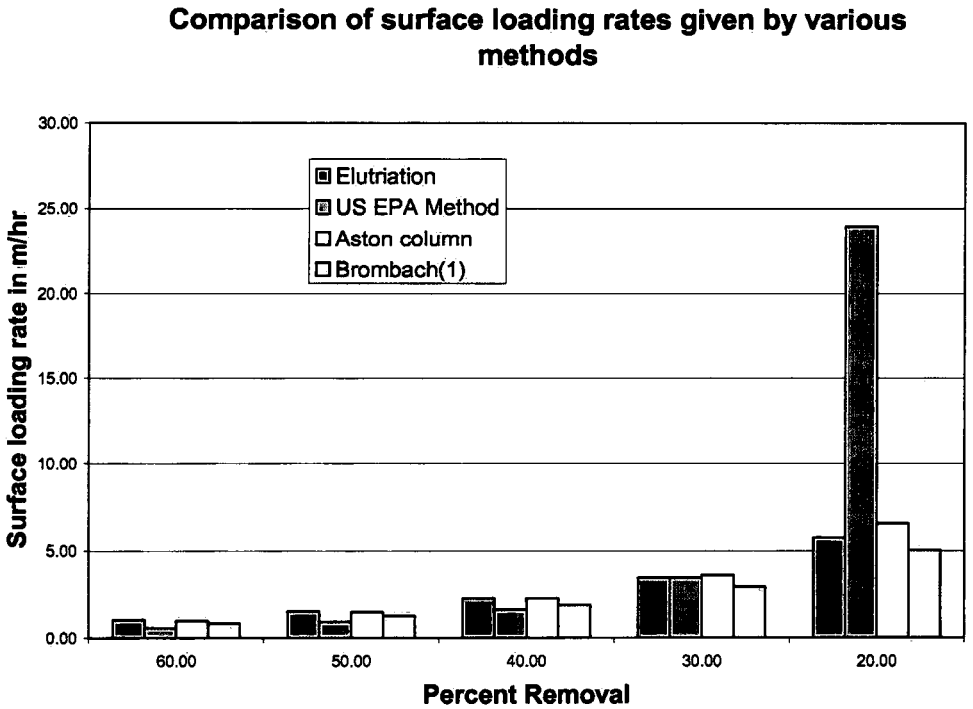

Fig. 5.42: Comparison of surface loading rates given by various methods for the wet-weather sample: August 5, 2003.

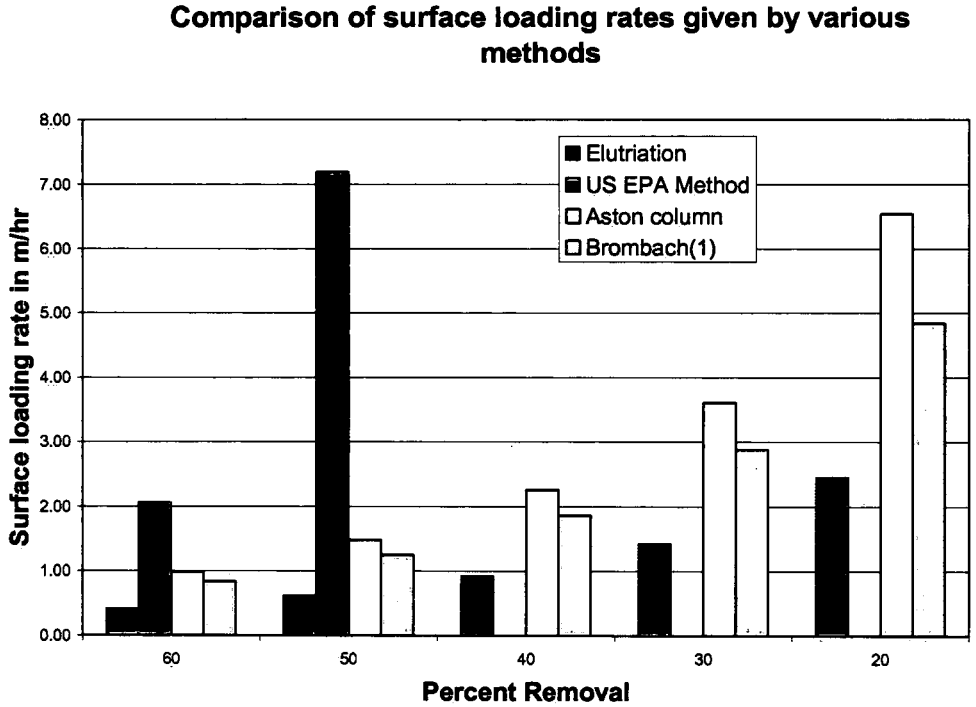

Fig. 5.43: Comparison of surface loading rates given by various methods for the wet-weather sample: November 19, 2003.

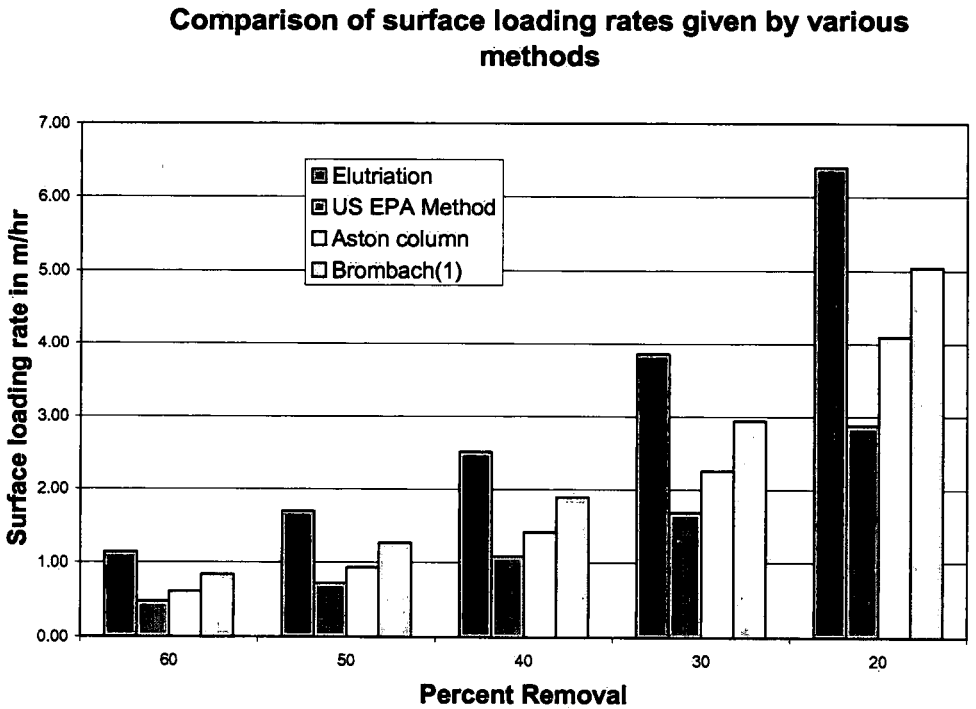

Fig. 5.44: Comparison of surface loading rates given by various methods for the wet-weather sample: December 11, 2003.

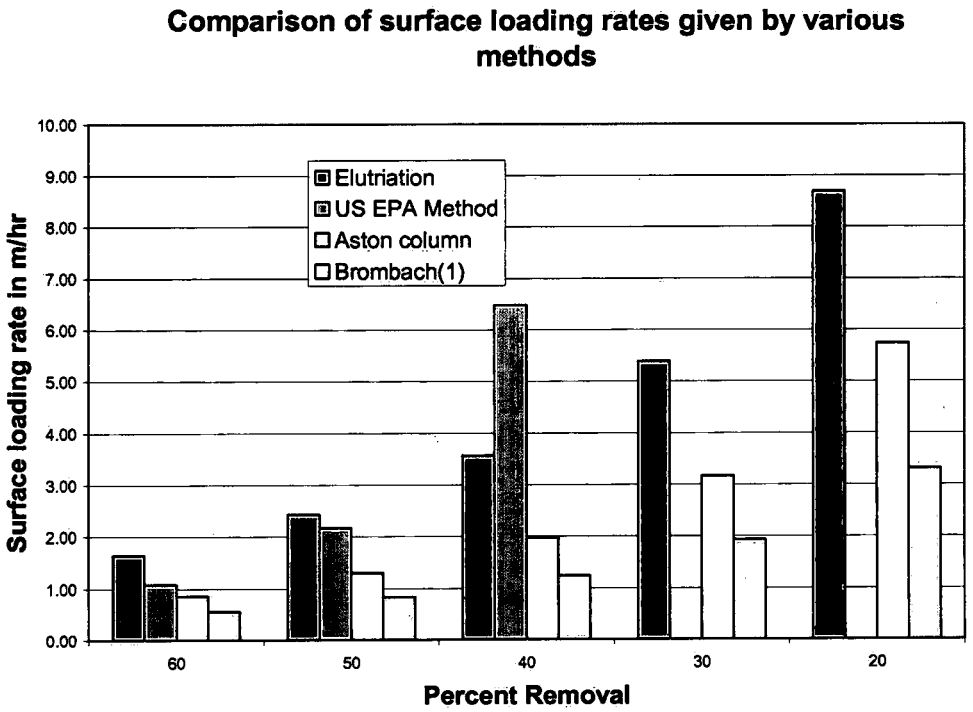

Fig. 5.45: Comparison of surface loading rates given by various methods for the wet-weather sample: March 2, 2004.

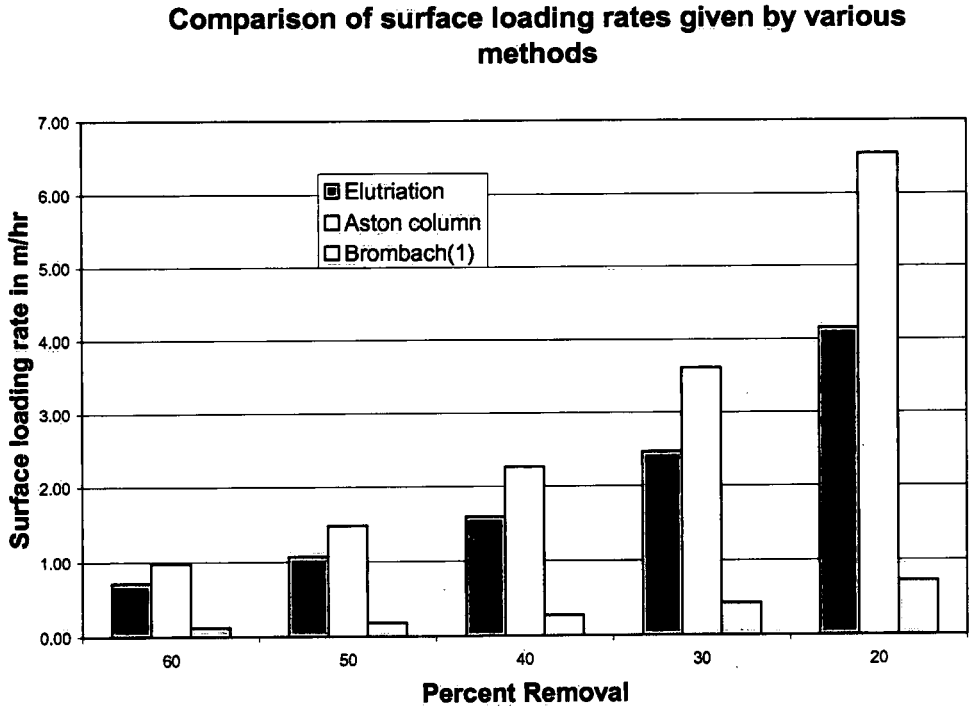

Fig. 5.46: Comparison of surface loading rates given by various methods for the wet-weather sample: March 6, 2004.

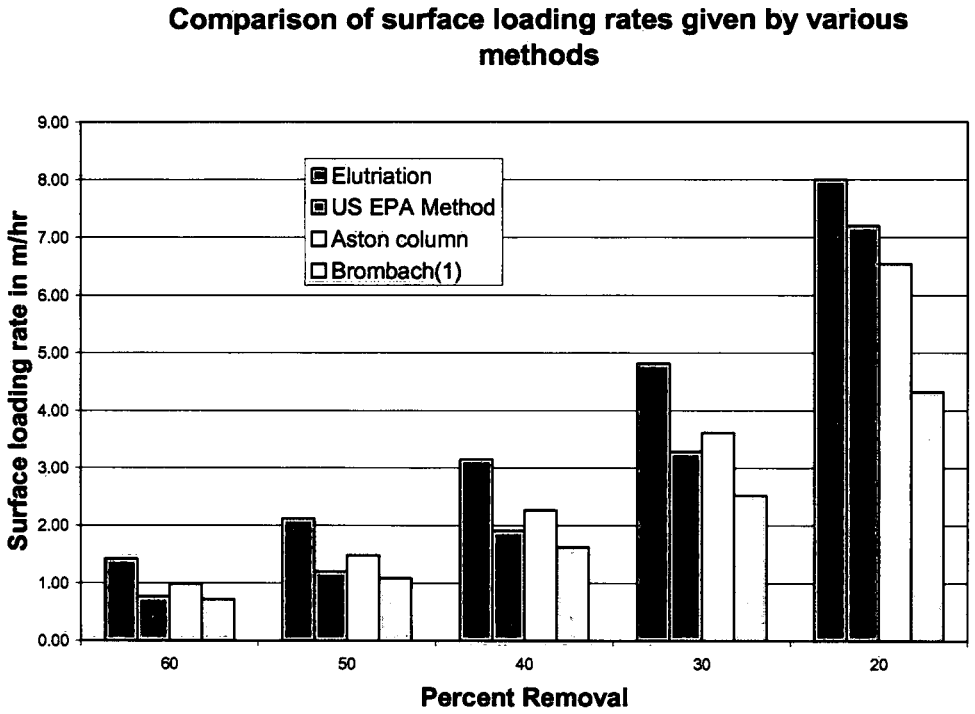

Fig. 5.47: Comparison of surface loading rates given by various methods for the wet-weather sample: March 20, 2004.

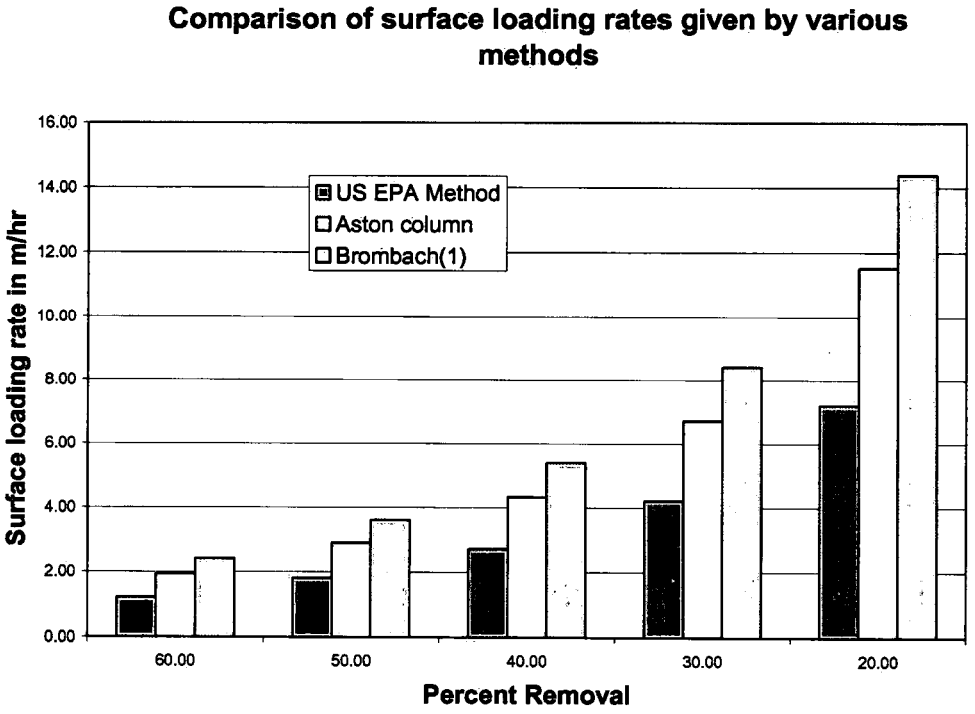

Fig. 5.48: Comparison of surface loading rates given by various methods for the wet-weather sample: April 18, 2004.

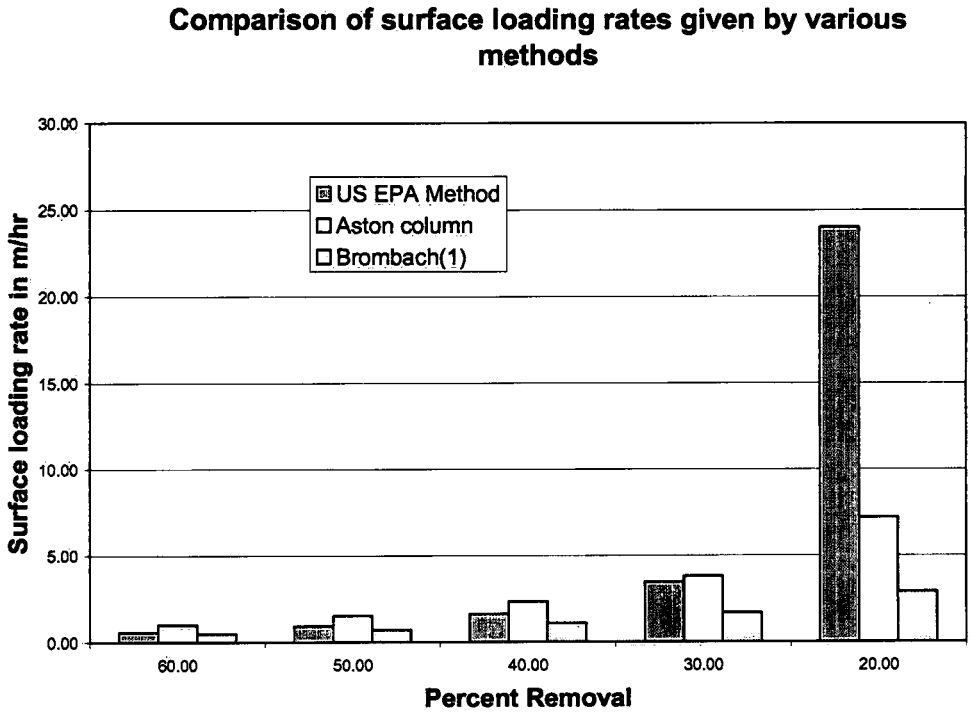

Fig. 5.49: Comparison of surface loading rates given by various methods for the wet-weather sample: April 21, 2004.

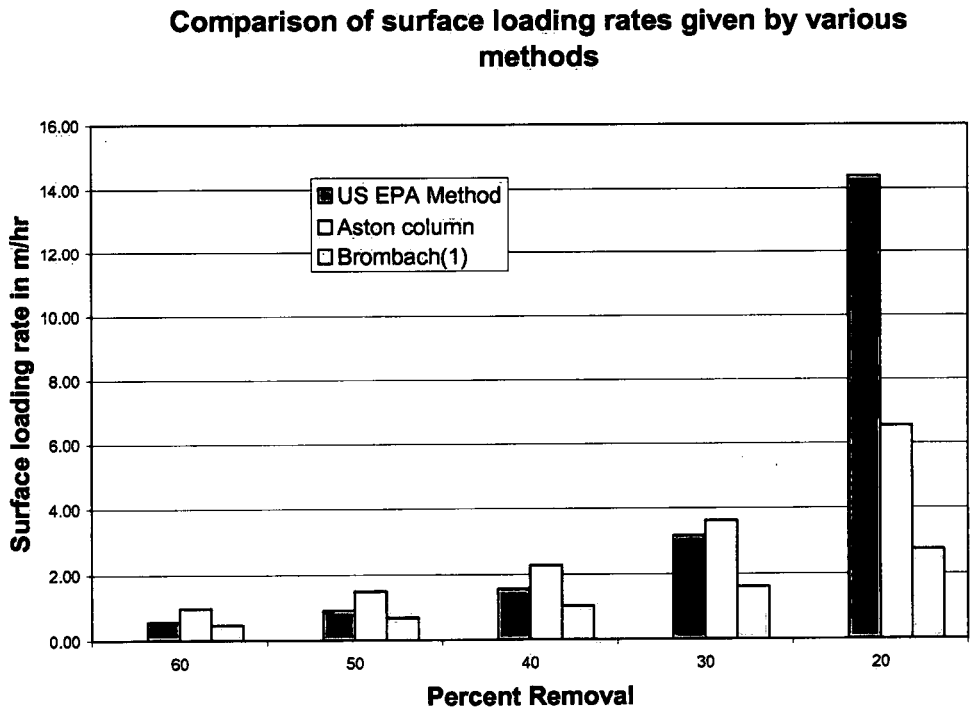

Fig. 5.50: Comparison of surface loading rates given by various methods for the wet-weather sample: May 2, 2004.

