

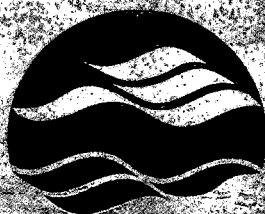
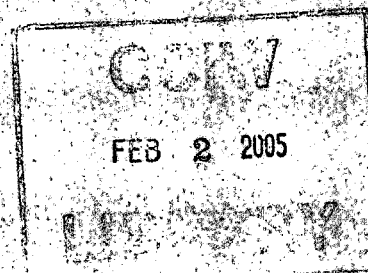
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**EVALUATION OF CSO TREATABILITY
FOR THE CITY OF WELLAND**

INTERIM REPORT

K. Exall, B.G. Krishnappan, J. Marsalek,
Q. Rochfort, P. Seto and M. Baker

NWRI Technical Note No. TN04-004

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Interim Report

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Preamble

The City of Welland, in partnership with the Regional Municipality of Niagara and the Great Lakes Sustainability Fund, has been studying ways to address the problem of combined sewer overflows (CSOs) discharging into the Welland River since February 2000. 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. 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 interim report summarizes the Institute's activities and progress to-date. 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, two column-based methods and the EAM provided comparable data, while one method indicated somewhat lower settleabilities. Treatability of dry-weather and CSO samples with chemical aids was assessed by jar testing. Data indicate that Welland CSOs may be well suited to chemically aided settling, with relatively inexpensive low dosages of a polymeric coagulant. Chemical characterization of the samples indicates that the municipal sewage at this site is of relatively weak strength and there were few statistically significant differences between the dry-weather and CSO water quality data. The results will be used by the study partners for the planning and set up of a subsequent pilot-scale study, and eventual design of a full-scale CSO treatment facility.

Préambule

La ville de Welland, en partenariat avec la Municipalité régionale de Niagara et du Fonds de durabilité des Grands Lacs, a étudié les moyens de faire face au problème des trop-pleins d'égouts unitaires (TPEU), déversés depuis février 2000 dans la rivière Welland. 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'INRE 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 résume les activités de l'Institut et les progrès accomplis jusqu'ici. 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. Aux fins d'applications pratiques, deux des méthodes utilisant les colonnes et l'EAM ont donné des résultats comparables, alors que, pour la troisième, les valeurs de décantabilité étaient un peu plus faibles. 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 Welland peuvent être traités efficacement par décantation assistée chimiquement, avec utilisation de faibles doses d'un coagulant polymérique, 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 n'y a que peu de 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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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 Welland River watershed is located within the Niagara River AOC and it is the largest and most stressed watershed within the jurisdiction of the Niagara Peninsula Conservation Authority. One of the primary goals identified in the Stage II Remedial Action Plan (RAP) report was the reduction and virtual elimination of combined sewer overflows (CSOs).

In February 2000, the City of Welland, in partnership with the Regional Municipality of Niagara and the Great Lakes Sustainability Fund, carried out a study to address the problem of CSOs discharging into the Welland River. Several possible solutions were evaluated in order to comply with the Ontario Ministry of Environment's CSO control policy (e.g., system optimization, sewer separation, detention storage and high rate treatment). Phases 1 and 2 of the Class Environmental Assessment (EA) Study to assess alternative solutions for CSO control identified high rate treatment as the preferred option for addressing the CSO discharges into the Welland River. A follow-up study, initiated in 2002 as Phases 3 and 4 of the Class EA process, was aimed at identifying specifically the preferred high rate CSO treatment technology to be used. Based on the evaluations completed to date, high rate sedimentation technology in the form of a retention treatment basin (RTB) has been highlighted as potentially the most promising technology for the control of Welland CSO.

For the effective design of such a treatment process, it is imperative to first understand the CSO characteristics with respect to chemical composition and settleability, with and without chemical additions. Towards that end, the City has retained a consultant (XCG Consultants Ltd.) to collect CSO characteristics data for the engineering design, and at the same time, initiated a joint study with the National Water Research Institute (NWRI) to further expand the database on CSO settleability and treatability. This interim report summarizes the Institute's activities and progress to-date, including results obtained so far.

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 at the Welland STP. 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.

Thus it is important to note that the joint NWRI-Welland study, described in the report that follows, does not duplicate but rather complements the on-going study by XCG. This report should enhance the completeness of the practical engineering data needed to develop the design concept for the high-rate CSO treatment in Welland and increase the confidence in performance projections.

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 Welland CSO samples. Samples were to be collected at the Welland STP by XCG staff for about 15 wet-weather events (overflows), and delivered to NWRI for testing. Each of the first five CSO samples was to be tested by all four methods, and the results of the three different of 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 are valid and provide additional information not available from the conventional methods. Thereafter, only the EAM would be applied to the remaining 10 CSO samples. 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), ammonia, total Kjeldahl nitrogen (TKN), total phosphorus (TP), trace metals and, if feasible, arrangements would be made for acute toxicity testing at the Ministry of the Environment (MOE) laboratories.

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. This testing by NWRI is intended to extend the similar XCG efforts by putting more emphasis on different types/dosages of polymers and metal salts. Jar testing should help in selecting the “best” coagulants/flocculants to be used for treating Welland CSOs and their optimum dosages. Such data obtained from the jar tests would then be applied to treat the CSO samples and the resulting improvement in solids settling would be measured by the EAM.

3. Experimental Methods

3.1 Sample Collection and Preparation

The Welland CSO samples were collected by the City of Welland and their consultant XCG Ltd. using three autosamplers (American Sigma Model 900) activated when the wastewater plant

inflow exceeded a flow rate of $Q = 55,000 \text{ m}^3/\text{d}$ ($0.63 \text{ m}^3/\text{s}$). The samplers were programmed to collect 3.75 L aliquots every 5 minutes during the first 2 hours of the elevated flows. Samples were pumped into 100 L plastic containers and subsequently transferred into carboys. The total collected sample volume was transported to the XCG office in Oakville, Ontario, to be thoroughly mixed and divided into 25 L sub-samples. Four of these sub-samples (100 L in total) were transported without refrigeration to NWRI in Burlington (driving time about 20 minutes), where the samples were stored at 4°C in a dark walk-in refrigerator until tested. Samples were usually received one day after the event. In two cases, March 30th and April 21st, 2004, NWRI was not notified of sample availability from XCG, and the sample transfer to the laboratory was delayed.

Prior to testing, the carboys were emptied into a mixing drum and the sample was mixed/homogenized by continuous pumping through a $\frac{1}{2}$ 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 ($20^\circ\text{C} \pm 1^\circ\text{C}$). At the start of each test, a whole-water sample of the well mixed sewage was collected and analyzed for TSS to determine total solids in the sample at the start of the test.

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 Aston column, 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 6 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 in a small volume of tap water, 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.

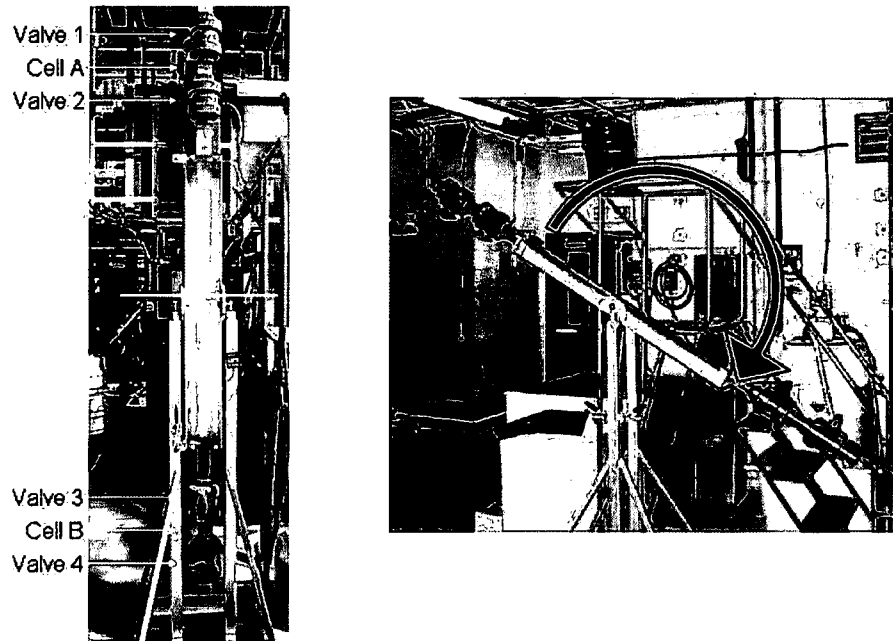


Fig. 3.1: Aston column: components and column rotation

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 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.

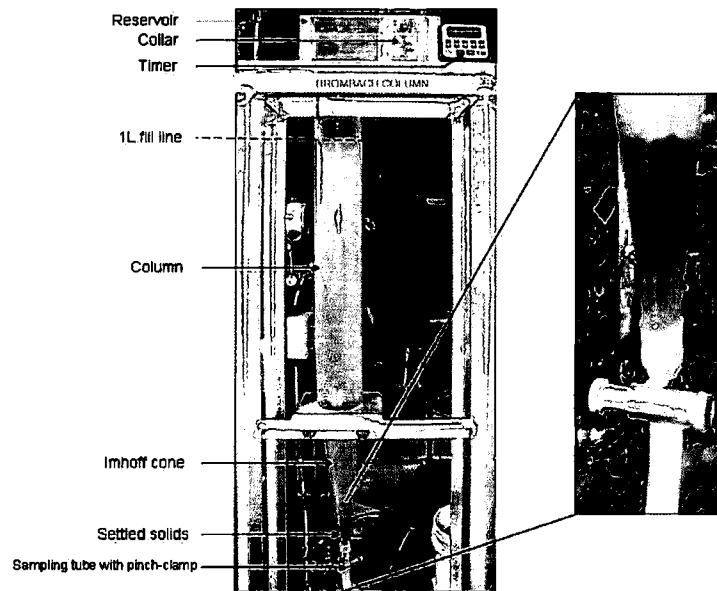


Fig. 3.2: Brombach column: overall view and a detailed view of the Imhoff cone

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 (Fig. 3.3) and a drain valve at the bottom. During the tests, it is quickly filled from the top with well mixed sewage. At set time intervals, samples are collected from the top, centre and bottom side ports. 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. As the test progresses, larger sample volumes may have to be withdrawn to maintain an appropriate accuracy of TSS determinations. At the conclusion of the test, a sample of the settled solids (accumulated on the bottom of the column), unsettled solids (remaining in the column), and a residual column flush are collected, analyzed for TSS, and the corresponding masses are used in mass balance calculations.

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 subsample 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. 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.

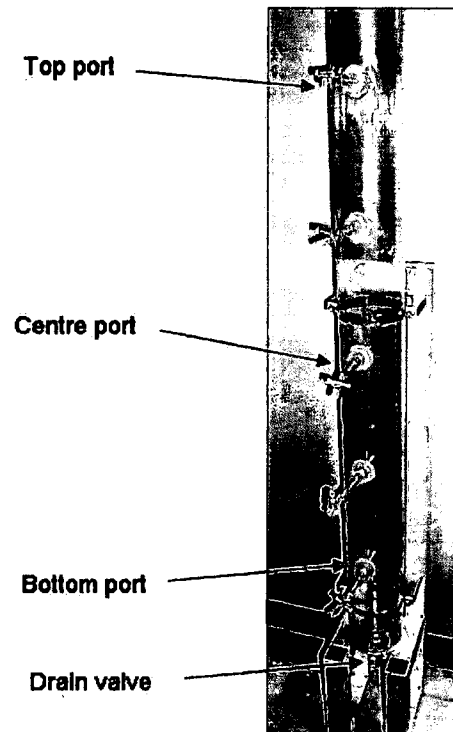


Fig. 3.3: U.S. EPA settling column

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 a 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 in press) used such a system and developed a protocol for measuring the settling velocity distribution of CSO solids. The Elutriation Apparatus Method used for the Welland samples is based on this protocol. The apparatus consists of eight cylinders (instead of four) to provide higher resolution of settling velocity distributions (first seven columns) and to trap the floatable material (8th 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 is designed 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. The masses of solids collected in each column (and effluent carboys) are determined using a conventional TSS analysis (APHA 1998).

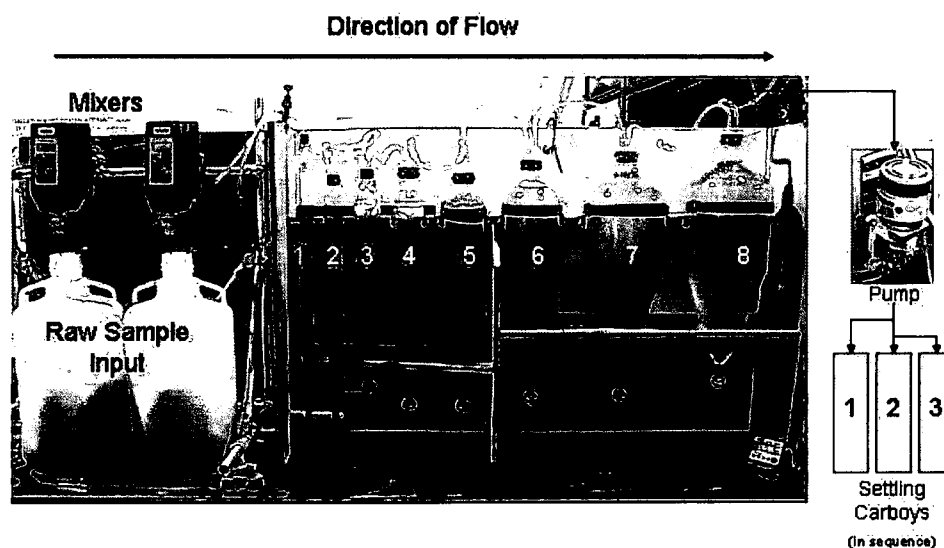


Fig. 3.4: Elutriation apparatus configuration

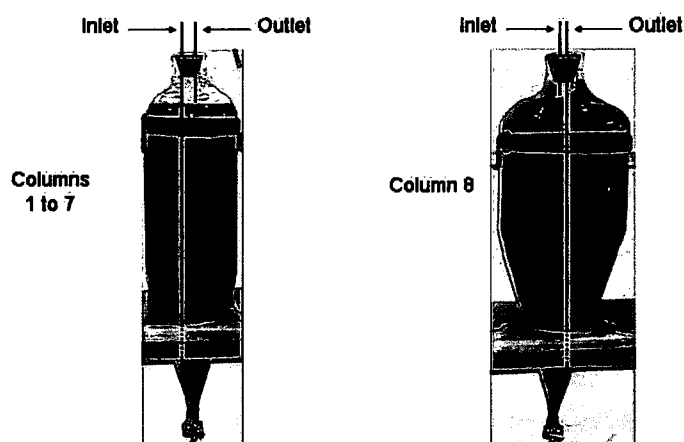


Fig. 3.5: Elutriation apparatus flow arrangements: upward flow in columns 1-7 and downward flow in column 8