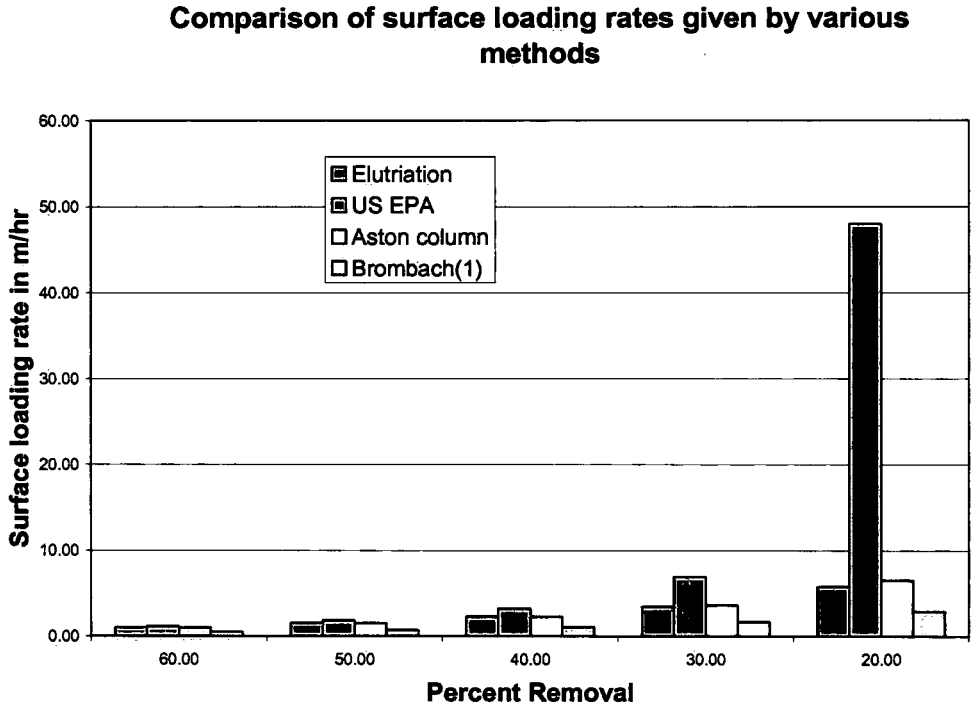

Fig. 5.51: Comparison of surface loading rates given by various methods for the wet-weather sample: May 9, 2004.

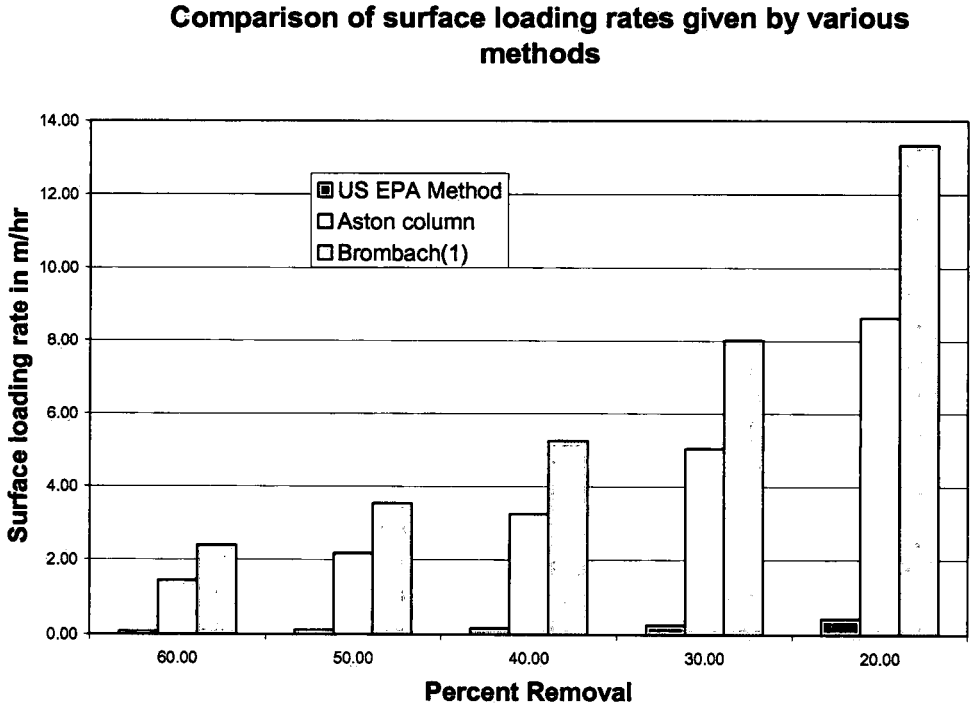

Fig. 5.52: Comparison of surface loading rates given by various methods for the wet-weather sample: July 2, 2004 (Muddy Run).

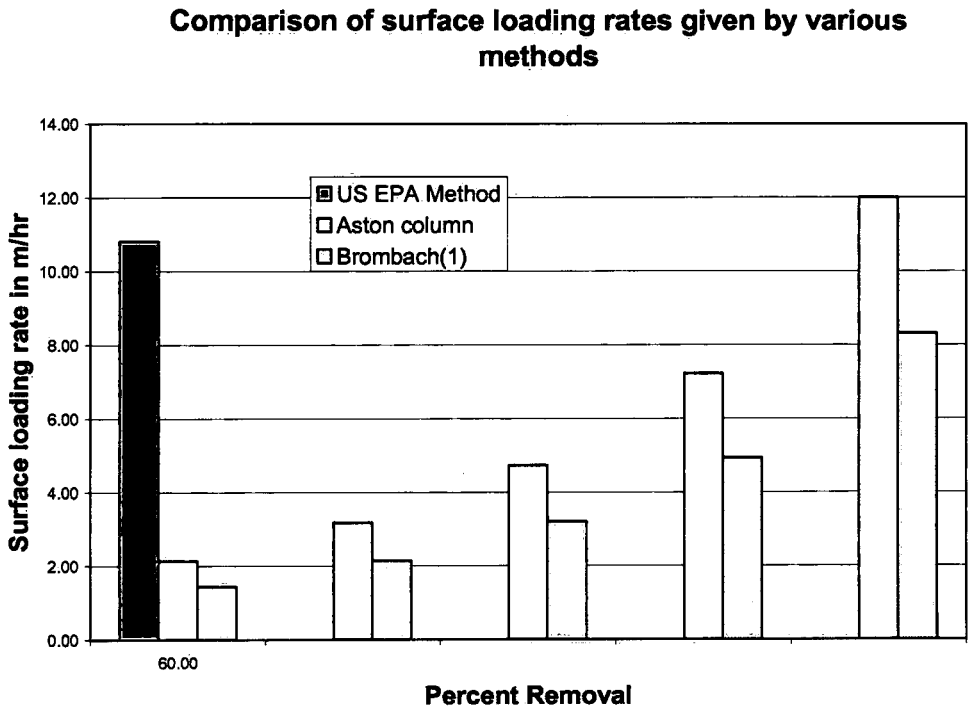

Fig. 5.53: Comparison of surface loading rates given by various methods for the wet-weather sample: July 7, 2004 (Central Pumping Station).

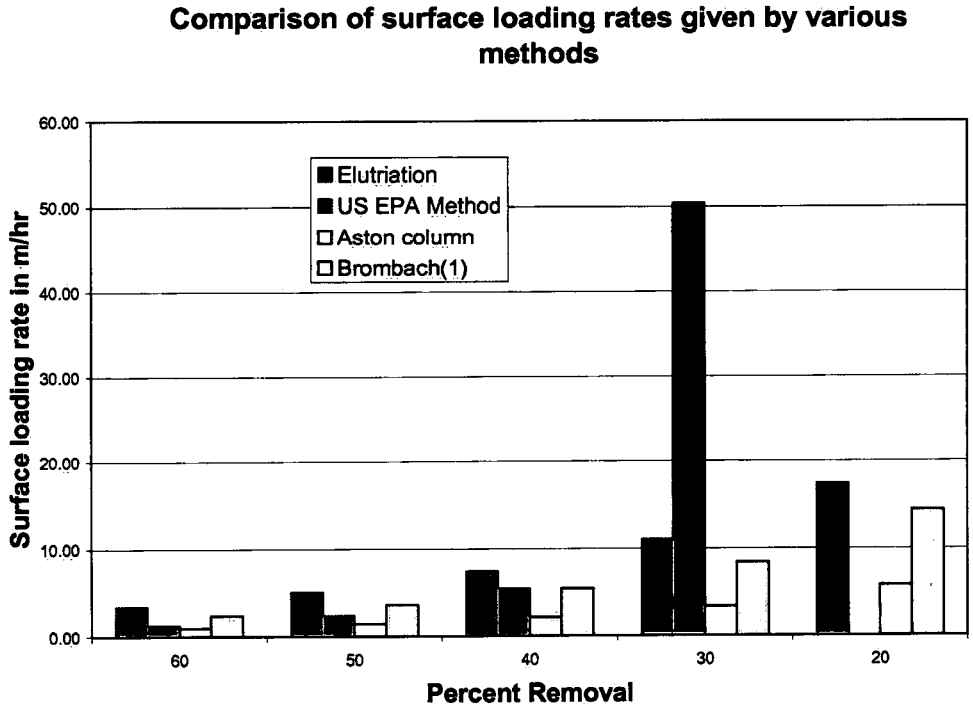

Fig. 5.54: Comparison of surface loading rates given by various methods for the wet-weather sample: July 14, 2004.

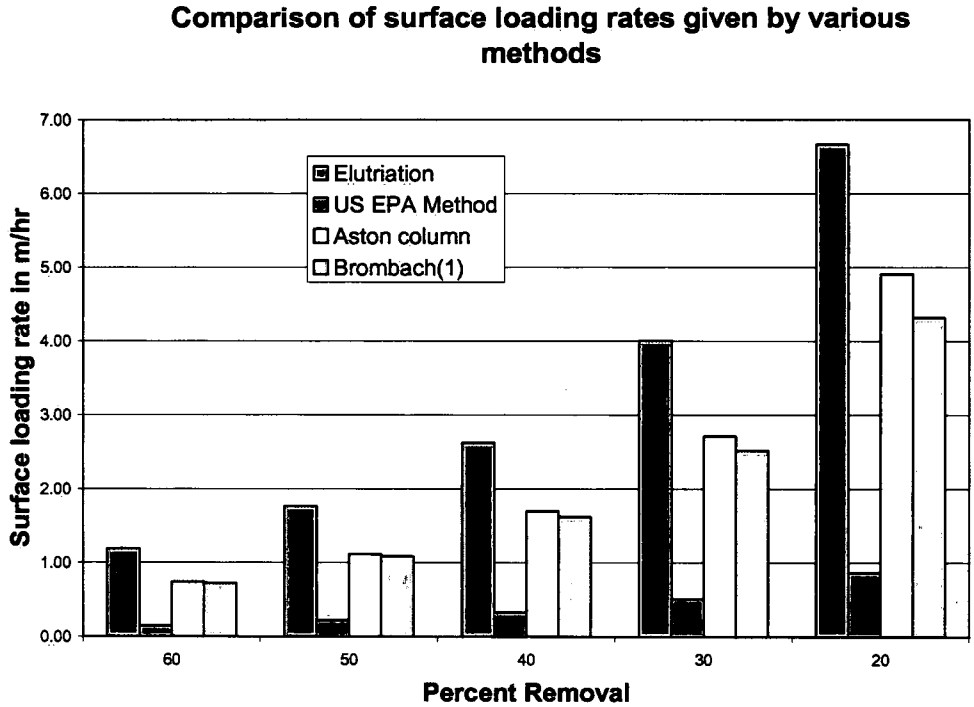

Fig. 5.55: Comparison of surface loading rates given by various methods for the wet-weather sample: July 14, 2004 (Central Pumping Station).

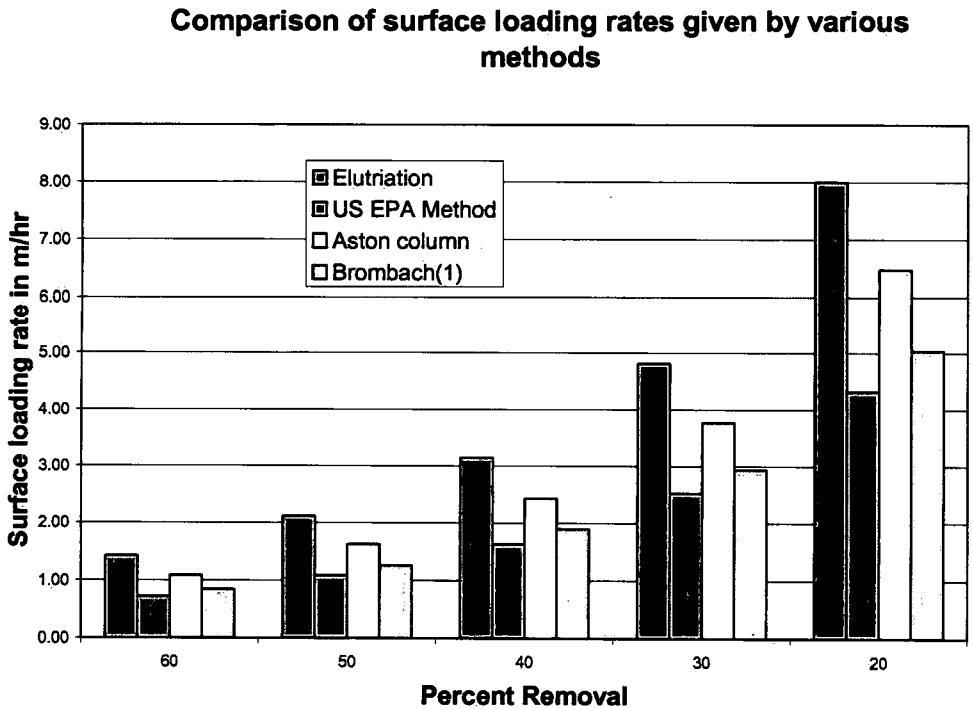

Fig. 5.56: Comparison of surface loading rates given by various methods for the wet-weather sample: July 27, 2004.

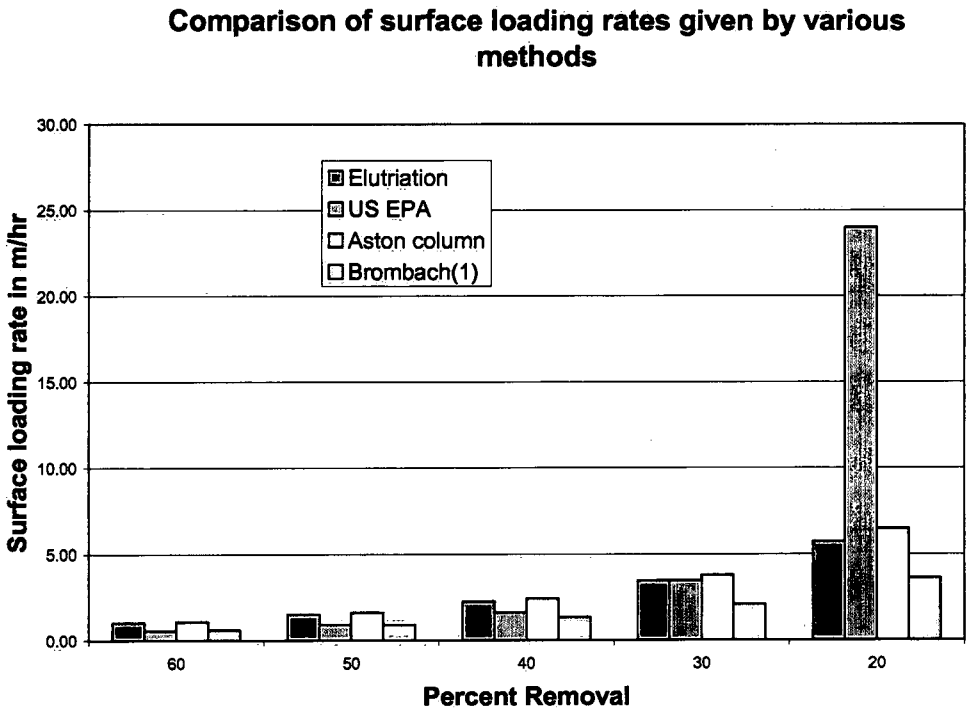

Fig. 5.57: Comparison of surface loading rates given by various methods for the wet-weather sample: November 5, 2004 (Central Pumping Station).

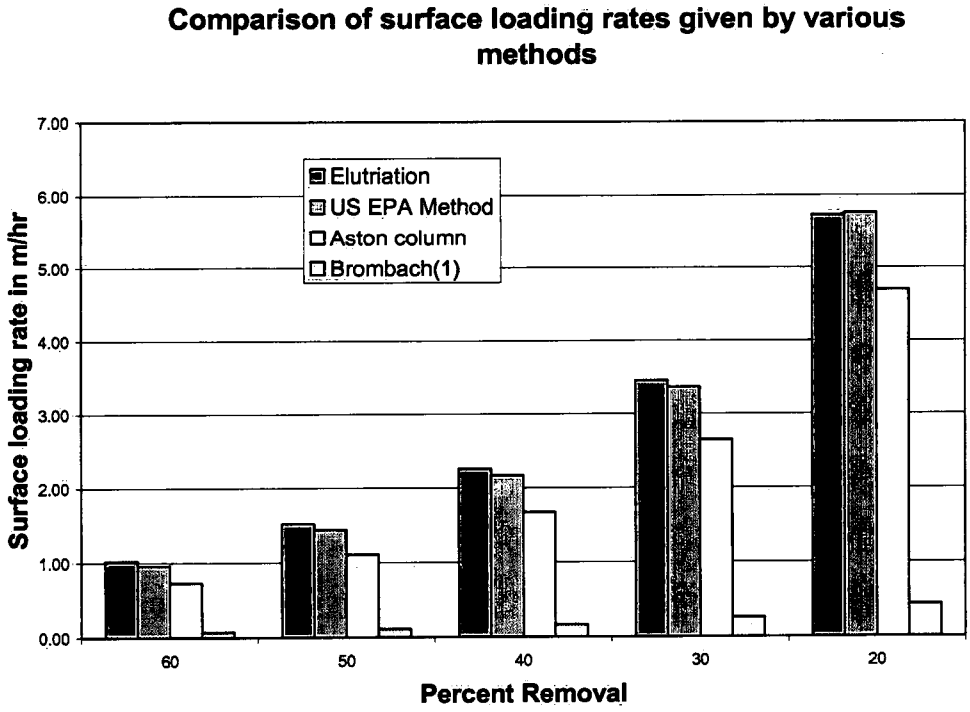

Fig. 5.58: Comparison of surface loading rates given by various methods for the dry-weather sample: September 5, 2003.

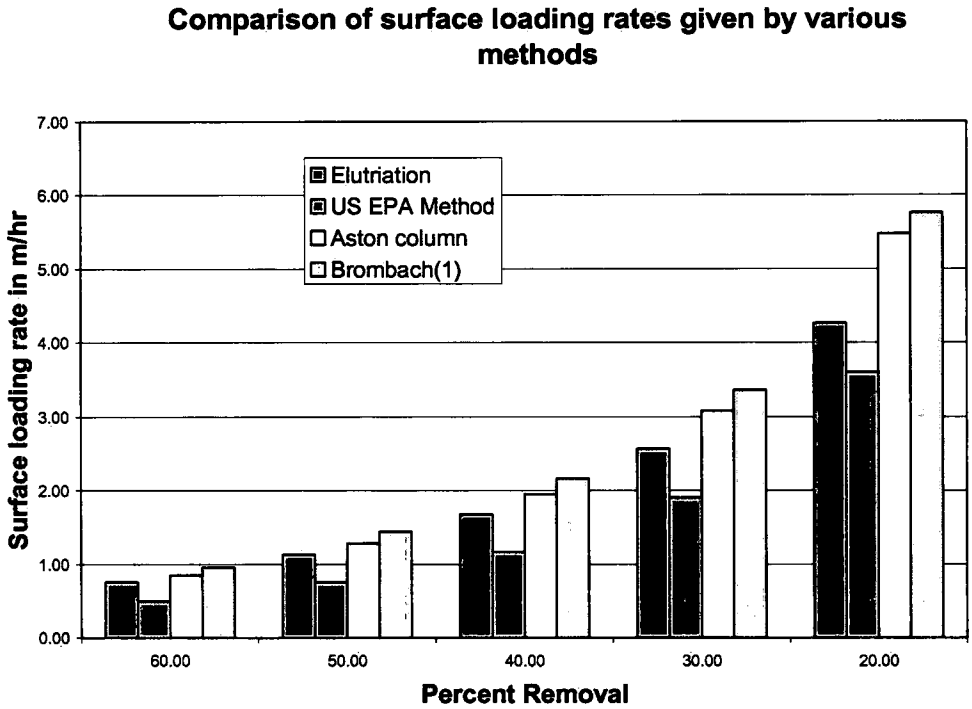

Fig. 5.59: Comparison of surface loading rates given by various methods for the dry-weather sample: October 9, 2003.