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 for 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 Al / L). The polymer flocculant chosen for the present tests was a high molecular weight, low cationic charge polyacrylamide, Zetag 7873 (CIBA) that has previously been shown to be successful in stormwater and CSO treatment studies (e.g. Wood *et al.*, 2004; Marsalek *et al.*, 2003; 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 contaminant removals that can be achieved 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 Welland 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 $20 (\pm 2) ^\circ\text{C}$. 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.

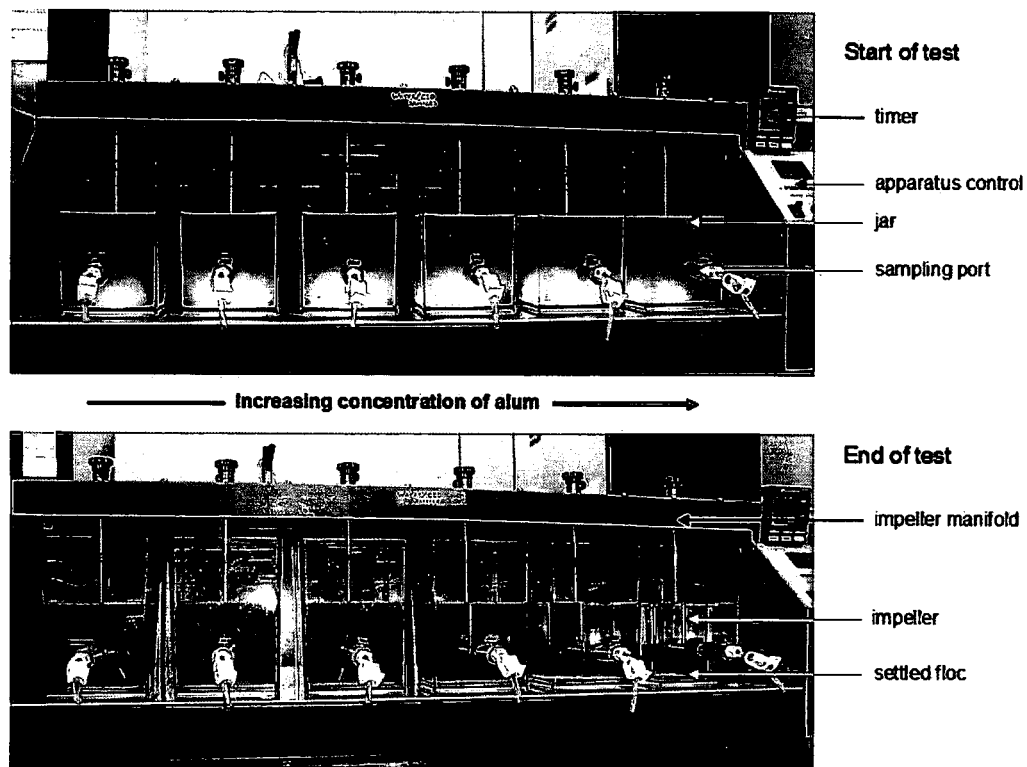


Fig. 3.6: Jar testing apparatus set-up.

3.4 Analytical methods

Conventional analyses were performed in accordance with *Standard Methods for the Examination of Water and Wastewater, 20th edition* (APHA 1998) (Table 3.4).

Table 3.4: Methodologies used for in-house analyses.

Method	Reference
TSS	Standard Methods 20 th Edition 2540 D Total Suspended Solids Dried at 103-105°C
VSS	Standard Methods 20 th Edition 2540 E Fixed and Volatile Solids Ignited at 550°C

Analyses for total organic carbon (TOC), dissolved organic carbon (DOC), chemical oxygen demand (COD), 5-day total biochemical oxygen demand (BOD), ammonia (NH₃), 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 (CAEAL-certified) according to the methods outlined in Table 3.5.

Table 3.5: Methodologies used by the Wastewater Technology Centre for samples submitted.

Analysis	Method Reference	Method Detection Limit (MDL)	Units
TOC	Standard Methods 20 th Edition 5310B Total Organic Carbon	0.50	mg/L as C
DOC	Standard Methods 20 th Edition 5310B Total Organic Carbon	0.50	mg/L as C
Total COD	WTCAL INW16	4.811	mg/L
Total BOD	WTCAL INW3	1.118	mg/L
NH ₃	Standard Methods 19 th Ed. 4500-NH3 (Ammonia)	0.02	mg/L as N
TKN	WTCAL INW10	0.157	mg/L as N
TP	WTCAL INW11	0.082	mg/L as P
Chloride	WTCAL INW13	0.51	mg/L
Cadmium, dissolved	WTCAL INW14	1.80	µg/L
Cadmium, total	WTCAL INW14	1.80	µg/L
Copper, dissolved	WTCAL INW14	9.00	µg/L
Copper, total	WTCAL INW14	9.00	µg/L
Lead, dissolved	WTCAL INW14	25.60	µg/L
Lead, total	WTCAL INW14	25.60	µg/L
Nickel, dissolved	WTCAL INW14	7.30	µg/L
Nickel, total	WTCAL INW14	7.30	µg/L
Zinc, dissolved	WTCAL INW14	1.90	µg/L
Zinc, total	WTCAL INW14	1.90	µg/L

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), usually the day after

sample reception, to minimize potential chemistry and particulate changes that may occur on storage. When each raw sample had been warmed to ambient temperature, prior to testing, a 'raw' sewage subsample was removed for each apparatus, to check the uniformity of the samples among column tests via TSS analyses. Ambient and initial temperatures of all samples were checked to determine if temperatures were the same ($\pm 1^\circ\text{C}$).

Samples were thoroughly mixed before any analyses were performed (including TSS, temperature measurement, or performing 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 Wastewater Technology Centre laboratory included suitable duplicate samples, spiked samples, and percentage recovery for reference samples.

4. Samples Tested

Between July 7th, 2003 and April 27th, 2004 a total of 14 wet-weather and 7 dry-weather samples have been tested by NWRI (Table 4.1). Wet-weather samples were collected from the grit channel using autosamplers (Sigma 900, with 3/8" holed strainer on intake) connected to the existing treatment plant flow monitoring system to trigger sampling (3.75 L every 5 minutes for 2 hours) when flow rate reached 55,000 m³/d. Dry-weather samples were collected from the grit

channel using a 1/6 hp submersible pump with a 1/8" mesh screened intake. Samples were generally subjected to testing one to four days after receipt; test dates are listed in Table 4.1.