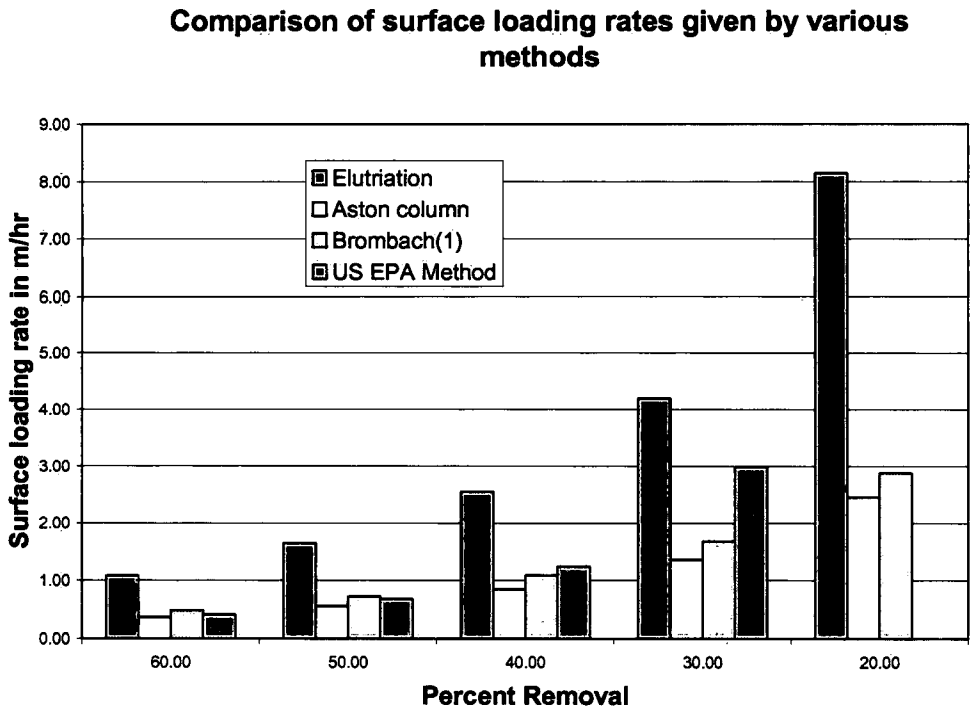

Fig. 5.60: Comparison of surface loading rates given by various methods for the dry-weather sample: November 10, 2003.

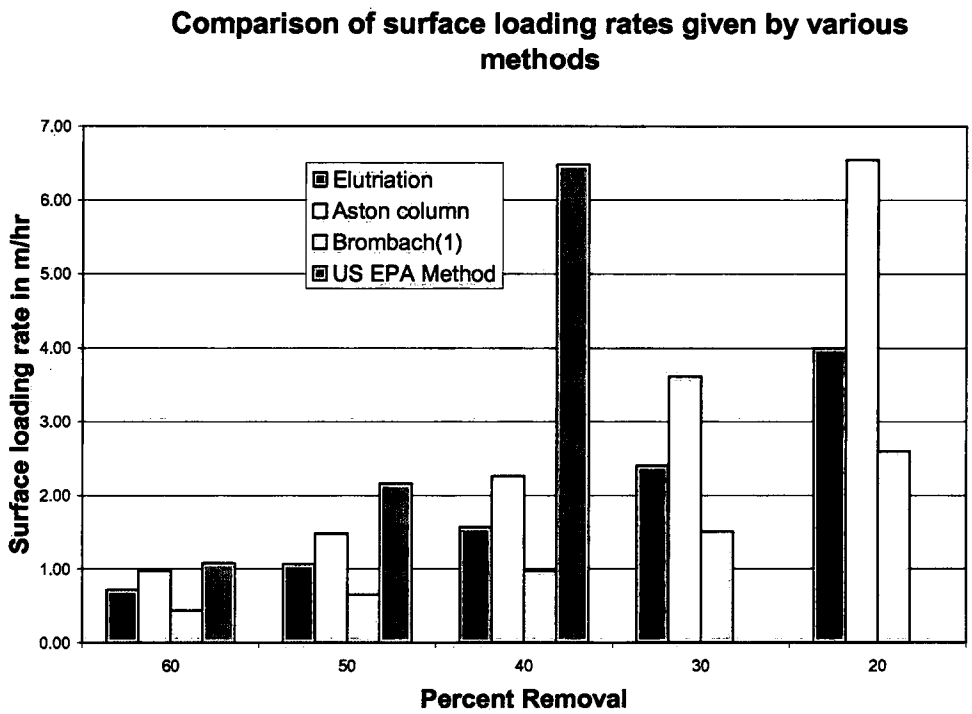

Fig. 5.61: Comparison of surface loading rates given by various methods for the dry-weather sample: February 12, 2004.

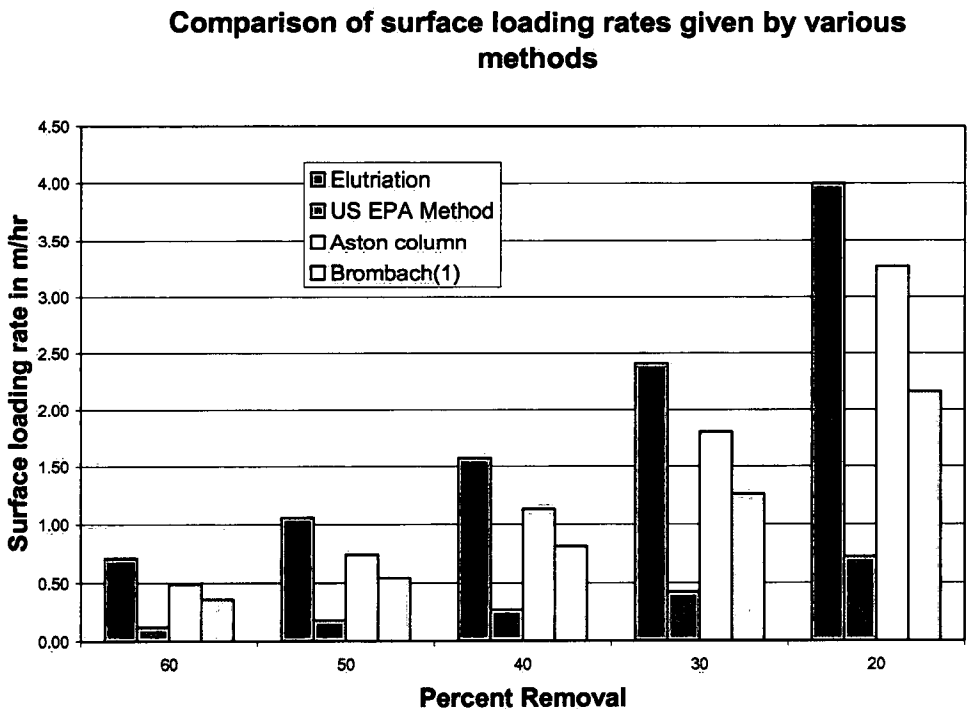

Fig. 5.62: Comparison of surface loading rates given by various methods for the dry-weather sample: March 29, 2004.

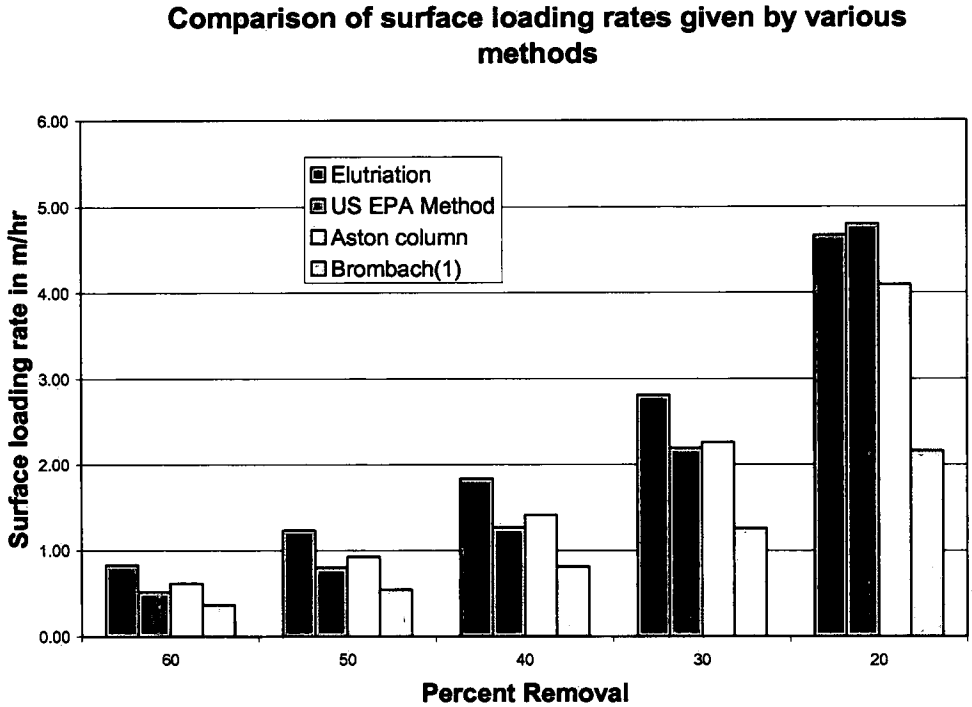

Fig. 5.63: Comparison of surface loading rates given by various methods for the dry-weather sample: April 19, 2004.

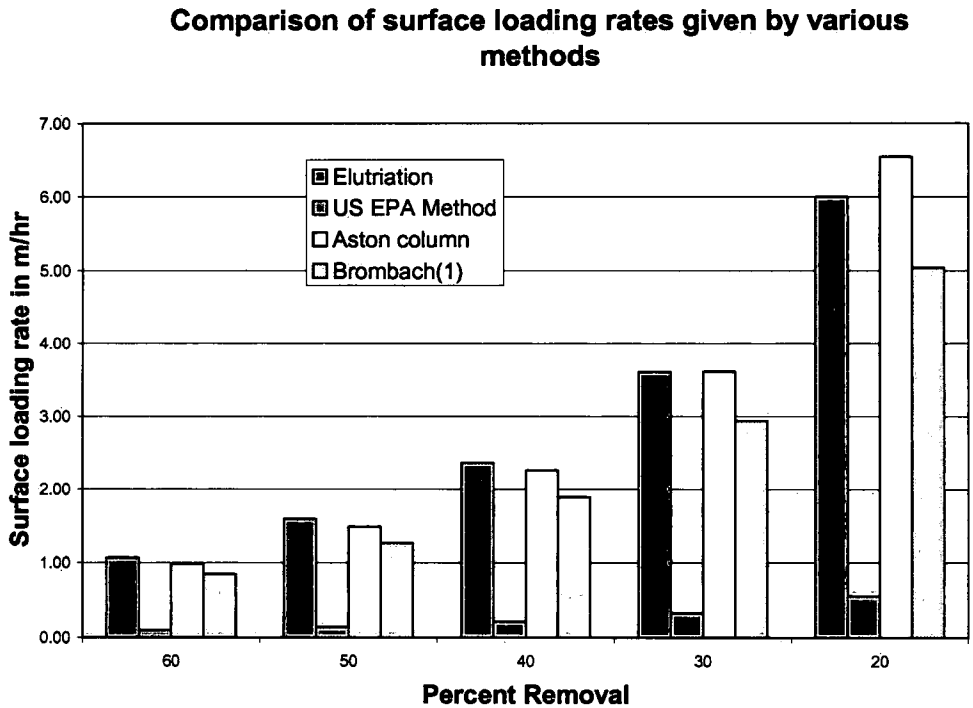

Fig. 5.64: Comparison of surface loading rates given by various methods for the dry-weather sample: June 3, 2004.

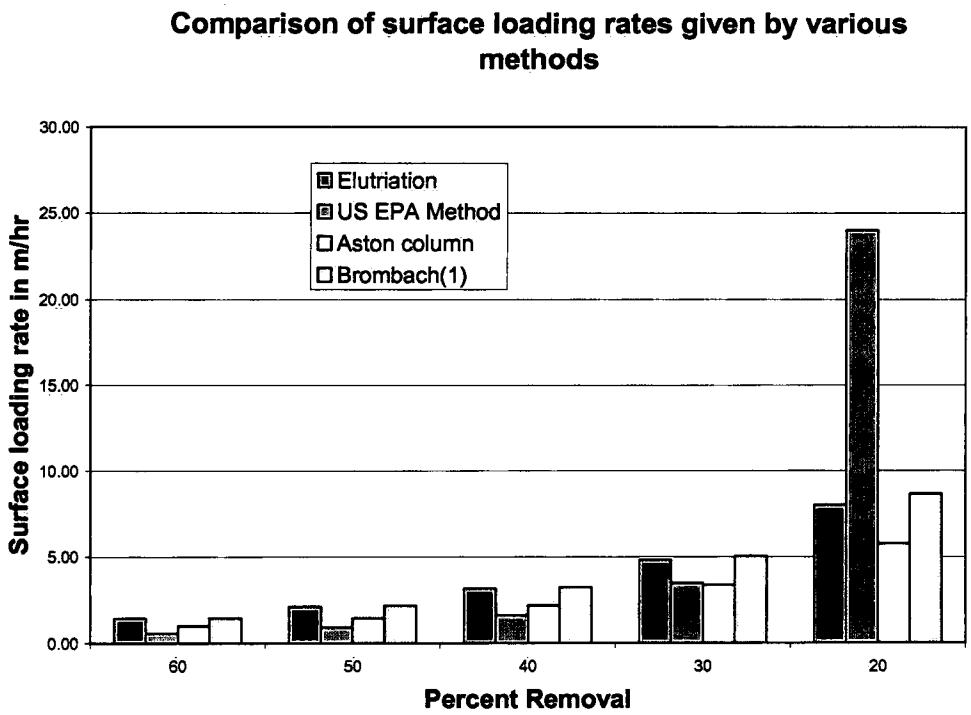

Fig. 5.65: Comparison of surface loading rates given by various methods for the dry-weather sample: July 12, 2004.

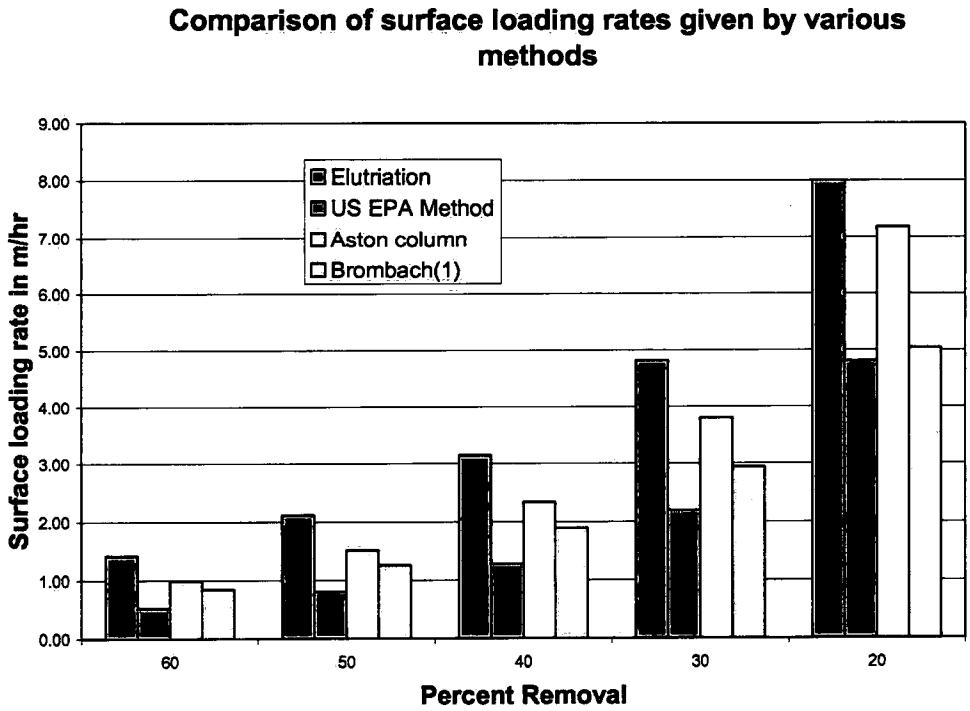

Fig. 5.66: Comparison of surface loading rates given by various methods for the dry-weather sample: September 7, 2004.

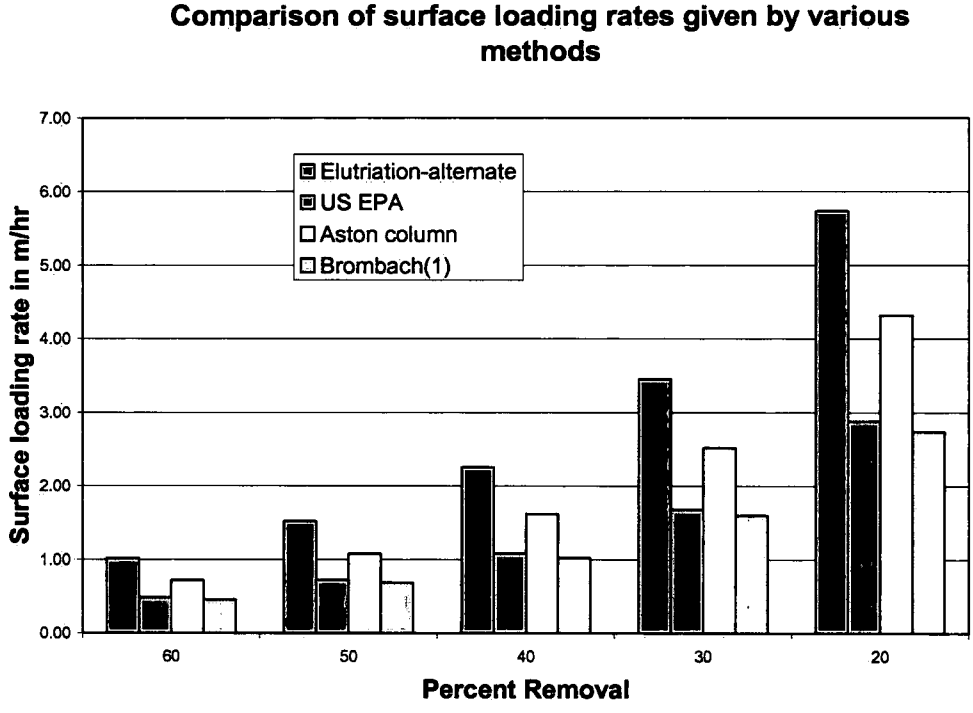

Fig. 5.67: Comparison of surface loading rates given by various methods for the dry-weather sample: January 25, 2004.

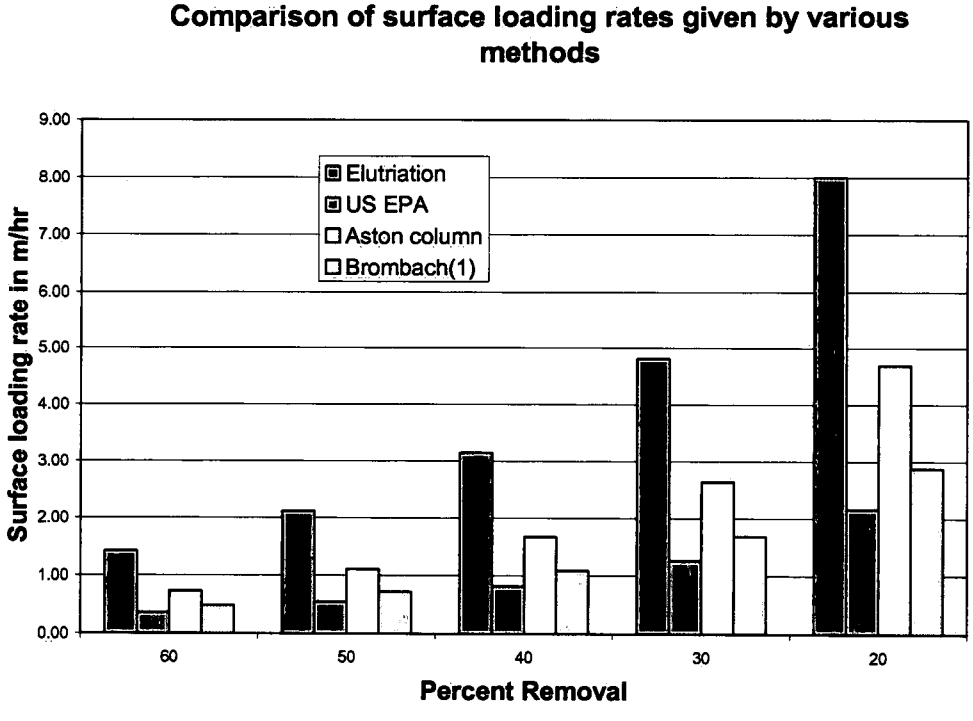

Fig. 5.68: Comparison of surface loading rates given by various methods for the dry-weather sample: January 28, 2004.

These figures indicate that for the lower percentages of removal, the variation in the surface loading rates given by the different methods is fairly large. As the percent removal increases, the deviation due to different methods decreases. For example, for the 50% removal, the surface loading rates given by different methods for different samples do not vary appreciably and are on the order of 1 m/hr.

To examine the variability in the cumulative settling velocity distributions among samples, the samples were divided into two groups, namely, dry-weather samples and wet-weather samples. For each group, the settling velocity distributions of some selected samples (six wet-weather samples and six dry-weather samples) are plotted for each method as shown in Figs. 5.69 to 5.76 (Figs. 5.69 to 5.72 are for dry-weather samples and Figs. 5.73 to 5.76 are for wet-weather samples).

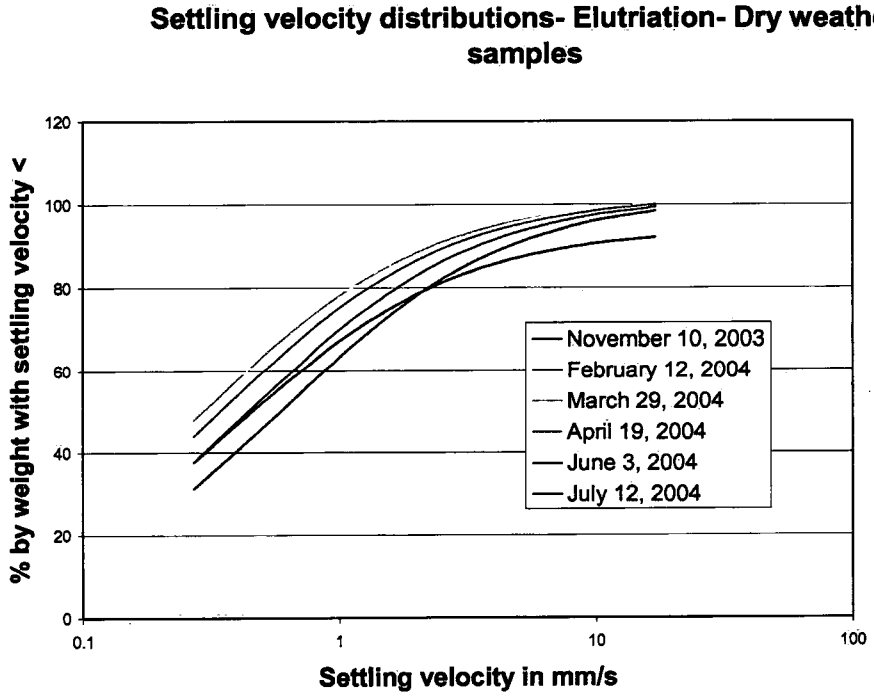

Fig. 5.69: Settling velocity distributions given by the elutriation apparatus for dry-weather samples. (Note: multiple curves coincide.)

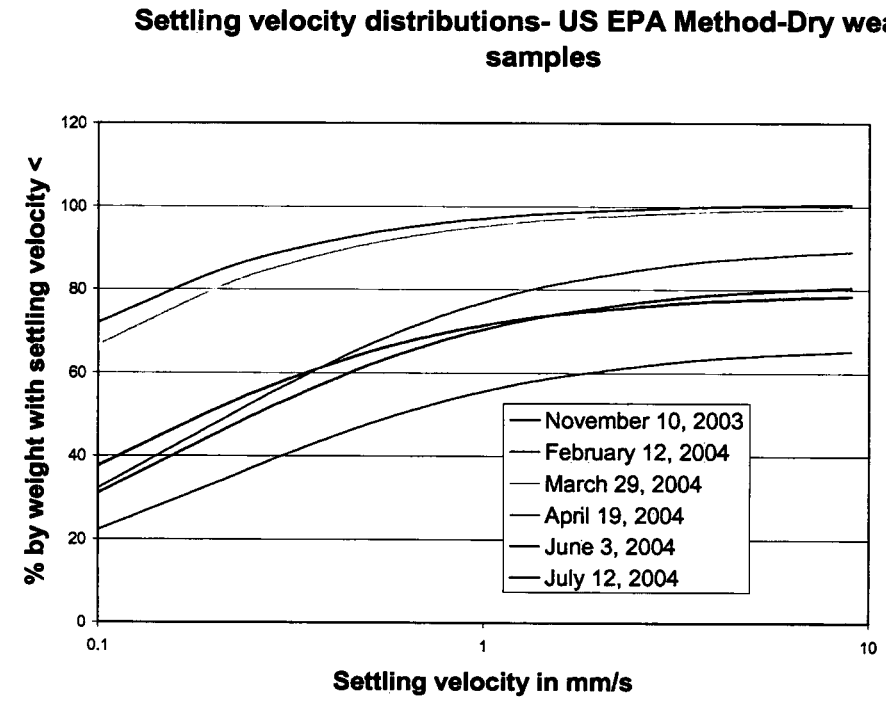

Fig. 5.70: Settling velocity distributions given by the U.S. EPA column for dry-weather samples.

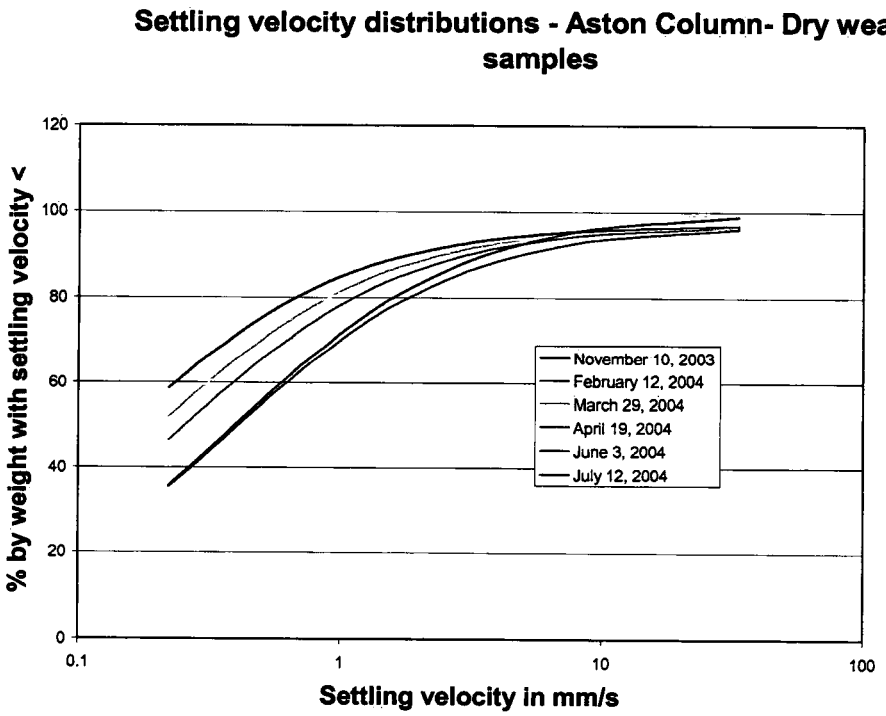

Fig. 5.71: Settling velocity distributions given by the Aston column for dry-weather samples. (Note: multiple curves coincide.)

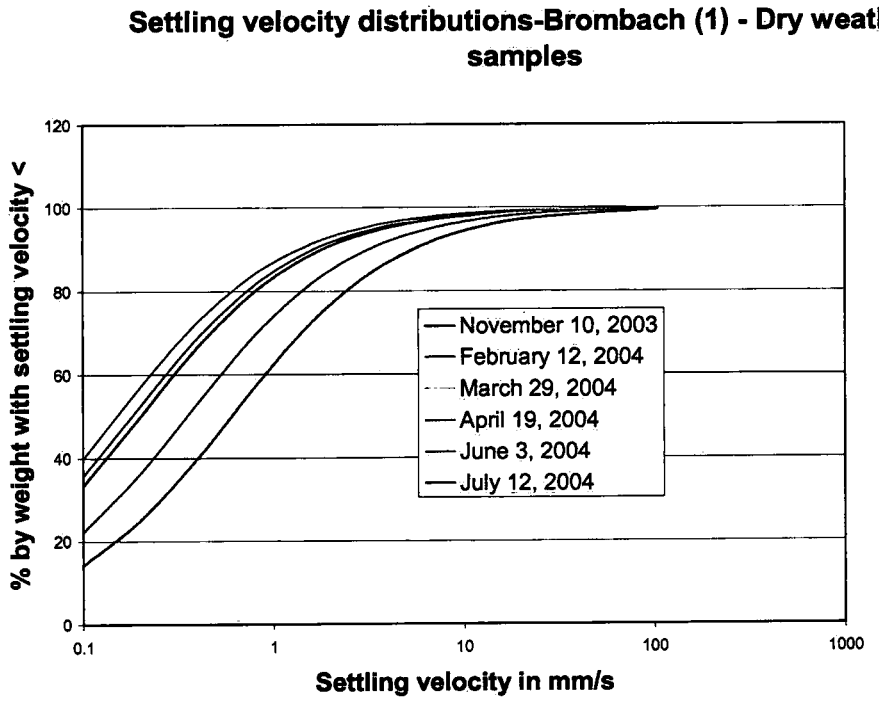

Fig. 5.72: Settling velocity distributions given by the Brombach column for dry-weather samples.

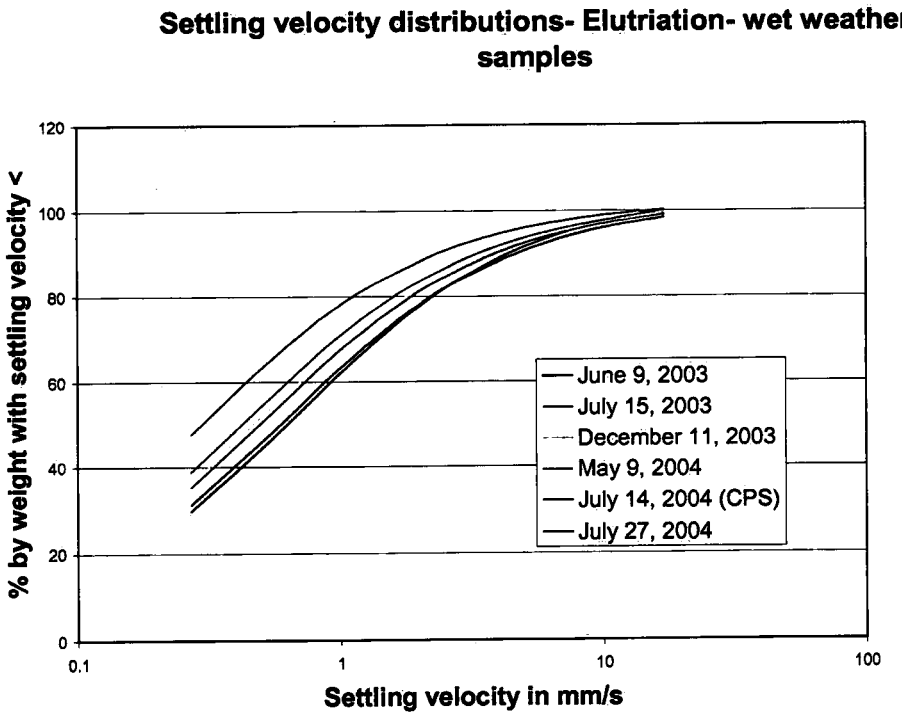

Fig. 5.73: Settling velocity distributions given by the elutriation apparatus for wet-weather samples.

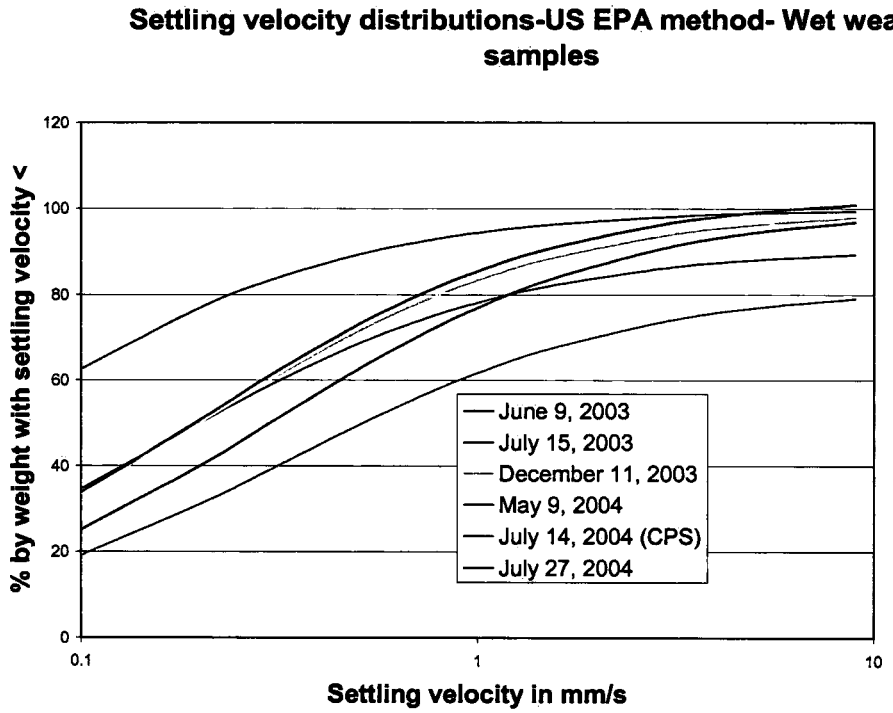

Fig. 5.74: Settling velocity distributions given by the U.S. EPA column for wet-weather samples.

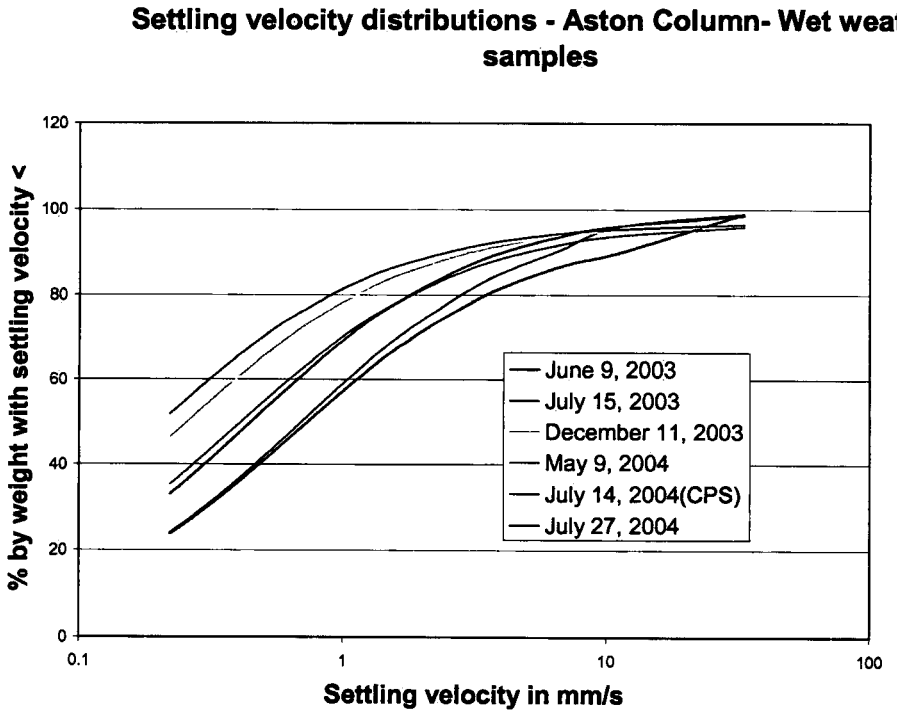

Fig. 5.75: Settling velocity distributions given by the Aston column for wet-weather samples.

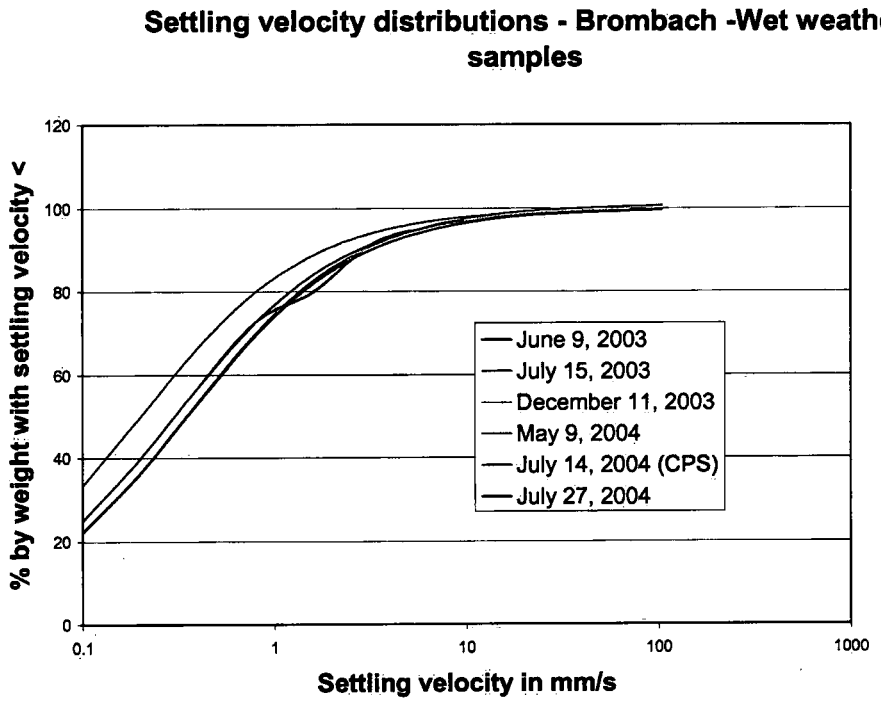

Fig. 5.76: Settling velocity distributions given by the Brombach column for wet-weather samples. (Note: multiple curves coincide).

From these figures, we can see that the variability in settling velocity distributions among samples depends on the measurement method employed. For example, the elutriation apparatus provides the least variability among dry-weather samples as can be seen in Fig. 5.69. The same samples show much larger variability when tested using the U.S. EPA method (see Fig. 5.70). In general, the dry-weather samples exhibit less variability in comparison to the wet-weather samples (except for the Brombach Column in Fig. 5.76). We can also conclude from these figures that the variability due to different samples is of the same order of magnitude as the variability due to measurement methods. Similar conclusions can be arrived at by examining the plots of surface loading rates as a function of percent removal given by different methods for selected samples as shown in Figs. 5.77 to 5.84 (Figs. 5.77 to 5.80 are for dry-weather samples and Figs. 5.81 to 5.84 are for wet-weather samples).