From March 1st through March 5th, 2004, the Welland wastewater plant was receiving a constant influent flow exceeding the 55,000 m³/d trigger flow rate. The March 3rd sample was collected using the pump method, and considered a wet-weather sample, even though there was no precipitation during that day, but the high influent flow rate was most likely due to spring snowmelt. The March 5th wet-weather sample was collected using autosamplers that were not connected to the flow triggering device, and were manually programmed to collect the influent sewage.

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

Event Date	Flow rate (m ³ /d)	Weather	Sampling Device	Test dates		
				Columns	Jar Test	Elutriation
Jul 16 2003	42,059	Wet	Autosampler	Jul 18 /03	Jul 21 /03	-
Sep 30 2003	69,439 – 127,000	Wet	Autosampler	Oct 2 /03	Oct 2 /03	Oct 2 /03
Oct 15 2003	109,048	Wet	Autosampler	Oct 16 /03	No sample	Oct 16 /03
Oct 26 2003	90,000 – 115,000	Wet	Autosampler	Oct 28 /03	Oct 29 /03	Oct 28 /03
Nov 20 2003	97,517	Wet	Autosampler	Nov 25 /03	Nov 25 /03	Nov 25 /03
Nov 28 2003	101,398	Wet	Autosampler	Dec 1 /03	Dec 3 /03	Dec 1 /03
Mar 3 2004	102,000	Wet	Pump	Mar 5 /04	Mar 5 /04	Mar 5 /04
Mar 5 2004	114,578	Wet	Autosampler	Mar 9 /04	Mar 9 /04	Mar 9 /04
Mar 9 2004	102,648	Wet	Autosampler	Mar 12 /04	Mar 12 /04	Mar 12 /04
Mar 24 2004	102,227	Wet	Autosampler	Mar 26 04	Mar 26 04	Mar 26 04
Mar 30 2004	92,957	Wet	Autosampler	Apr 2 04	Apr 2 04	Apr 2 04
Apr 6 2004	104,667	Wet	Pump	Apr 7 04	Apr 7 04	Apr 7 04
Apr 21 2004	N/A	Wet	Autosampler	Apr 26 04	Apr 26 04	Apr 26 04
Apr 25 2004	N/A	Wet	Autosampler	Apr 27 04	Apr 29 04	Apr 27 04
July 7 2003	34,549	Dry	Pump	Jul 8 03	Jul 10 03	-
Aug 28 2003	29,830	Dry	Pump	Aug 28 03	Aug 29 03	-
Sep 23 2003	49,669	Dry	Pump	Sep 24 03	Sep 24 03	Sep 25 03
Oct 29 2003	51,359	Dry	Pump	Oct 30 03	Oct 30 03	Oct 30 03
Jan 21 2004	40,679	Dry	Pump	Jan 22 04	Jan 22 04	Jan 22 04
Feb 2 2004	34,319	Dry	Pump	Feb 3 04	Feb 3 04	Feb 3 04
Mar 24 2004	46,399	Dry	Pump	Mar 25 04	Mar 25 04	Mar 25 04

N/A = Not Available

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 ($i=1, 2 \dots 11$). 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.

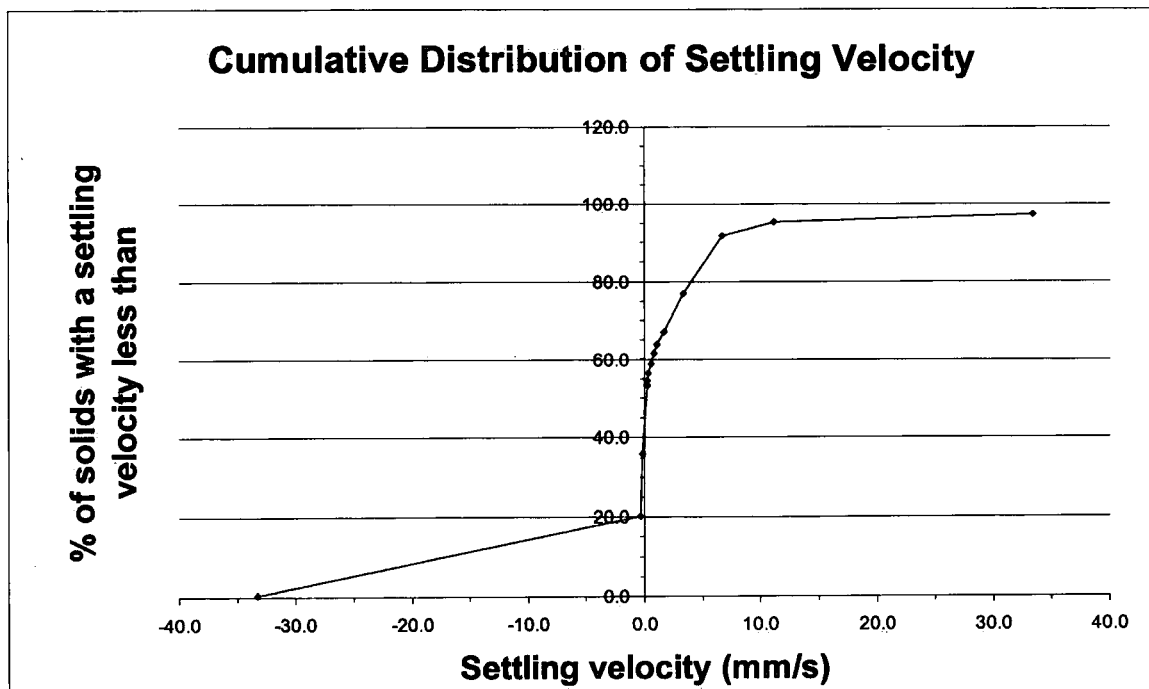


Fig. 5.1: A typical settling velocity distribution measured using the Aston column.

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:

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

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.

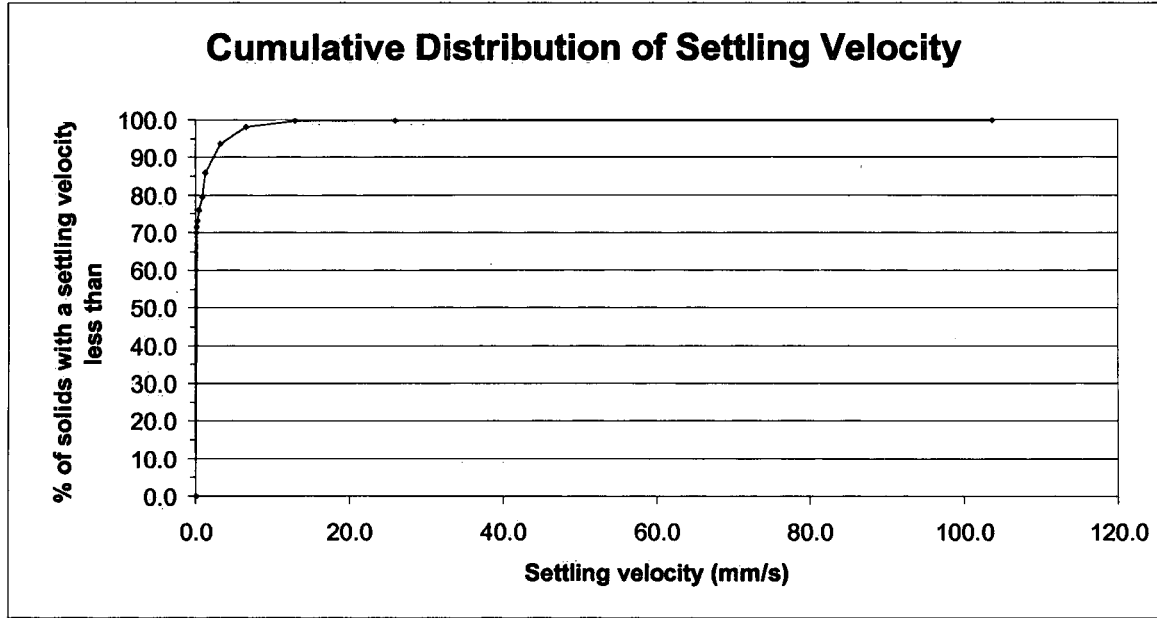


Fig. 5.2: A typical settling velocity distribution measured using the Brombach column.