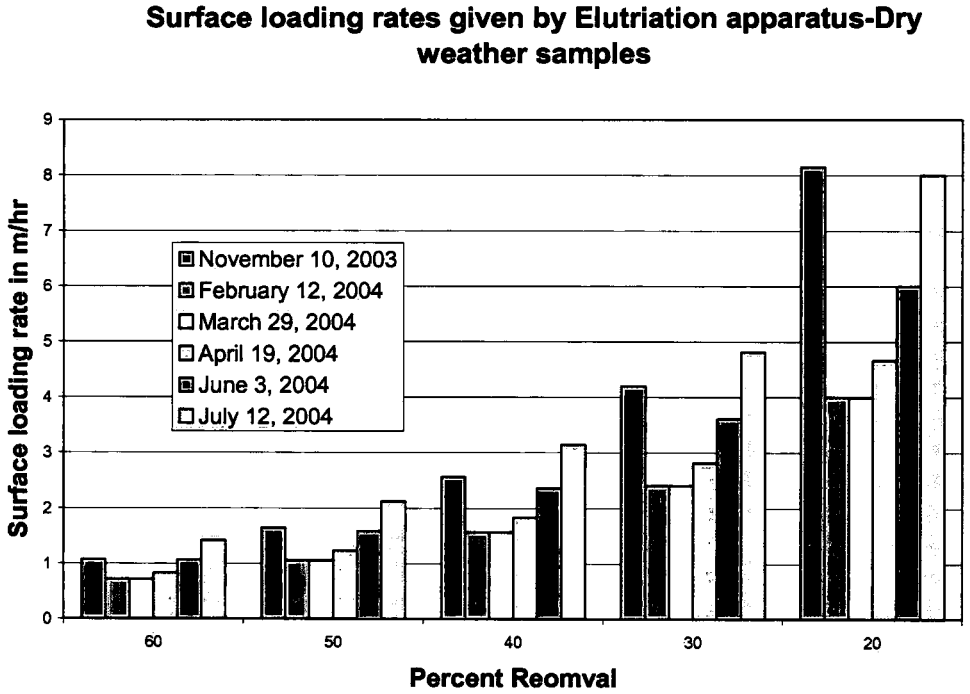

Fig. 5.77: Surface loading rates given by the elutriation apparatus for dry-weather samples.

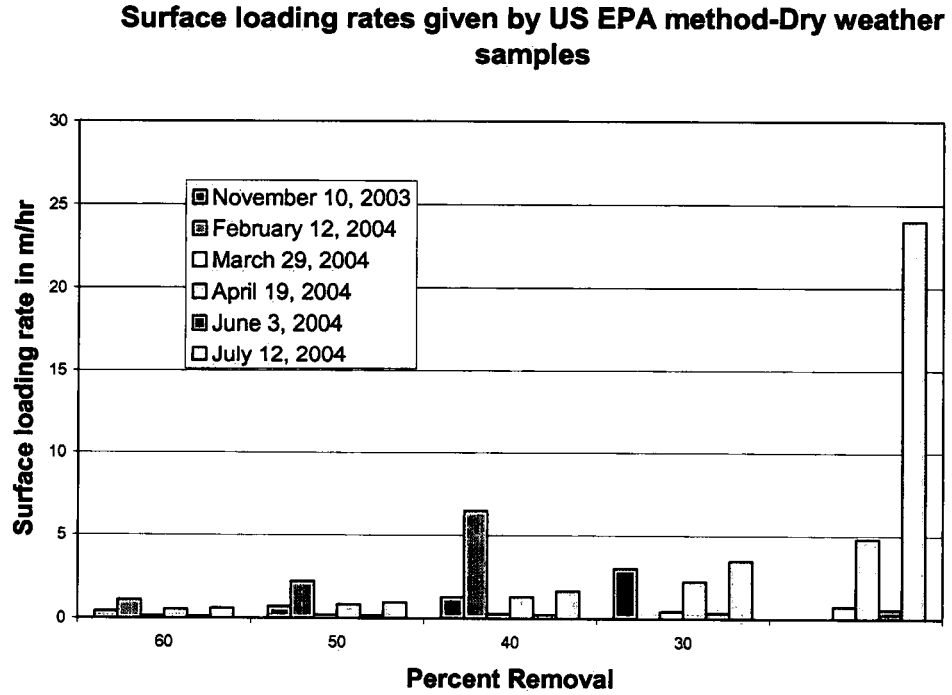

Fig. 5.78: Surface loading rates given by the U.S. EPA column for dry-weather samples.

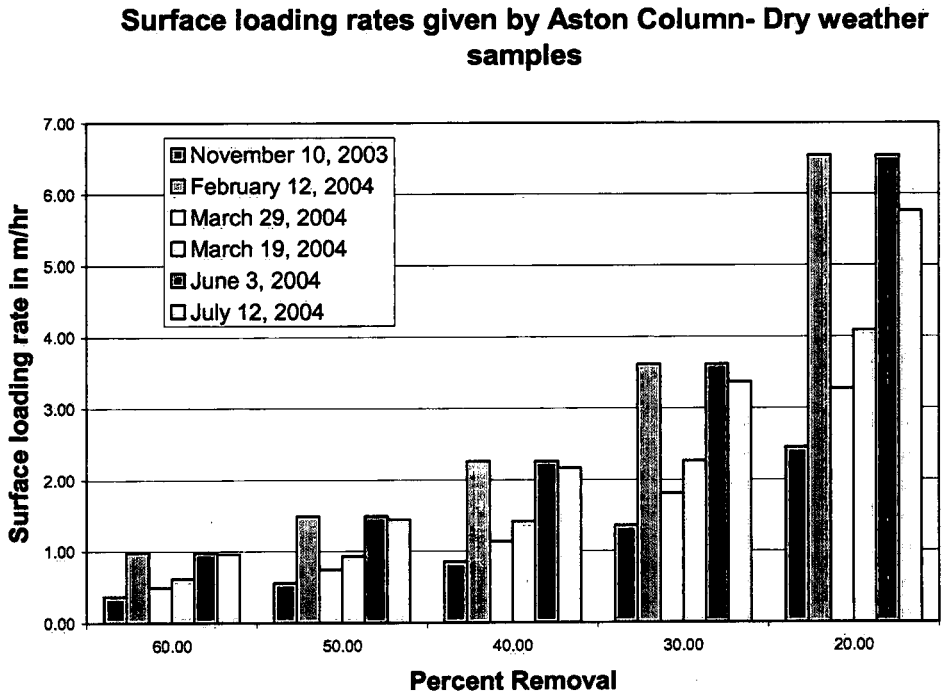

Fig. 5.79: Surface loading rates given by the Aston column for dry-weather samples.

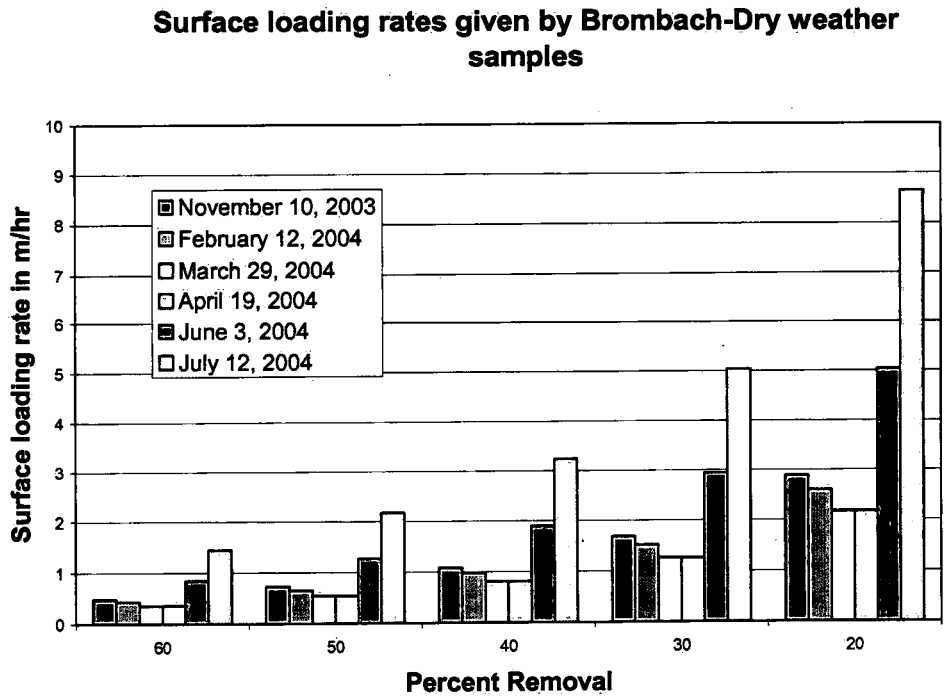

Fig. 5.80: Surface loading rates given by the Brombach column for dry-weather samples.

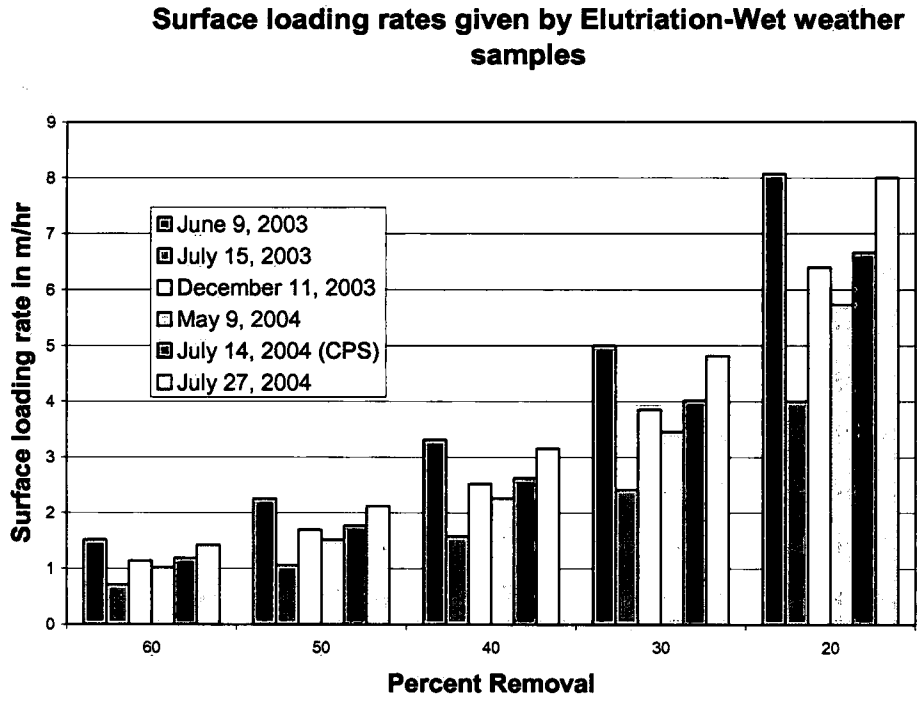

Fig. 5.81: Surface loading rates given by the elutriation apparatus for wet-weather samples.

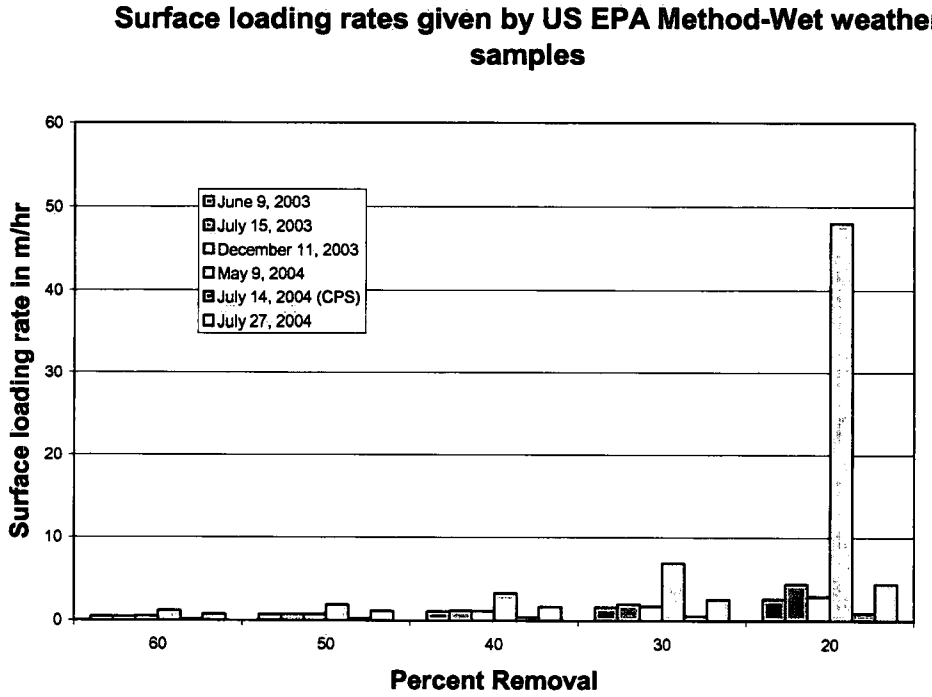

Fig. 5.82: Surface loading rates given by the U.S. EPA column for wet-weather samples.

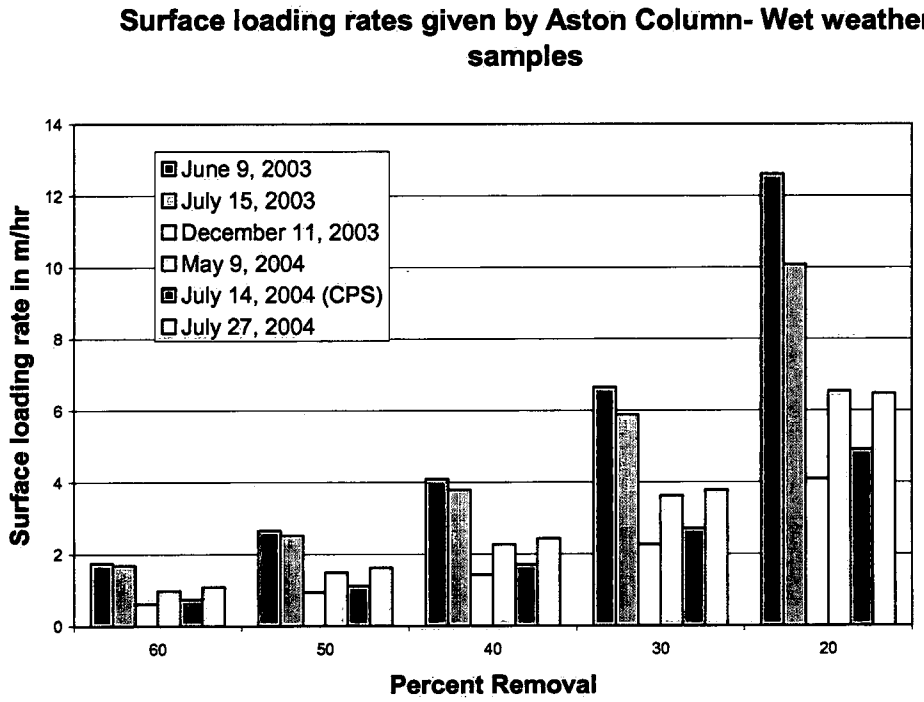

Fig. 5.83: Surface loading rates given by the Aston column for wet-weather samples.

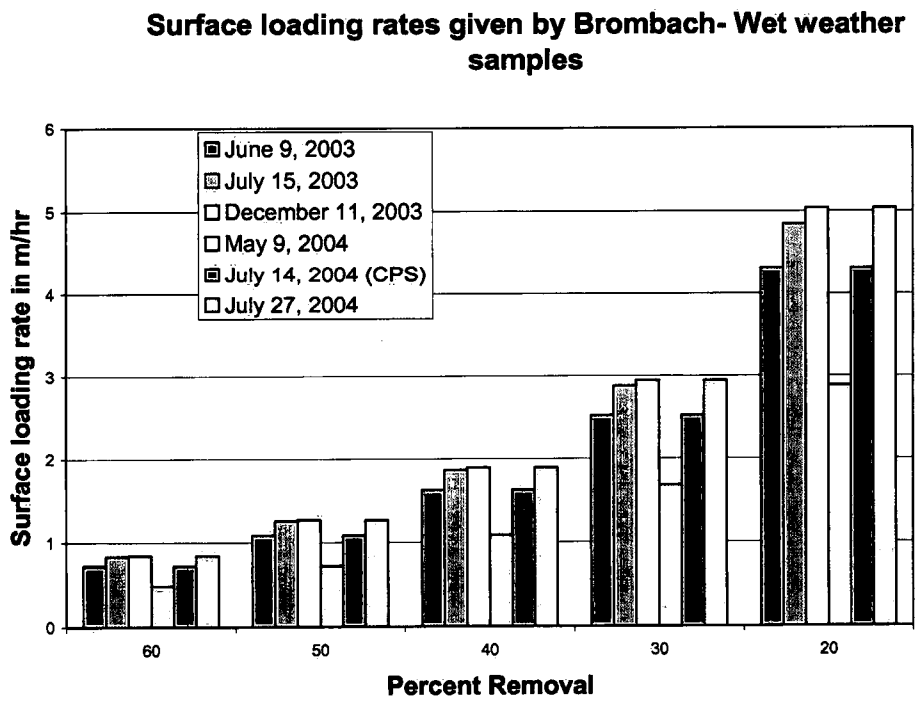

Fig. 5.84: Surface loading rates given by the Brombach column for wet-weather samples.

5.2 Jar testing

5.2.1 Zetag 7873

Jar tests were performed on all wet-weather and dry-weather samples when volume sufficed. Jar tests were typically performed in duplicate using the polymer flocculant, Zetag 7873 (Ciba Specialty Chemicals); when time and sample volume allowed, the use of alum was also evaluated. On the 19-Apr-04, no replicates could be obtained using the polymer due to insufficient sample volume, and results reflect only a single test. The results of the jar tests with Zetag 7873 are summarized for wet-weather samples in Table 5.6; the results for dry-weather samples are included in Table 5.7. Mean relative TSS removals are shown (with 95% confidence limits) in Fig. 5.85; the red line indicates the 90 mg/L level.

Table 5.6: Summary of jar test results for wet-weather samples treated with Zetag 7873

Sample date	Sample location	Initial TSS (mg / L)	TSS remaining at specified polymer dosage (mg / L)				
			0.0	1.0	2.0	4.0	6.0
09-Jun-03	HLS	149	40.5	21.5	18.5	18.0	20.5
11-Jul-03	HLS	158	36.4	14.0	14.2	13.8	11.8
15-Jul-03	HLS	259	84.0	30.7	25.0	21.3	15.0
05-Aug-03	HLS	131	86.5	31.5	31.0	27.0	22.0
19-Nov-03	HLS	334	76.5	32.5	30.0	27.5	25.7
11-Dec-03	HLS	246	63.0	40.0	31.5	25.0	27.5
02-Mar-04	HLS	130	34.2	20.1	20.3	16.4	16.2
06-Mar-04	HLS	108	32.7	20.5	18.0	17.1	17.1
20-Mar-04	HLS	173	34.9	21.9	18.3	16.6	16.4
21-Apr-04	HLS	116	43.5	28.9	28.1	24.9	22.0
09-May-04	HLS	69.7	28.7	21.2	19.4	19.5	19.6
02-Jul-04	MR	411	54.7	23.9	22.0	21.6	21.2
07-Jul-04	CPS	428	59.6	24.7	20.5	17.7	N/A
14-Jul-04	HLS	484	104	38.8	31.6	26.1	25.5
14-Jul-04	CPS	155	58.7	32.9	30.3	27.3	26.9
27-Jul-04	HLS	173	62.4	29.9	27.6	28.0	26.4
05-Nov-04	CPS	171	61.1	36.7	33.2	27.9	25.6
	Mean	**217**	**56.6**	**27.6**	**24.7**	**22.1**	**21.2**
	SD	**124**	**21.7**	**7.4**	**6.1**	**4.9**	**4.9**

Table 5.7: Summary of jar test results for dry-weather samples treated with Zetag 7873

Sample date	Initial TSS (mg / L)	TSS remaining at specified polymer dosage (mg / L) 0.0	1.0	2.0	4.0	6.0
16-Jun-03	191	95.0	-	56.0	52.0	53.0
05-Sep-03	214	81.5	47.8	46.7	45.7	48.0
09-Oct-03	176	83.0	53.0	52.0	47.0	43.5
10-Nov-03	133	49.5	36.5	30.5	29.5	29.0
12-Feb-04	126	55.1	44.9	42.7	38.6	35.1
29-Mar-04	76.9	36.9	32.9	32.2	30.2	-
19-Apr-04	85.9	37.4	35.5	34.5	30.2	31.4
03-Jun-04	208	69.2	47.3	37.5	28.8	28.1
12-Jul-04	238	79.1	55.4	50.8	46.0	44.0
07-Sep-04	170	61.6	45.7	41.3	38.1	35.3
25-Jan-05	157	47.7	28.3	28.3	25.5	25.5
28-Jan-05	144	52.3	33.3	28.3	25.0	25.0
Mean	**160**	**62.4**	**41.9**	**40.1**	**36.4**	**36.2**
SD	**49.7**	**19.0**	**9.0**	**9.7**	**9.4**	**9.6**

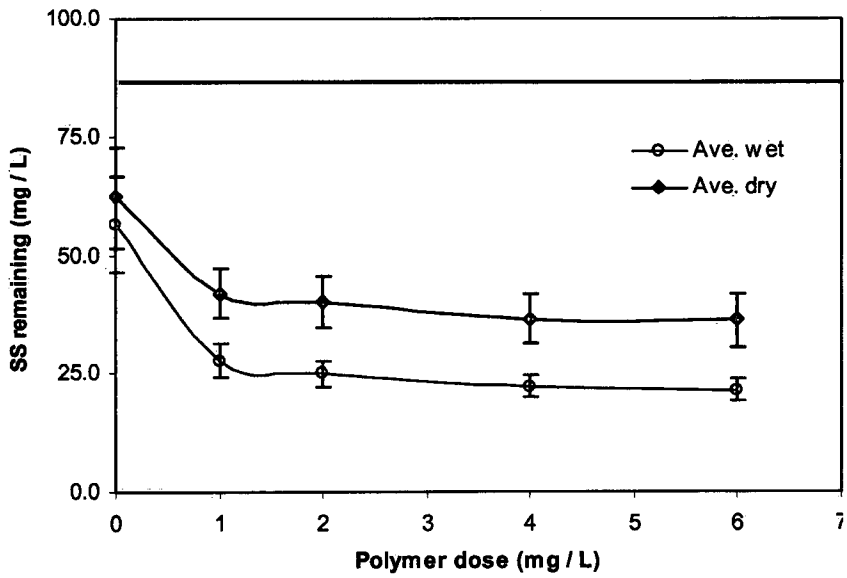

Fig. 5.85: Mean TSS remaining during jar tests of wet-weather and dry-weather samples treated with Zetag 7873.