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:

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

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 US 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.

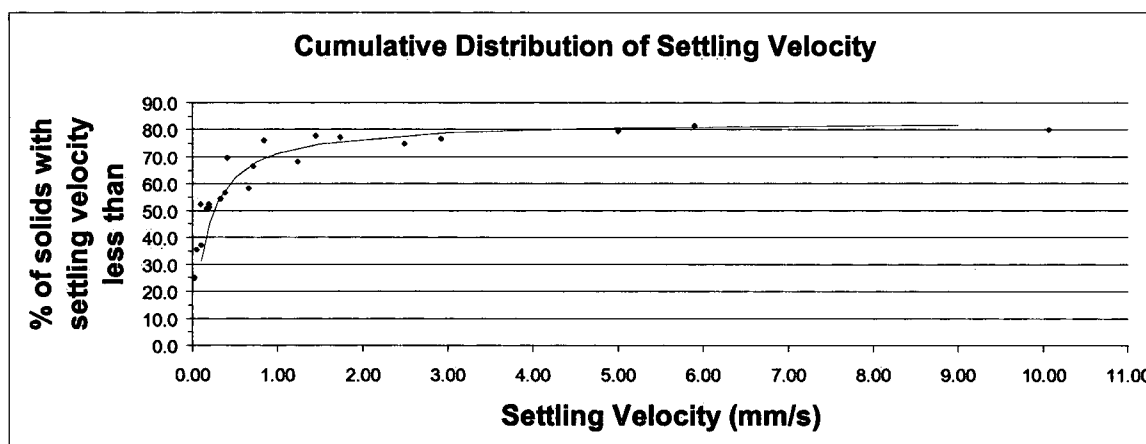


Fig. 5.3: A typical settling velocity distribution measured using the U.S. EPA settling column.

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.

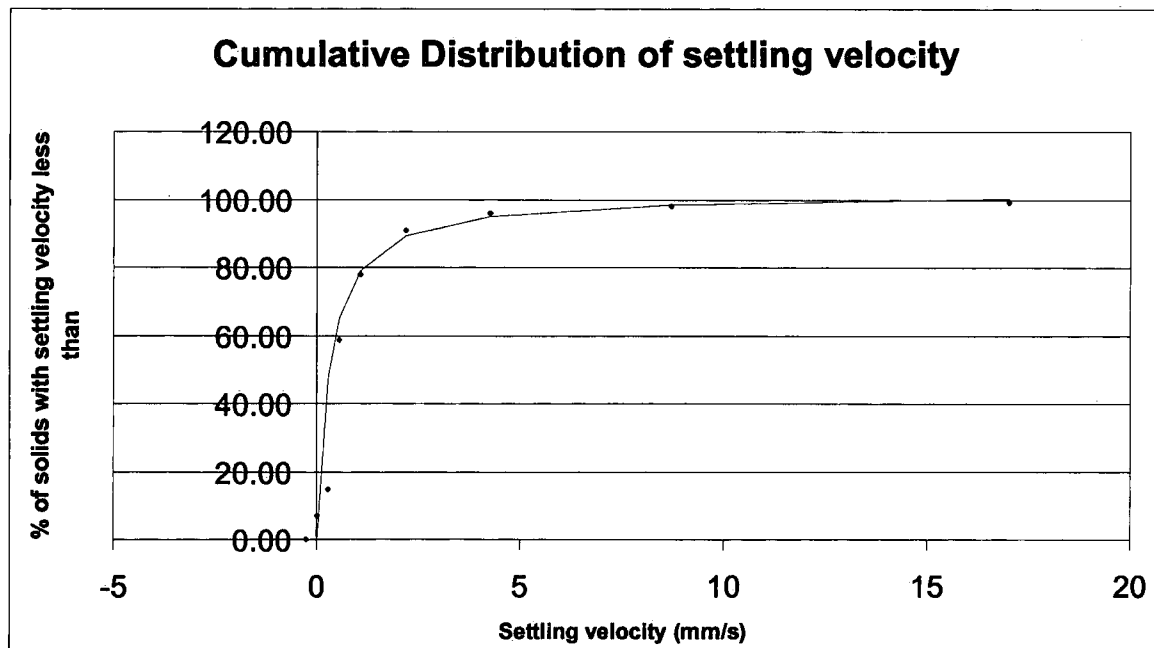


Fig. 5.4: A typical settling velocity distribution measured using the Elutriation apparatus.

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 Welland study

Method	Method Characteristics				
	Sample volume (L)	Flow conditions during test	Measurement of sinkers	Measurement of floatables	Chemical additions
Aston column	6	Quiescent	Yes	Yes	No
Brombach column	1	Quiescent	Yes	No	No
Elutriation apparatus	50	Dynamic	Yes	Yes (with limitations)	Yes
US EPA column	20	Quiescent	Yes	No	No

a) Comparison of mass balance errors

So far, the settling velocity distribution data for twelve samples from Welland were analyzed and compared. Out of these twelve, six were for dry-weather samples and the remaining six were for wet-weather samples. The samples for which the data analysis is complete are listed in Table 5.4.

Table 5.4: Summary of Welland samples for which the data analysis is complete.

Dry-Weather	Wet-weather
July 7, 2003	October 1, 2003
August 28, 2003	October 15, 2003
September 23, 2003	October 26, 2003
October 29, 2003	November 20, 2003
January 21, 2004	November 28, 2003
February 2, 2004	March 9, 2004

The mass balance errors measured for all samples and for all four methods are tabulated in Table 5.5.

Table 5.5: Summary of mass balance errors in percentage

Sample	Aston Column	Brombach column	US EPA column	Elutriation Apparatus
July 7, 2003	-3.23	1.37	0.09	16.39
August 28, 2003	-15.74	1.43	1.36	-0.18
September 23, 2003	-13.57	23.50	10.44	2.25
October 29, 2003	-16.97	-4.72	0.86	-1.51
January 21, 2003	0.43	13.61	8.37	-5.42
February 2, 2004	3.09	5.93	3.72	-0.68
October 1, 2003	-0.53	8.26	-10.37	6.16
October 15, 2003	-7.81	0.56	-2.01	16.15
October 26, 2003	35.35	-12.23	-1.16	-13.74
November 20, 2003	-11.32	-0.64	1.80	6.71
November 26, 2003	-0.07	-10.79	-5.56	-8.13
March 9, 2004	-2.52	11.34	-18.12	-16.14
Standard Deviation	13.80	10.20	7.76	10.30

The overall mass balance errors range from + 35 percent to -18 percent. In the majority of tests, the mass balance error is much smaller than these extreme values. Based on the standard deviations, the Aston column has the largest mass balance error, while the US EPA column has the least error. Both the Brombach column and the Elutriation apparatus have about the same magnitude of mass balance error.

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:

$$y = \frac{\frac{1}{\alpha}x}{\frac{\beta}{\alpha}x + 1} \quad (5)$$

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.

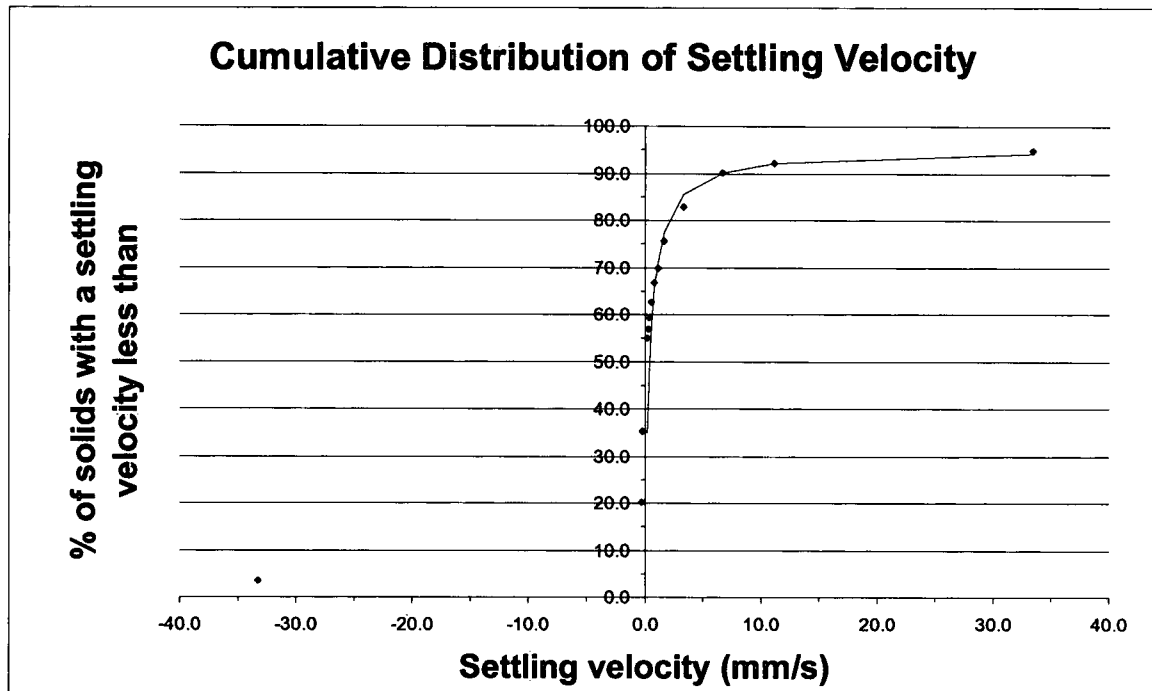


Fig. 5.5: Typical match between equation 5 and measured data using the Aston Column.

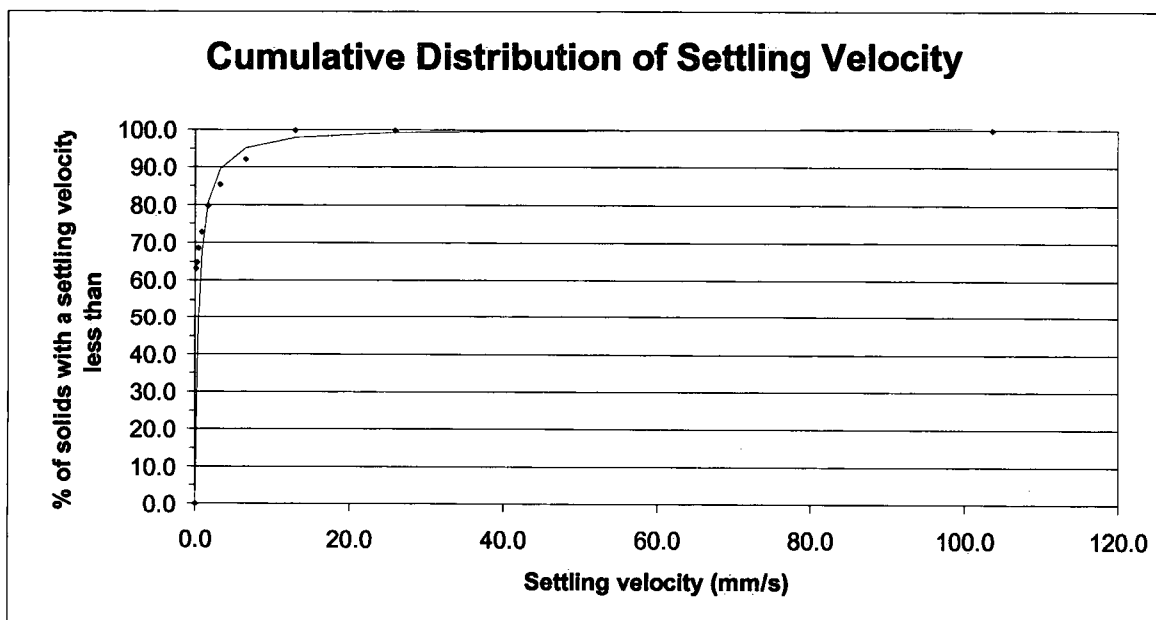


Fig. 5.6: Typical match between equation 5 and measured data using the Brombach column.

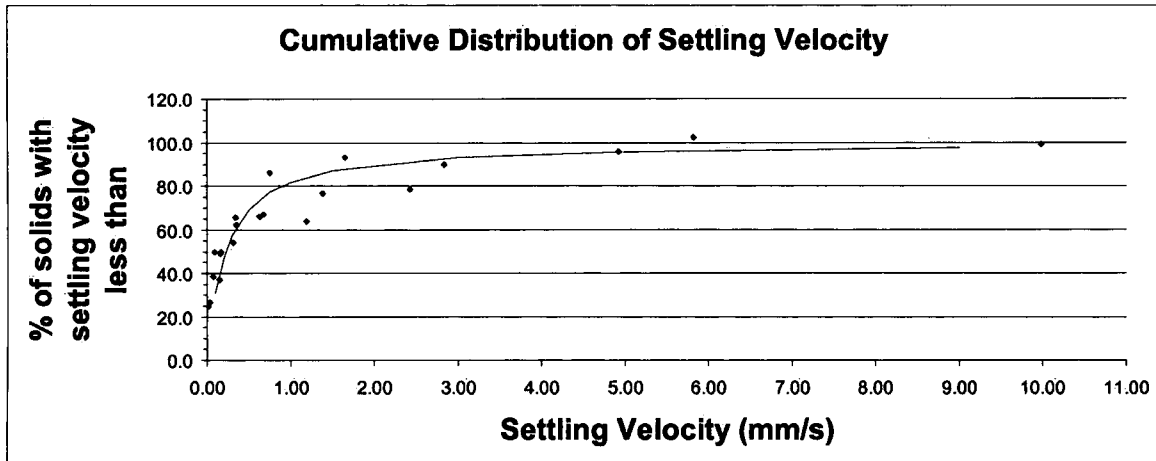


Fig. 5.7: Typical match between equation 5 and measured data using US EPA column.