In all cases, very good TSS removals were observed even in the absence of polymer; on average, 70% of suspended solids in wet-weather samples were removed by settling during the jar tests, and 62% of SS in dry-weather samples. The final TSS concentrations ranged from 29-104 mg/L, but were typically below 90 mg/L, so both TSS reduction criteria in the Ontario Ministry of Environment Procedure F-5-5 (50% removal and an average effluent TSS $\leq$ 90 mg/L) could be met under these settling conditions. Previous studies (e.g., Li *et al.*, 2003; Averill *et al.*, 1997) have reported average settleable solids fractions of ~60-70% in southern Ontario wet-weather samples, although this varies with both the sample and surface loading rate. As noted above, the jar test examines TSS removal under ideally quiescent settling conditions, which may be difficult to achieve in the full scale.

For both wet- and dry-weather samples, suspended solids removal was further enhanced with the addition of polymer, with insignificant improvements in TSS removal as flocculant dosage increased. The wet-weather samples appeared to be somewhat more amenable to treatment with polymer than the dry-weather samples. A dosage of 1.0 mg/L of polymer (expressed as product as supplied) resulted in average TSS values after settling of < 28 mg/L in wet-weather samples and < 42 mg/L in dry-weather samples, or TSS removals of 84% and 72%, respectively. Overdosing (i.e. impairment of suspended solids removal at high flocculant doses) was not observed in these tests. Qualitative observations recorded during each jar test indicate that floc size and settling rate generally increased with polymer dose.

5.2.2 Alum

Five of the dry-weather samples and seven of the wet-weather samples (all from the High Lift Station site) were also tested with alum; results for the wet-weather and dry-weather samples are listed in Tables 5.8 and 5.9, respectively. On 03-Jun-04 and 28-Jan-05, replicates of the alum tests could not be performed due to insufficient sample volume; results reflect only a single test for these samples. All other jar tests were performed in duplicate. It should be recognized that due to the small number of samples, the summary statistics below should not be considered particularly meaningful.

Table 5.8: Summary of jar test results for wet-weather samples treated with alum

Sample date	Initial TSS (mg / L)	TSS remaining at specified alum dosage (mg Al / L) 0.0	1.0	2.0	4.0	6.0
09-Jun-03	153	14.3	14.9	7.0	2.7	N/A
11-Jul-03	159	13.5	14.0	9.1	3.0	3.2
15-Jul-03	239	22.7	31.5	8.5	3.8	3.8
05-Aug-03	134	27.5	24.5	17.3	12.0	8.5
02-Mar-04	128	15.6	13.5	3.6	2.1	1.5
06-Mar-04	109	18.7	13.9	3.7	2.6	1.5
09-May-04	73.1	9.4	8.8	4.2	4.0	4.0
Mean	**142**	**17.4**	**17.3**	**7.6**	**4.3**	**3.8**
SD	**52**	**6.1**	**7.8**	**4.8**	**3.5**	**2.6**

Table 5.9: Summary of jar test results for dry-weather samples treated with alum

Sample date	Initial TSS (mg / L)	TSS remaining at specified alum dosage (mg Al / L) 0.0	1.0	2.0	4.0	6.0
16-Jun-03	140	37.0	-	25.0	4.0	1.0
29-Mar-04	80.2	22.3	33.5	16.5	8.1	6.2
03-Jun-04	199	42.1	42.4	32.7	12.9	6.3
25-Jan-05	131	18.9	26.0	19.4	17.3	7.5
28-Jan-05	142	23.3	-	33.9	14.4	8.8
Mean	**138**	**28.7**	**34.0**	**25.5**	**11.3**	**6.0**
SD	**42**	**10.2**	**8.2**	**7.8**	**5.3**	**3.0**

The samples tested with alum form only a subset of the group used for the polymer tests, leading to changes in the mean values of initial TSS in the wet-weather and dry-weather samples. The jar tests with alum also included a flocculation, or slow mixing, step, which further improved SS removal in the control jars (with no coagulant added) over that seen in jar tests with Zetag 7873. Typical SS removals in the control jars of the alum tests with slow mixing were in the range of 79-87%, compared to 60-70% in the polymer tests without slow mixing. Although it has been shown that coagulation with polymers can be effective without a slow mixing step (Li *et al.*, 2003; Young *et al.*, 2003), the reactions leading to floc growth on alum addition are slower, and

a slow mix step is necessary to allow the growth of settleable flocs when alum is added (Amirtharajah and O'Melia, 1990). The result of the added mixing time is that aggregation and natural floc growth are promoted through an increased frequency of interparticle collisions, resulting in lower TSS concentrations after settling in the control jar.

The addition of alum enhanced TSS removal further, once the coagulant demand had been met. Dosages below this threshold concentration resulted in TSS levels equal to or higher than in the control jar, as can be seen in the tables below for the wet-weather samples 09-Jun-03, 11-Jul-03 and 15-Jul-03, and the dry-weather sample 29-Mar-04. Above the threshold dosage, the concentrations of TSS remaining were extremely low. Typical TSS removals with alum were in the range of 88-97% in wet-weather samples and 72-97% in dry-weather samples. Final TSS concentrations ranged from 1-42 mg/L, well below the MOE Procedure F-5-5 goal of 90 mg/L.

In general, the inclusion of a slow mix step greatly improved TSS removal, with very little difference between wet- and dry-weather samples (Fig. 5.86). The addition of alum further enhanced solids removal, leading to extremely low residual TSS levels.

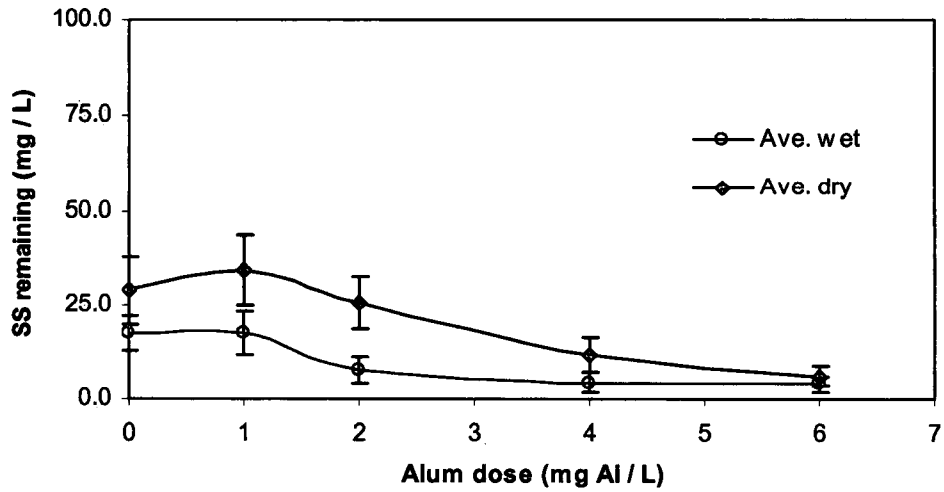

Fig. 5.86: Mean TSS remaining during jar tests of wet-weather and dry-weather samples treated with alum.

5.3 Chemical characterization

5.3.1 Chemical characterization of CSO and dry-weather samples (raw water)

Analysis of TSS and VSS were performed on all samples in-house; additional aliquots of raw water were sent to outside laboratories for analysis of TOC, DOC, COD, TP, TKN, ammonia, and dissolved and total Cu and Zn. All samples after July 16, 2003 were analyzed for BOD, as well. Several samples in each group were also analyzed for Cd, Ni and Cr, but as results for these metals were generally reported as near or below the method detection limit (MDL), later analyses were adjusted to focus on measurable constituents. Chloride was added to the list of analytes during the winter season, when concentrations in runoff would be expected to increase due to application of road salts, and Mn was added in April 2004.

The results are listed in Tables 5.10, 5.11 and 5.13, and summarized for wet-weather and dry-weather samples in Tables 5.12 and 5.14, respectively.

Table 5.10: Chemical analysis results for wet-weather flow samples from the High Lift Station

		Collection Date				
Analysis	**Units**	**09-Jun-03**	**11-Jul-03**	**15-Jul-03**	**05-Aug-03**	**19-Nov-03**
TSS	mg/L	132	136	272	393	373
VSS	mg/L	92	63	162	172	220
TOC	mg/L as C	60.2	38.7	60.4	107.0	68.5
DOC	mg/L as C	17.8	9.9	22.9	22.9	13.1
Total COD	mg/L	228	147	322	394	379
Total BOD	mg/L	86	N/A	N/A	141	138
NH_3	mg/L as N	N/A	6.20	8.26	9.29	6.08
TKN	mg/L as N	N/A	11.1	15.7	18.6	16.3
TP	mg/L as P	2.91	2.21	2.90	3.75	2.84
Chloride	mg/L	N/A	N/A	N/A	N/A	N/A
Cadmium, dissolved	µg/L	N/A	ND	ND	ND	N/A
Cadmium, total	µg/L	N/A	3.30	ND	2.18	N/A
Copper, dissolved	µg/L	N/A	ND	21.90	16.70	ND
Copper, total	µg/L	N/A	31.0	81.4	128.0	67.0
Lead, dissolved	µg/L	N/A	ND	ND	ND	N/A
Lead, total	µg/L	N/A	ND	ND	ND	N/A
Nickel, dissolved	µg/L	N/A	ND	ND	ND	N/A
Nickel, total	µg/L	N/A	9.46	ND	9.81	N/A
Zinc, dissolved	µg/L	N/A	25.0	57.1	20.5	13.8
Zinc, total	µg/L	N/A	110.0	313.0	250.0	151.0

N/A - Data not available

ND – Below detection limit or non-detect

Table 5.10 continued: Chemical analysis results for wet-weather flow samples from the High Lift Station

		Collection Date				
Analysis	**Units**	**11-Dec-03**	**02-Mar-04**	**06-Mar-04**	**20-Mar-04**	**18-Apr-04**
TSS	mg/L	273	129	107	191	97
VSS	mg/L	169	89	69	103	80
TOC	mg/L as C	65.1	33.5	38.7	48.2	22.9
DOC	mg/L as C	14.4	9.1	11.5	7.1	13.9
Total COD	mg/L	332	134	136	134	314
Total BOD	mg/L	102	66	60	72	152
NH_3	mg/L as N	8.32	5.44	4.78	4.13	5.10
TKN	mg/L as N	21.6	14.9	8.2	11.7	18.1
TP	mg/L as P	1.06	1.72	1.26	2.89	3.65
Chloride	mg/L	N/A	218.0	172.0	160.0	67.0
Cadmium, dissolved	µg/L	N/A	N/A	N/A	N/A	N/A
Cadmium, total	µg/L	N/A	N/A	N/A	N/A	N/A
Copper, dissolved	µg/L	ND	ND	ND	ND	ND
Copper, total	µg/L	78.5	35.9	31.1	61.8	104.0
Lead, dissolved	µg/L	N/A	N/A	N/A	N/A	N/A
Lead, total	µg/L	N/A	N/A	N/A	N/A	N/A
Manganese, dissolved	µg/L	N/A	N/A	N/A	N/A	125
Manganese, total	µg/L	N/A	N/A	N/A	N/A	267
Nickel, dissolved	µg/L	N/A	N/A	N/A	N/A	N/A
Nickel, total	µg/L	N/A	N/A	N/A	N/A	N/A
Zinc, dissolved	µg/L	25.1	9.6	6.5	ND	13.9
Zinc, total	µg/L	130.0	65.2	60.7	103.0	296.0

N/A - Data not available

ND – Below detection limit or non-detect

Table 5.10 continued: Chemical analysis results for wet-weather flow samples from the High Lift Station

		Collection Date				
Analysis	**Units**	**21-Apr-04**	**02-May-04**	**09-May-04**	**14-Jul-04**	**27-Jul-04**
TSS	mg/L	123	110	71	470	183
VSS	mg/L	79	68	61	322	130
TOC	mg/L as C	26.4	22.6	21.8	83.0	49.5
DOC	mg/L as C	22.6	13.2	13.0	29.8	14.4
Total COD	mg/L	163	189	142	449	217
Total BOD	mg/L	85	83	72	180	128
NH_3	mg/L as N	8.16	7.40	15.20	15.90	20.9
TKN	mg/L as N	16.4	16.9	22.3	35.4	27.3
TP	mg/L as P	2.29	2.54	2.61	5.63	3.70
Chloride	mg/L	89.5	94.5	108.0	44.0	55.5
Cadmium, dissolved	µg/L	N/A	N/A	N/A	N/A	N/A
Cadmium, total	µg/L	N/A	N/A	N/A	N/A	N/A
Copper, dissolved	µg/L	ND	ND	ND	ND	ND
Copper, total	µg/L	49.6	38.50	20.3	128	41.3
Lead, dissolved	µg/L	N/A	N/A	N/A	N/A	N/A
Lead, total	µg/L	N/A	N/A	N/A	N/A	N/A
Manganese, dissolved	µg/L	N/A	N/A	43.5	63.3	34.6
Manganese, total	µg/L	N/A	N/A	45.1	116	39.2
Nickel, dissolved	µg/L	N/A	N/A	N/A	N/A	N/A
Nickel, total	µg/L	N/A	N/A	N/A	N/A	N/A
Zinc, dissolved	µg/L	8.8	3.50	5.14	ND	4.52
Zinc, total	µg/L	77.8	66.40	41.3	203	48.8

N/A - Data not available

ND – Below detection limit or non-detect

Table 5.11: Chemical analysis results for wet-weather flow samples from Muddy Run and Central Pumping Station sites

		Collection Date and Location			
		MR	CPS	CPS	CPS
Analysis	Units	02-Jul-04	07-Jul-04	14-Jul-04	05-Nov-04
TSS	mg/L	444	604	159	213
VSS	mg/L	197	229	107	96
TOC	mg/L as C	24.8	18.1	46.8	40.0
DOC	mg/L as C	11.9	15.3	15.0	40.0
Total COD	mg/L	416	263	227	290.0
Total BOD	mg/L	86	147	119	110.0
NH_3	mg/L as N	4.95	8.68	11.9	18.0
TKN	mg/L as N	18.3	15.0	21.9	26.0
TP	mg/L as P	2.95	3.15	3.01	3.2
Chloride	mg/L	40.5	75.3	50.3	68.0
Copper, dissolved	µg/L	ND	ND	11.3	ND
Copper, total	µg/L	147	60.7	52.3	160
Manganese, dissolved	µg/L	80.7	130	51.5	110
Manganese, total	µg/L	317	204	79.6	220
Zinc, dissolved	µg/L	14.9	7.46	5.74	6
Zinc, total	µg/L	297	142	98.8	190

N/A - Data not available

ND – Below detection limit or non-detect

MR = Muddy Run; CPS = Central Pumping Station

Table 5.12: Summary of chemical analysis results for wet-weather flow samples from the High Lift Station

Parameter	Units	MDL	n†	ND†	Median	Mean†	SD†	CV†
TSS	mg/L	2.0	15	0	136.0	204	124	0.61
VSS	mg/L	2.0	15	0	91.9	125	73	0.58
TOC	mg/L as C	0.50	15	0	48.2	49.8	24.6	0.50
DOC	mg/L as C	0.50	15	0	13.9	15.7	6.3	0.40
Total COD	mg/L	4.81	15	0	217.0	245	109	0.45
Total BOD	mg/L	1.12	13	0	85.5	105	39	0.37
Ammonia	mg/L as N	0.02	14	0	7.8	8.9	4.9	0.55
TKN	mg/L as N	0.157	14	0	16.7	18	7	0.38
TP	mg/L as P	0.082	15	0	2.84	2.8	1.1	0.40
Chloride	mg/L	0.51	9	0	94.5	112	59	0.53
Diss. Cd	µg/L	1.8	0	3	N/A	N/A	N/A	N/A
Total Cd	µg/L	1.8	2	1	2.7	2.7	N/A	N/A
Diss. Cu	µg/L	9.0	2	12	19.3	19	N/A	N/A
Total Cu	µg/L	9.0	14	0	55.7	64	36	0.56
Diss. Pb	µg/L	25.6	0	3	N/A	N/A	N/A	N/A
Total Pb	µg/L	25.6	0	3	N/A	N/A	N/A	N/A
Diss. Mn	µg/L	1.9	4	0	53.4	67	41	0.61
Total Mn	µg/L	1.9	4	0	80.6	117	106	0.91
Diss. Ni	µg/L	7.3	0	3	N/A	N/A	N/A	N/A
Total Ni	µg/L	7.3	2	1	9.6	9.6	N/A	N/A
Diss. Zn	µg/L	1.9	12	2	11.7	16	15	0.93
Total Zn	µg/L	1.9	14	0	106.5	137	93	0.68

† n = number of results measured above the MDL; ND = number of non-detect values; mean = arithmetic mean of values >MDL; SD = standard deviation; CV = coefficient of variation

N/A - Not applicable

Table 5.13: Chemical analysis results for dry-weather flow samples

		Collection Date			
Analysis	**Units**	**16-Jun-03**	**05-Sep-03**	**09-Oct-03**	**10-Nov-03**
TSS	mg/L	272	113	166	138
VSS	mg/L	162	91	140	119
TOC	mg/L as C	230.0	137.0	111.0	135.0
DOC	mg/L as C	28.1	42.8	49.6	37.6
Total COD	mg/L	347	502	437	304
Total BOD	mg/L	248	239	171	129
NH_3	mg/L as N	N/A	34.5	25.1	22.7
TKN	mg/L as N	N/A	58.2	35.8	32.1
TP	mg/L as P	4.24	5.85	4.04	3.47
Chloride	mg/L	N/A	N/A	N/A	N/A
Cadmium, dissolved	µg/L	N/A	ND	ND	N/A
Cadmium, total	µg/L	N/A	1.81	ND	N/A
Copper, dissolved	µg/L	N/A	34.8	58.0	45.5
Copper, total	µg/L	N/A	79.6	102.0	64.0
Lead, dissolved	µg/L	N/A	ND	ND	N/A
Lead, total	µg/L	N/A	ND	ND	N/A
Nickel, dissolved	µg/L	N/A	ND	ND	N/A
Nickel, total	µg/L	N/A	13.6	11.0	N/A
Zinc, dissolved	µg/L	N/A	31.3	43.1	21.2
Zinc, total	µg/L	N/A	106.0	141.0	100.0