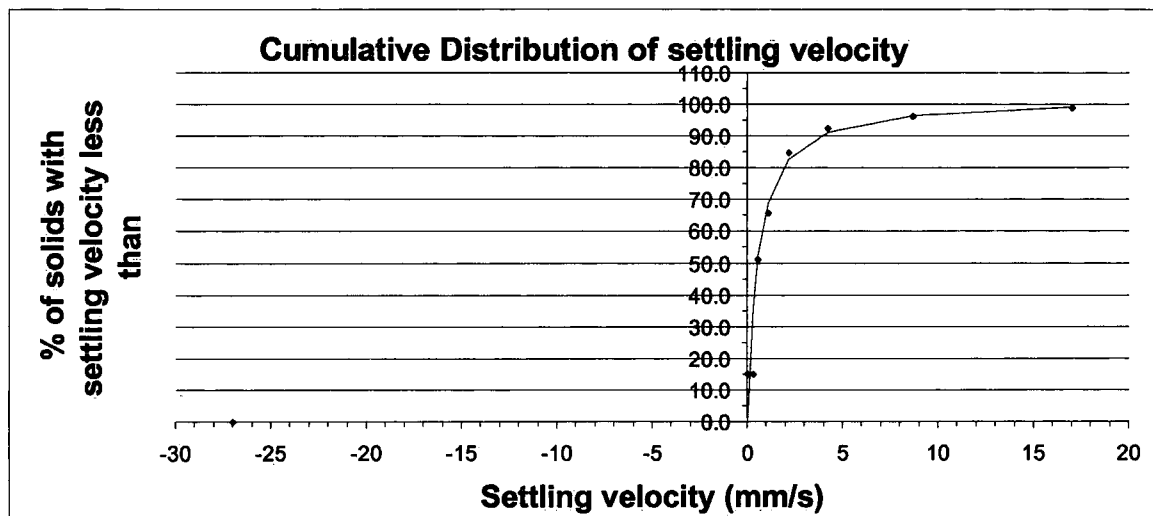


Fig. 5.8: Typical match of equation 5 with measured data using the Elutriation Apparatus.

The values of α , β that gave the best fit of Equation 5 to measured data from all four methods and for all Welland samples are listed in Table 5.6. Appropriately fitted Equation 5 was used to evaluate the cumulative settling velocity distribution curves for all the Welland samples as shown in Figs. 5.9 to 5.20.

Table 5.6: 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
July 7, 2003	0.007	0.0103	0.0022	0.0099	0.0008	0.0098	0.002	0.0099
August 28, 2003	0.006	0.0103	0.0025	0.0099	0.0020	0.0110	0.003	0.0099
September 23, 2003	0.006	0.0011	0.0006	0.0100	0.0003	0.0099	0.003	0.0099
October 29, 2003	0.003	0.0103	0.0019	0.0099	0.0013	0.010	0.003	0.0098
January 21, 2004	0.003	0.0102	0.0023	0.0099	0.0008	0.010	0.003	0.0098
February 2, 2004	0.004	0.0106	0.0040	0.0099	0.001	0.012	0.003	0.0098
October 1, 2003	0.004	0.0105	0.0040	0.0099	0.0022	0.010	0.005	0.0098
October 15, 2003	0.008	0.0103	0.0100	0.0099	0.003	0.010	0.004	0.0098
October 26, 2003	0.003	0.0100	0.0028	0.0100	0.002	0.012	0.002	0.0098
November 20, 2003	0.005	0.0103	0.0027	0.0099	0.002	0.012	0.003	0.0099
November 28, 2003	0.002	0.0103	0.0030	0.0099	0.001	0.015	0.006	0.0098
March 9, 2004	0.004	0.0103	0.0023	0.0099	0.002	0.012	0.007	0.0098

Comparison of settling velocity distributions from various methods

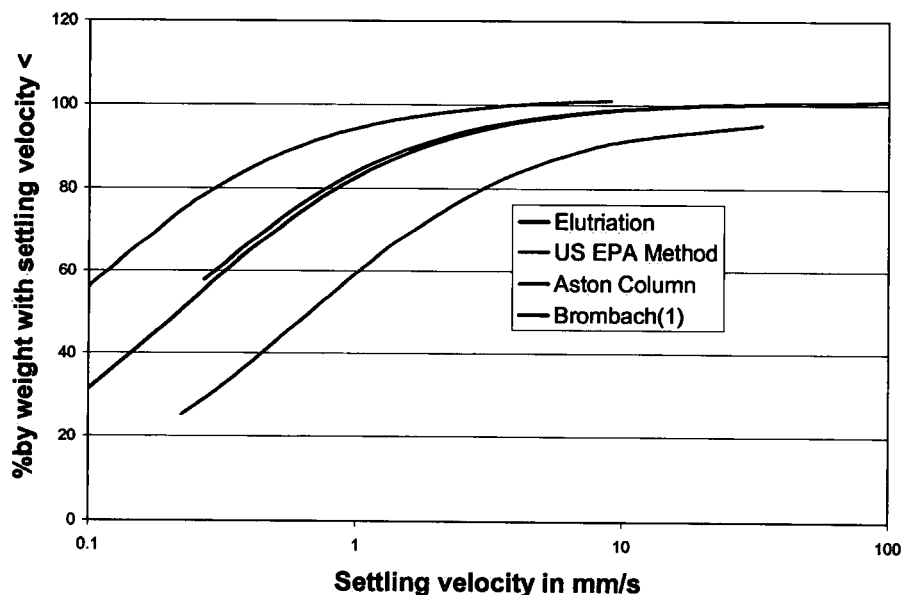


Fig. 5.9: Comparison of settling velocity distributions from various methods for dry-weather sample: July 7, 2003.

Comparison of settling velocity distributions given by various methods

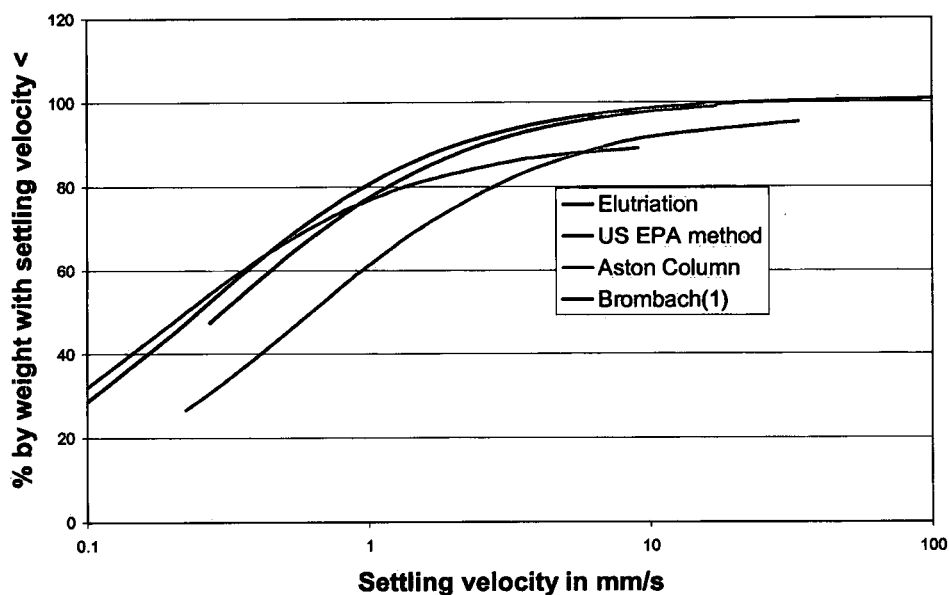


Fig. 5.10: Comparison of settling velocity distributions from various methods for dry-weather sample: August 28, 2003.