N/A - Data not available

ND – Below detection limit or non-detect

Table 5.13 continued: Chemical analysis results for dry-weather flow samples

		Collection Date			
Analysis	**Units**	**12-Feb-04**	**29-Mar-04**	**19-Apr-04**	**03-Jun-04**
TSS	mg/L	101	83	587	219
VSS	mg/L	76	73	200	158
TOC	mg/L as C	44.7	104.0	28.2	73.2
DOC	mg/L as C	17.7	6.8	17.9	36.8
Total COD	mg/L	225	263	148	383
Total BOD	mg/L	158	71	79	369
NH_3	mg/L as N	21.8	12.9	14.6	21.1
TKN	mg/L as N	30.0	22.8	22.1	37.5
TP	mg/L as P	4.06	2.85	2.87	5.46
Chloride	mg/L	165.0	131.0	108.0	99.0
Cadmium, dissolved	µg/L	N/A	N/A	N/A	N/A
Cadmium, total	µg/L	N/A	N/A	N/A	N/A
Copper, dissolved	µg/L	19.5	11.2	12.2	26.9
Copper, total	µg/L	52.7	37.7	57.4	100.0
Lead, dissolved	µg/L	N/A	N/A	N/A	N/A
Lead, total	µg/L	N/A	N/A	N/A	N/A
Manganese, dissolved	µg/L	N/A	N/A	N/A	51.7
Manganese, total	µg/L	N/A	N/A	N/A	69.9
Nickel, dissolved	µg/L	N/A	N/A	N/A	N/A
Nickel, total	µg/L	N/A	N/A	N/A	N/A
Zinc, dissolved	µg/L	6.19	24.4	10.6	22.5
Zinc, total	µg/L	67.6	52.5	61.3	86.1

N/A - Data not available

ND – Below detection limit or non-detect

Table 5.13 continued: Chemical analysis results for dry-weather flow samples

		Collection Date			
Analysis	**Units**	**12-Jul-04**	**07-Sep-04**	**25-Jan-05**	**28-Jan-05**
TSS	mg/L	241	173	160	158
VSS	mg/L	207	144	133	133
TOC	mg/L as C	45.4	24.0	20.0	16.0
DOC	mg/L as C	28.3	26.0	17.0	14.0
Total COD	mg/L	522	150	340	300
Total BOD	mg/L	380	130	89	91
NH_3	mg/L as N	37.10	27.0	22.0	11.0
TKN	mg/L as N	53.0	44.0	37.0	38.0
TP	mg/L as P	6.57	4.30	3.20	4.50
Chloride	mg/L	65.0	100.0	120.0	110.0
Cadmium, dissolved	µg/L	N/A	ND	ND	ND
Cadmium, total	µg/L	N/A	ND	ND	ND
Copper, dissolved	µg/L	18.4	22	11.0	12.0
Copper, total	µg/L	80.3	81	75.0	66.0
Lead, dissolved	µg/L	N/A	ND	ND	ND
Lead, total	µg/L	N/A	ND	ND	ND
Manganese, dissolved	µg/L	41.4	25	41.0	40.0
Manganese, total	µg/L	45.6	34	51.0	48.0
Nickel, dissolved	µg/L	N/A	ND	ND	ND
Nickel, total	µg/L	N/A	ND	22.00	ND
Zinc, dissolved	µg/L	11.0	10	10.0	9.0
Zinc, total	µg/L	96.6	92	110.0	93.0

N/A - Data not available

ND – Below detection limit or non-detect

Table 5.14: Summary of chemical analysis results for dry-weather flow samples

Parameter	Units	MDL*	n†	ND†	Median	Mean†	SD†	CV†
TSS	mg/L	2.0	12	0	163.2	201	134	0.67
VSS	mg/L	2.0	12	0	136.7	136	43	0.32
TOC	mg/L as C	0.50 / 0.50	12	0	59.3	80.7	64.9	0.80
DOC	mg/L as C	0.50 / 0.50	12	0	27.1	26.9	12.9	0.48
Total COD	mg/L	4.81 / 10.0	12	0	322.0	327	122	0.37
Total BOD	mg/L	1.12 / 5.0	12	0	144.0	179	108	0.60
Ammonia	mg/L as N	0.02 / 0.02	11	0	22.0	22.7	8.2	0.36
TKN	mg/L as N	0.157 / 0.16	11	0	37.0	37	11	0.30
TP	mg/L as P	0.082 / 0.010	12	0	4.15	4.3	1.2	0.27
Chloride	mg/L	0.51 / 0.05	8	0	109.0	112	29	0.26
Diss. Cd	µg/L	1.8 / 5.0	0	5	N/A	N/A	N/A	N/A
Total Cd	µg/L	1.8 / 5.0	1	4	N/A	N/A	N/A	N/A
Diss. Cu	µg/L	9.0 / 6.0	11	0	19.5	25	16	0.63
Total Cu	µg/L	9.0 / 6.0	11	0	75.0	72	19	0.27
Diss. Pb	µg/L	25.6 / 20.0	0	5	N/A	N/A	N/A	N/A
Total Pb	µg/L	25.6 / 20.0	0	5	N/A	N/A	N/A	N/A
Diss. Mn	µg/L	1.9 / 5.0	6	0	40.5	39.7	8.6	0.22
Total Mn	µg/L	1.9 / 5.0	6	0	46.8	49	12	0.25
Diss. Ni	µg/L	7.3 / 10.0	0	5	N/A	N/A	N/A	N/A
Total Ni	µg/L	7.3 / 10.0	3	2	13.6	15.5	5.7	0.37
Diss. Zn	µg/L	1.9 / 5.0	11	0	11.0	18	12	0.64
Total Zn	µg/L	1.9 / 5.0	11	0	93.0	92	25	0.27

* Where two MDLs are listed, the first is that given by the WTC Analytical Laboratory and the second by PSC Analytical (for samples after August 2004)

† n = number of results measured above the MDL; ND = number of non-detect values; mean = arithmetic mean of values >MDL; SD = standard deviation; CV = coefficient of variation

N/A - Not applicable

The results for many of the quantifiable analytes in wet- and dry-weather samples were comparable, although the differences under the two conditions were statistically significant for some constituents. The mean concentrations of TOC (49.8 mg/L wet and 80.7 mg/L dry), DOC (15.7 mg/L wet and 26.9 mg/L dry), COD (245 mg/L wet and 327 mg/L dry), BOD (105 mg/L wet and 179 mg/L dry), ammonia (8.9 mg/L wet and 22.7 mg/L dry), TKN (18 mg/L wet and 37 mg/L dry), and TP (2.8 mg/L wet and 4.3 mg/L dry) were significantly lower in wet weather than in dry weather. Such results are to be expected with the mixing of urban runoff with sewage during wet-weather flows, as the concentrations of organics and nutrients arising primarily from sanitary sewage are diluted by the added volume of water. Interestingly, the solids and metals concentrations were not significantly higher in wet weather than in dry weather, as might be expected when such substances are washed off paved surfaces into the combined sewer system. As noted above, concentrations of Cd, Pb and Ni were typically near or below the MDL and could not be properly quantified.

Typical concentrations of various constituents in weak, medium and strong wastewater are listed in Table 5.15. The dry-weather flow samples (DWF) taken at Niagara Falls (Table 5.15) can be characterized as relatively 'weak' to 'medium' in strength in terms of the concentrations of solids, oxygen-demanding constituents and nutrients (TSS, VSS, TOC, COD, BOD, ammonia, TKN, and TP). On average, the samples proved to be 'strong' in chloride concentration.

Table 5.15: Typical concentrations of various constituents in wastewater of various strengths

Analyte	Units	Typical wastewater*			Niagara DWF (this study)
		Weak	Medium	Strong	
TSS	mg/L	120	210	400	201
VSS	mg/L	95	160	315	136
TOC	mg/L	80	140	260	80.7
COD	mg/L	250	430	800	327
BOD	mg/L	110	190	350	179
Ammonia	mg/L	12	25	45	22.7
TKN	mg/L	20	40	70	37
Total P	mg/L	4	7	12	4.3
Chloride	mg/L	30	50	90	112

*Adapted from Metcalf and Eddy, 2003.

Typical concentrations of a number of constituents of stormwater and CSOs are listed for various studies in Table 5.16. It should be noted that the values listed for lead in Ontario stormwater (Marsalek and Ng, 1989) and under the U.S. Nationwide Urban Runoff Program (NURP; U.S. EPA, 1983) relate to results obtained in the 1980's, which reflect the influence of the use of leaded gasoline (banned in Canada in 1990). The results from the National Stormwater Quality Database (NSQD) program currently underway at the University of Alabama (Pitt *et al.*, 2003) and from samples in the current study indicate that present lead levels are far below these values, and indeed were consistently below the level of detection in Niagara Falls' wet-weather flows.

Table 5.16: Typical concentrations of various analytes in stormwater and CSO

Analyte	Units	Stormwater			CSOs		
		Ontario range or mean	NURP median[3]	NSQD median[4]	Ontario[1]	Typical[5]	Niagara CSO (this study)
TSS	mg/L	170[1]	100	58	190	270-550	204
COD	mg/L	N/A	65	53	N/A	260-480	245
BOD	mg/L	14[1]	9	8.6	41	60-220	105
Total N	mg/L	3.5[1]	N/A	N/A	8.3	N/A	N/A
Ammonia	mg/L	0.30-0.75[2]	N/A	0.44	N/A	N/A	8.9
TKN		N/A	1.5	1.4	N/A	N/A	18
Total P	mg/L	0.35[1]	0.33	0.27	1.4	1.2-2.8	2.8
Chloride	mg/L	230-340[2]	N/A	N/A	N/A	N/A	112
Copper	µg/L	43.4-47.2[2]	34	16	N/A	N/A	64
Lead	µg/L	97-233[2]	144	16	N/A	N/A	N/A
Zinc	µg/L	234-307[2]	160	116	N/A	N/A	137

N/A - Data not available

Sources of data:
1 Waller and Novak, 1981
2 Marsalek and Ng, 1989
3 U.S. EPA Nationwide Urban Runoff Program, 1983
4 Pitt *et al.*, 2003
5 Metcalf and Eddy, 2003

In general, the constituents of the wet-weather flows observed at Niagara Falls during this study were present at typical concentrations for such samples. At 204 mg/L, the mean TSS concentration was somewhat lower than the typical CSO values reported by Metcalf and Eddy (2003), but was very close to the mean found for Ontario CSO (Waller and Novak, 1981). Conversely, the mean BOD and TP concentrations were somewhat higher than seen in the Ontario study, but were roughly within the range reported as typical for CSOs. Zinc was present at a lower concentration than seen in Ontario stormwater (Marsalek and Ng, 1989), while the mean concentrations of copper and TKN were higher than reported in any of the stormwater studies. Ammonia and chloride were present at concentrations between typical values for stormwater and wastewater.

5.3.2 Chemical characterization of elutriation apparatus fractions

Chemical analyses were also performed on a number of samples taken from each of the elutriation apparatus columns. The fractions have been measured and reported for eleven wet-weather samples. Average distributions for the wet-weather samples are shown in Fig. 5.87. The settling velocity distributions of most constituents quite closely follow that of TSS, emphasizing the importance of solids removal in reducing the contaminant load of an event. The BOD distribution was not measured in the fractions, as sample volume in the smallest columns (i.e., those with the highest upward flow rates) was insufficient.

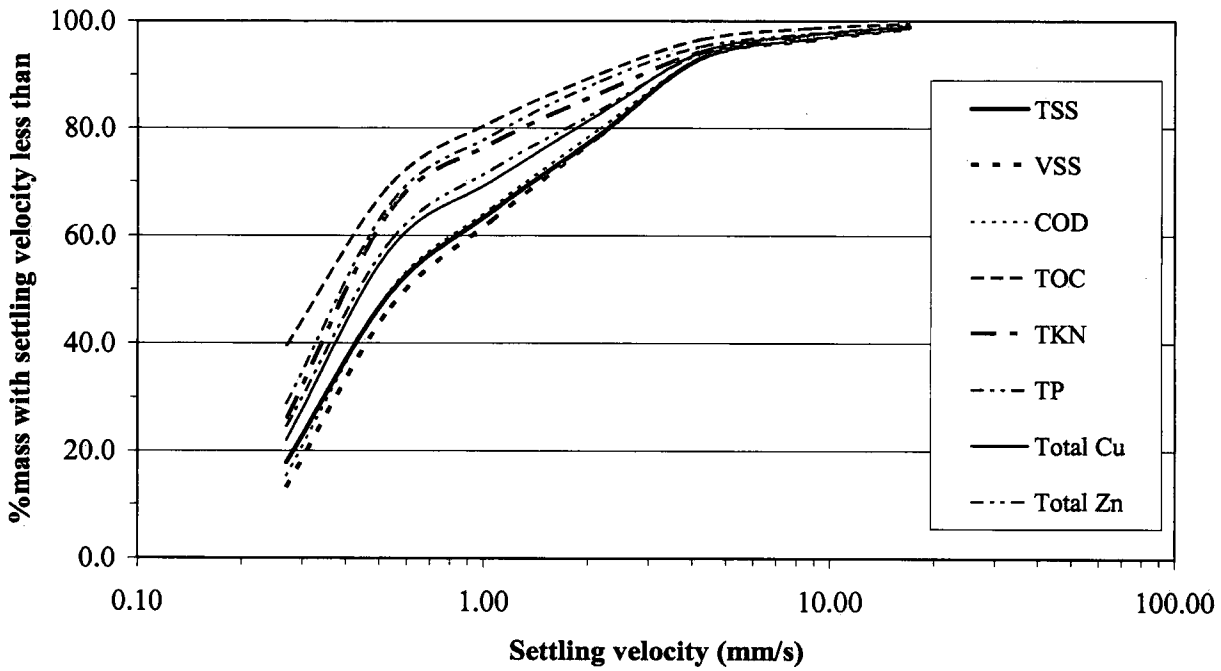

Fig. 5.87: Average settling velocity distributions for wet-weather constituents fractionated by elutriation.

The mean and standard deviation results are summarized in Table 5.17 for each collected fraction of selected constituents for the wet-weather samples.

Table 5.17: Elutriation fraction chemistry results: wet weather summary

	Analyte	TSS		VSS		COD		TOC	
	MDL	2.3		2.3		4.81		0.5	
	Conc. units	mg/L		mg/L		mg/L		mg/L	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Raw CSO	Concentration	217	135	129.3	73.6	234.1	95.9	51.5	16.7
	Mass (mg)	9759	6106	5793	3329	10485	4377	2307	766
Column 1	Concentration	278	233	217	179	276	161	36.4	20.2
	Mass (mg)	97	77	77	60	96	47	12.8	6.8
17 mm/s	Mass %	1.15	0.55	1.36	0.55	1.00	0.27	0.50	0.26
Column 2	Concentration	320	313	237	241	382	324	36.4	15.6
	Mass (mg)	182	170	133	134	213	177	21.4	8.9
8.7 mm/s	Mass %	2.06	0.81	2.21	0.98	2.13	1.29	0.91	0.41
Column 3	Concentration	299	255	223	209	404	253	41.0	19.6
	Mass (mg)	302	222	203	180	367	215	44.4	29.5
4.24 mm/s	Mass %	3.68	2.20	3.36	1.52	3.76	1.70	2.00	1.75
Column 4	Concentration	748	1130	587	875	958	1471	69.1	56.4
	Mass (mg)	1410	1946	1044	1532	1698	2575	143.3	107.3
2.17 mm/s	Mass %	14.24	9.64	14.41	10.39	13.22	10.75	6.41	5.57
Column 5	Concentration	320	328	236	241	389	319	58.6	50.8
	Mass (mg)	1216	1207	905	888	1486	1177	219.9	186.8
1.06 mm/s	Mass %	14.36	9.32	15.72	8.36	14.73	8.68	8.99	7.84
Column 6	Concentration	177	94	123	54	225	93	42.8	18.2
	Mass (mg)	1109	621	776	392	1420	678	263.4	114.3
0.54 mm/s	Mass %	15.09	9.00	16.30	8.00	15.36	6.20	11.65	8.84
Column 7/8	Concentration	121	47	72	23	141	39	41.1	18.4
	Mass (mg)	2443	1251	1604	502	3142	866	828.7	472.7
0.27 mm/s	Mass %	31.64	13.50	33.51	8.88	34.60	7.51	30.08	11.61
Unsettled	Concentration	28	25	14	9	34	16	25.0	19.9
	Mass (mg)	1291	1134	626	430	1566	740	1138.3	907.0
<0.27 mm/s	Mass %	17.79	18.58	13.14	9.24	15.21	9.51	39.45	20.68
	Recovery	90	23	95	24	95	21	119	43

Table 5.17 continued: Elutriation fraction results: wet weather summary

	Analyte	TKN		TP		Total Cu		Total Zn	
	MDL	0.157		0.082		9.0		1.9	
	Conc. units	mg/L		mg/L		µg/L		µg/L	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Raw CSO	Concentration	18	9.95	2.89	1.35	56	35.92	116	92.56
	Mass (mg)	785	445	129	61	2489	1624	5235	4234
Column 1	Concentration	27	14.8	5.27	3.65	85	61.16	151	124.30
	Mass (mg)	10	5.14	1.87	1.22	29	19.35	51	37.59
17 mm/s	Mass %	1.23	0.83	1.07	0.30	0.94	0.41	0.83	0.29
Column 2	Concentration	25	12.0	4.56	3.49	98	71.09	199	142.83
	Mass (mg)	15	7.75	2.58	1.95	58	40.12	115	75.50
8.7 mm/s	Mass %	1.66	0.52	1.44	0.38	1.74	0.57	1.76	0.51
Column 3	Concentration	24	11.9	4.26	2.98	97	60.44	206	167.04
	Mass (mg)	29	22.7	3.95	2.72	109	90.53	233	228.27
4.24 mm/s	Mass %	2.84	1.20	2.25	0.61	3.12	1.27	3.50	2.44
Column 4	Concentration	34	34.7	7.66	10.89	210	318.68	332	435.80
	Mass (mg)	81	87.0	13.6	19.1	423	560.1	714	833.5
2.17 mm/s	Mass %	7.69	5.3	6.51	4.76	11.4	9.6	10.5	8.7
Column 5	Concentration	22	13.8	4.64	3.62	105	94.67	177	148.60
	Mass (mg)	83	56.1	17.8	13.7	396	349.3	662	533.2
1.06 mm/s	Mass %	9.4	4.6	10.1	3.9	12.6	8.5	11.1	6.0
Column 6	Concentration	17	9.23	3.29	1.24	58	32.99	126	93.53
	Mass (mg)	110	64.4	20.7	8.9	362	214.3	774	563.1
0.54 mm/s	Mass %	12.4	4.8	12.7	3.9	12.5	6.5	13.2	6.2
Column 7/8	Concentration	17	6.15	2.68	1.11	50	22.44	103	70.45
	Mass (mg)	340	180	60.1	24.9	1016	574.7	2090	1624.6
0.27 mm/s	Mass %	38.9	13.4	37.2	8.6	35.6	16.2	34.6	12.9
Unsettled	Concentration	6	6.44	1.12	1.01	37	28.95	39	43.96
	Mass (mg)	261	290	51.7	46.2	1694	1290.6	1783	2002.9
<0.27 mm/s	Mass %	25.9	17.9	28.7	15.1	22.0	25.1	24.4	16.4
	Recovery	104	13	142	60	123	53	116	33

As the columns increase in size and volume from Column 1 to 7, the measured concentration of an analyte may have decreased, but the total mass of that analyte collected in the column typically increased. In general, only a small portion of each constituent is collected in the first four elutriation columns. The bulk of the mass of each constituent is collected in the final four fractions, or with solids possessing a settling velocity of 1.06 mm/s or less. One might expect this result for analytes associated with solids; as the relative proportion of solids increases in a fraction, so does the total mass of associated contaminant in that fraction. With the exception of TP and Cu, typical recoveries are quite good.

Treating the above data in the same way as shown for TSS in Section 5.1, an empirically fitted equation (equation 5) can be developed for the average distribution of each constituent. Fitted curves are shown with the data for TOC and COD in Fig. 5.88. The values of α and β are provided for individual constituents in wet-weather samples in Table 5.18. Note that the average values of α and β for TSS are not identical to those given for wet-weather samples in section 5.1.5, as the samples examined for elutriation fraction chemistry form only a subset of those tested for settleability alone.

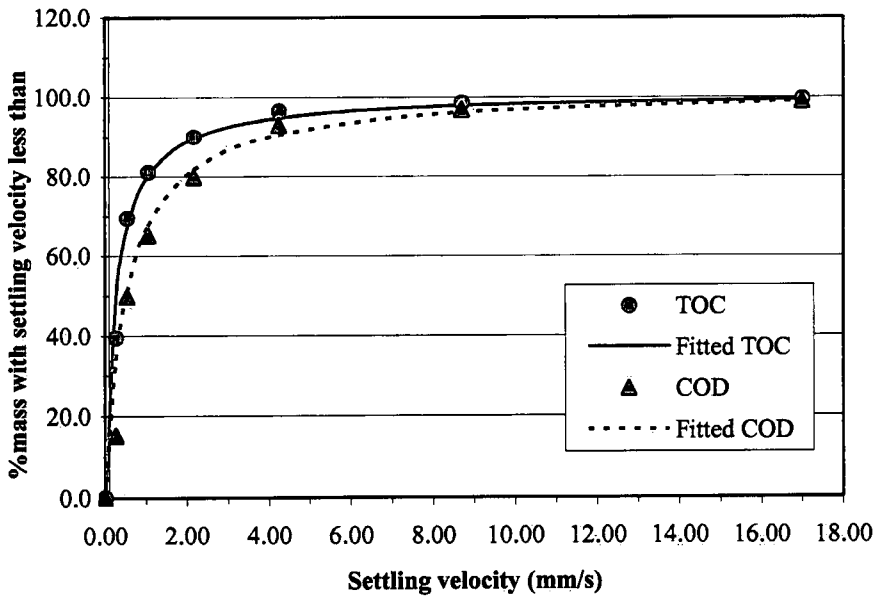

Fig. 5.88: Typical match between equation 5 and measured data for TOC and COD.

Table 5.18: Values of α, β for the average distributions of individual constituents

Constituent	α	β
TSS	0.0054	0.0098
VSS	0.0059	0.0098
COD	0.0053	0.0098
TOC	0.0027	0.0099
TKN	0.0034	0.0099
TP	0.0030	0.0099
Total Cu	0.0044	0.0098
Total Zn	0.0042	0.0098

Using the fitted curve, the surface loading rates for given removals of the constituents can also be estimated, as shown in Fig. 5.89.

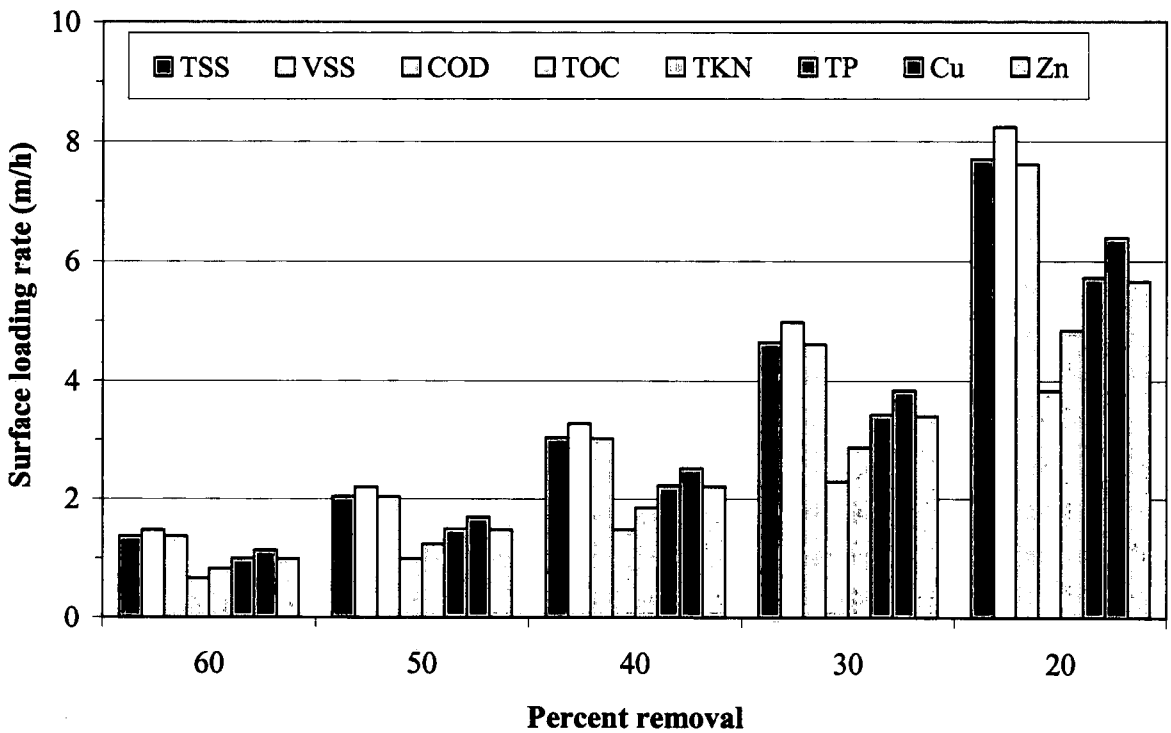

Fig. 5.89: Surface loading rates given by the elutriation apparatus for individual constituents.

The removals of many constituents of the wet-weather samples were closely correlated to the removal of TSS, particularly those of VSS, COD, and Cu. Removals of TOC, TKN, TP, and Zn were lower than for the other constituents in each elutriation apparatus chamber, resulting in weaker correlations between the removals of those constituents and that of TSS, and lower values of α for the fitted curves. The nutrients tend to have higher proportions of dissolved material or to be associated with lower density, less settleable solids. Surprisingly, VSS and COD removal appear to be more closely tied to that of TSS than to that of TOC; this indicates the difficulty of using these parameters interchangeably when describing the organic content of wastewater systems. As mentioned above, BOD could not be measured in all columns, so it is not possible to know if the removal of BOD would better correlate with that of TOC or of COD. As might be expected, significantly lower surface loading rates would be required to achieve comparable removals of TOC, TP, TKN, and Zn than for TSS, VSS, COD, and Cu.

6. Conclusions

Characteristics of both wet-weather (CSOs) and dry-weather (municipal sewage) flows at the Niagara Falls high lift station and sewage treatment plant were determined through laboratory testing of samples collected at the plant between July 2003 and January 2005. Specifically, the following conclusions can be drawn:

1. Settleability of both dry-weather and CSO samples was assessed by four methods, including three settling column based methods, Aston Column Method (ACM), Brombach Column Method (BCM) and U.S. EPA Column Method (EPACM), and a newly proposed elutriation apparatus method (EAM). Test results were processed by the same procedure and approximated by a single empirical equation with fitted parameters. Visual comparisons of entire settling velocity distributions for the four methods tested showed large differences in results obtained with various methods. Recognizing the primary interest in these results with respect to the Ontario Procedure F-5-5, requiring TSS removal of 50%, more refined comparisons of the four methods focused on this TSS removal rate and the corresponding surface load. For dry-weather samples and 50% TSS removal, the ACM, BCM and EPACM

produced fairly similar results, with mean surface loads of 1.16, 0.92 and 0.8 m/h, respectively. The EAM indicated a somewhat higher rate of 1.55 m/h. The small number of samples prevented calculation of meaningful standard deviations, but EAM and BCM produced the least variation in results. For CSO samples, the average surface load rates for 50% TSS removal were 2.01, 1.78, 1.42 and 1.59 m/h, for EAM, ACM, BCM and EPACM, respectively. Such rates are appreciably higher than those observed for dry-weather samples. At 95% level of confidence, the differences among the surface loads produced by these four methods were not statistically significant. Thus, considering the variability between samples, the results indicate that any of the four methods (EAM, ACM, BCM or EPACM) would be acceptable and produce comparable designs. The final choice within this group would depend on other considerations. The EAM indicated somewhat higher settleabilities but produces the most consistent results (even for older samples), can be used for testing chemical addition, and is undergoing further development for assessing floatables; the main advantage of ACM is the best assessment of floatables among the methods tested; and the main advantage of BCM is the small volume of samples required (1 L) and a relatively simple apparatus.

2. Settleability of dry-weather and CSO samples with chemical aids was assessed by jar testing. Recognizing that this procedure approximates ideal settling conditions and therefore overestimates field solids removals, it was of interest to note that high removals of TSS were achieved in the Niagara Falls CSO samples with low polymer dosages. Without any additions, 70% of TSS settled in jar tests after 20 minutes; with polymer addition of 1 mg/L, this removal increased to 84% and changed little with larger polymer dosages (2, 4, and 6 mg/L). Inclusion of a slow mix phase further improved settleability, and addition of low dosages of alum resulted in extremely low TSS values. Thus, the data indicate that Niagara Falls CSOs may be well suited to chemically aided settling, with relatively inexpensive low dosages of coagulant.

3. Dry-weather flow and CSO chemical characteristics – the municipal sewage at this site is characterized by relatively weak strength, with mean concentrations of TSS (201 mg/L), VSS (136 mg/L), TOC (81 mg/L), BOD (179 mg/L), COD (328 mg/L), TP (4.3 mg/L), TKN (37

mg/L) and NH_3 (23 mg/L) being comparable to those listed in common handbooks for weak- to medium-strength sewage. Chloride concentration (112 mg/L) was elevated to the "strong sewage" value. CSO samples related well to the composition of municipal sewage; as expected, they contained lower concentrations of organic carbon and oxygen-demanding substances (mean concentrations of TOC = 49.8 mg/L, DOC = 15.7 mg/L, BOD = 105 mg/L and COD = 245 mg/L) and nutrients (mean concentrations NH_3= 8.9 mg/L, TKN = 18.2 mg/L, and TP = 2.8 mg/L) typically associated with sewage. Variability in concentrations was not excessive, with a mean coefficient of variation (i.e., standard deviation/mean) of about 0.41 for dry-weather samples and 0.50 for CSOs.

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8. References

Aiguier, E.; Chebbo, G.; Bertrand-Krajewski, J-L.; Gagné, B.; and Hedges, P. (1998). Analysis of the methods for determining the settling characteristics of sewage and stormwater solids. Water Sci. Tech. Vol. 37, No. 1, pp 53-60.

Aiguier, E.; Chebbo, G.; Bertrand-Krajewski, J-L.; Hedges, P.; and Tyack, N. (1996). Methods for determining the settling velocity profiles of solids in storm sewage. Water Sci. Tech. Vol. 33, No. 9, pp 117-125.

American Public Health Association (APHA) (1998). Standard methods for the examination of water and wastewater, 20th edition. L. Clesceri, A. Greenberg, and A. Eaton, eds. American Public Health Association, Washington, D.C.

Amirtharajah, A. and O'Melia, C.R. (1990). "Coagulation Processes: Destabilization, Mixing and Flocculation" in Water Quality and Treatment. 4th ed. McGraw Hill, Toronto, pp 269-365.

Andoh, R.Y.G. and Smisson, R.P.M. (1996). The practical use of wastewater characterization in design. Water Sci. Tech. Vol. 33, No. 9, pp 127-134.

Averill, D.; Mack-Mumford, D.; Marsalek, J.; Andoh, R.; and Weatherbe, D. (1997). Field facility for research and demonstration of CSO treatment technologies. Water Sci. Tech. Vol. 36, No. 8-9, pp 391-396.

Bolto, B.A.; Dixon, D.R.; Gray, S.R.; Chee, H.; Harbour, P.J.; Ngoc, L.; and Ware, A.J. (1996). The use of soluble organic polymers in waste treatment. Water Sci. Tech. Vol. 34, No. 9, pp. 117-124.

Hennis, S.; Brown, D.; Vasconcellos, S.R.; and Gucciardi, J.M. (2001). Polymer technology boosts wastewater treatment performance. Chemical Processing (On-line). Accessed April 22, 2004 at <http://www.chemicalprocessing.com>.

Krishnappan, B.G.; Marsalek, J.; Exall, K.; Stephens, R.P.; Rochfort, Q.; and Seto, P. (2004). A water elutriation system for measuring settling velocity distribution of suspended solids in combined sewer overflows. Water Qual. Res. J. Canada. Vol. 39, No. 4, pp. 432-438.

Li, J.; Dhanvantari, S.; Averill, D.; and Biswas, N. (2003). Windsor combined sewer overflow treatability study with chemical coagulation. Water Qual. Res. J. Canada. Vol. 38, No. 2, pp 317-334.

Marsalek, J. and Ng, H.Y.F. (1989). Evaluation of pollution loadings from urban non-point sources: methodology and applications. J. Great Lakes Res. Vol. 15, No. 3, pp 444-451.

Marsalek, J.; He, C.; Rochfort, Q.; Exall, K.; Wood, J.; Krishnappan, B.G.; Seto, P.; and Chessie, P. (2004). Upgrading of the North Toronto CSO storage and treatment facility. In: J. Marsalek, D. Sztruhar, M. Giulianelli and B. Urbonas (eds), Enhancing urban environment by environmental upgrading and restoration. NATO Science Series Vol. 43, Kluwer Academic Publishers, Boston, pp 111-121.

Metcalf and Eddy. (2003). Wastewater Engineering: Treatment and Reuse. 4th Ed. McGraw Hill, Toronto.

Michelbach, S. and Wöhrle, C. (1992). Settleable solids in a combined sewer system – measurement, quantity, characteristics. Water Sci. Tech. Vol. 25, No. 8, pp 181-188.

Michelbach, S. and Wöhrle, C. (1993). Settleable solids in a combined sewer system, settling characteristics, heavy metals, efficiency of stormwater tanks. Water Sci. Tech. Vol. 27, No. 5-6, pp 153-164.

Michelbach, S. and Wöhrle, C. (1994). Settleable solids from combined sewers: settling, stormwater treatment, and sedimentation rates in rivers. Water Sci. Tech. Vol. 29, No. 1-2, pp 95-102.

O'Connor, T.P.; Fischer, D.; Field, R.; Cigana, J.; Gagné, B.; and Couture, M. (2002). Testing solids settling apparatuses for design and operation of wet-weather flow solids-liquid separation processes. EPA/600/R-02/090. Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Odegaard, H. (1988). Coagulation as the first step in wastewater treatment. In H.H. Hahn. and R. Klute (eds.). Pretreatment in Chemical Water and Wastewater Treatment. Springer-Verlag, Berlin, pp 249-260.

OMOE (Ontario Ministry of the Environment). (Undated). Procedure F-5-5, Determination of treatment requirements for municipal and private combined and partially separated sewer systems. 8 p.

Pisano, W.C. (1996). Summary: United States "sewer solids" settling characterization methods, results, uses and perspective. Water Sci. Tech. Vol. 33, No. 9, pp 109-115.

Pisano, W.C. and Brombach, H. (1996). Solids settling curves – Wastewater solids data can aid design of urban runoff controls. Water Env. Tech., Vol. 8, No. 4, pp 27-33.

Pitt, R.; Maestre, A.; and Morquecho, R. (2003). Compilation and review of nationwide MS4 stormwater quality data. Water Environment Federation Technical Exposition and Conference Proceedings, Los Angeles, October 11-15, 2003.

Rasmusen, M.R. and Larsen, T. (1996). A method for measuring sludge settling characteristics in turbulent flows. Water Res. Vol. 30, No.10, pp 2363-2370.

Tyack, J.N.; Hedges, P.D.; and Smisson, R.P.M. (1993). A device for determining the settling velocity grading of storm sewage. 6th Int. Conf. on Urban Storm Drainage. Niagara Falls, Ontario, Canada, pp 1805-1810.

U.S. Environmental Protection Agency (EPA). (1983). Results of the Nationwide Urban Runoff Program Volume I - Final Report. Water Planning Division, U.S. EPA, Washington, DC.

Waller, D.H. and Novak, Z. (1981). Pollution loading to the Great Lakes from municipal sources in Ontario. J of WPCF, Vol. 53, No. 3, pp 387-395.

Walling, D.E. and Woodward, J.C. (1993). Use of a field-based water elutriation system for monitoring the in-situ particle size characteristics of fluvial suspended sediment. Water Res., Vol. 27, No. 9, pp 1413-1421.

Wood, J.; Yang, M.; Rochfort, Q.; Chessie, P.; Marsalek, J.; and Seto, P. (2004). Feasibility of stormwater treatment by conventional and lamellar settling with and without polymeric flocculant addition. In: Proc. of NOVATECH 2004, 5th Inter. Conf. on Sustainable Techniques and Strategies in Urban Water Management, June 6-10, 2004, Lyon, France, pp 227-234.

Young, S.; Stanley, S.J.; and Smith, D.W. (2003). Effect of mixing on the kinetics of polymer-aided flocculation. J. Water Supply. Vol. 49, pp 1-8.

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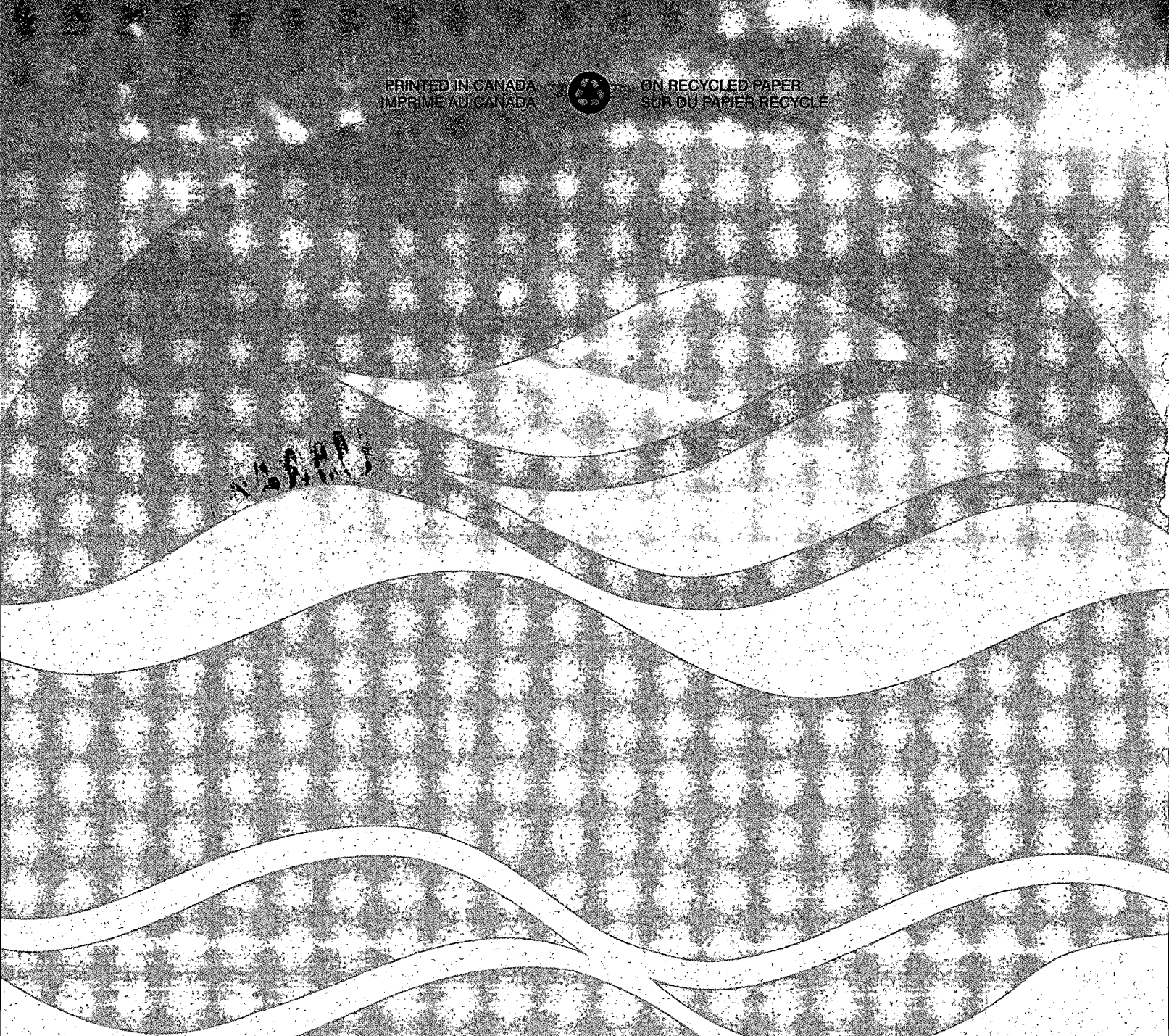

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