Comparison of settling velocity distributions from various methods

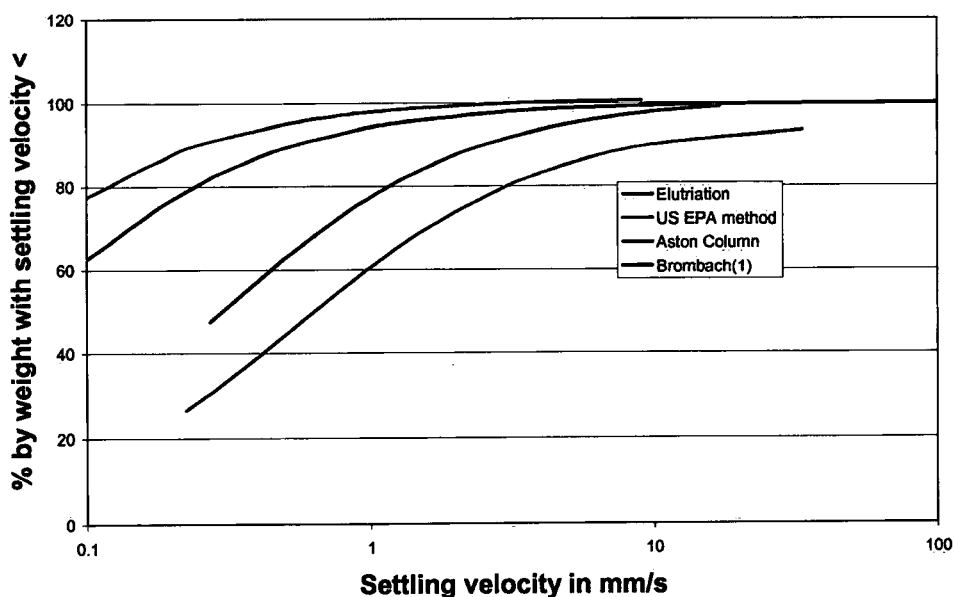


Fig. 5.11: Comparison of settling velocity distributions from various methods for dry-weather sample: September 23, 2003.

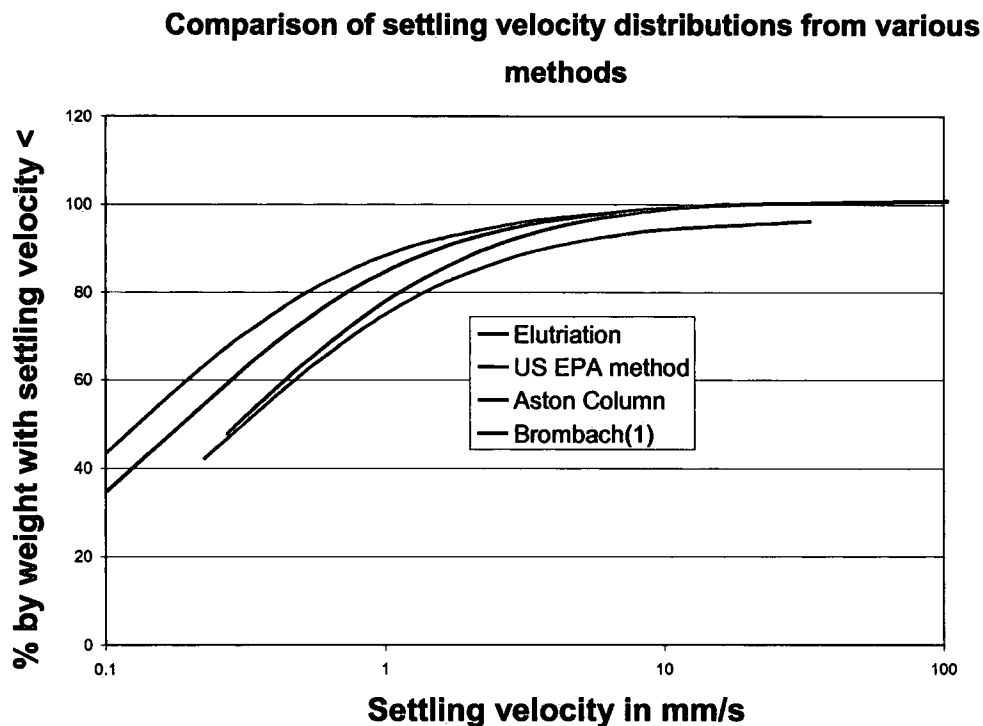


Fig. 5.12: Comparison of settling velocity distributions from various methods for dry-weather sample: October 29, 2003.

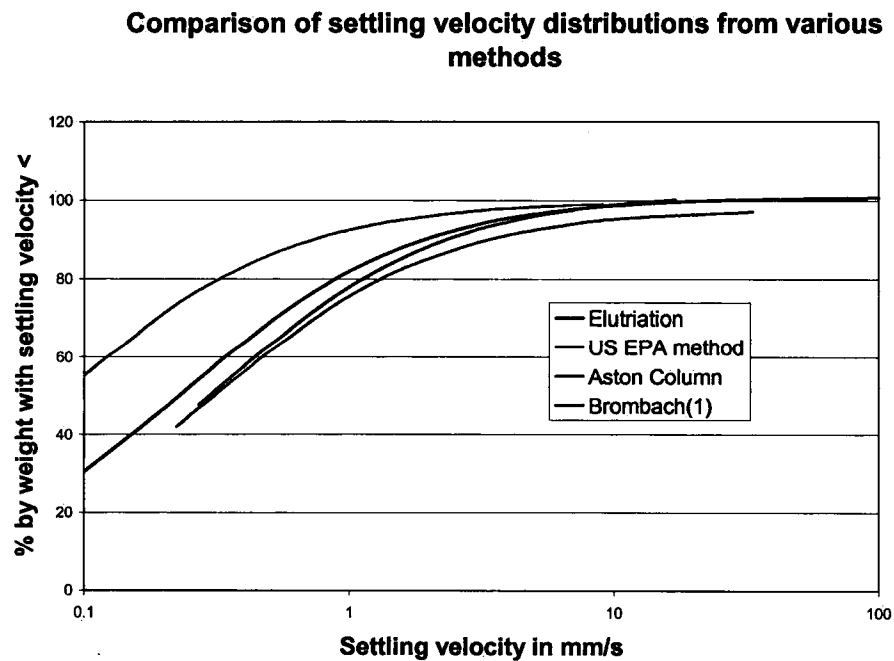


Fig. 5.13: Comparison of settling velocity distributions from various methods for dry-weather sample: January 21, 2004.

Comparison of settling velocity distributions from various methods

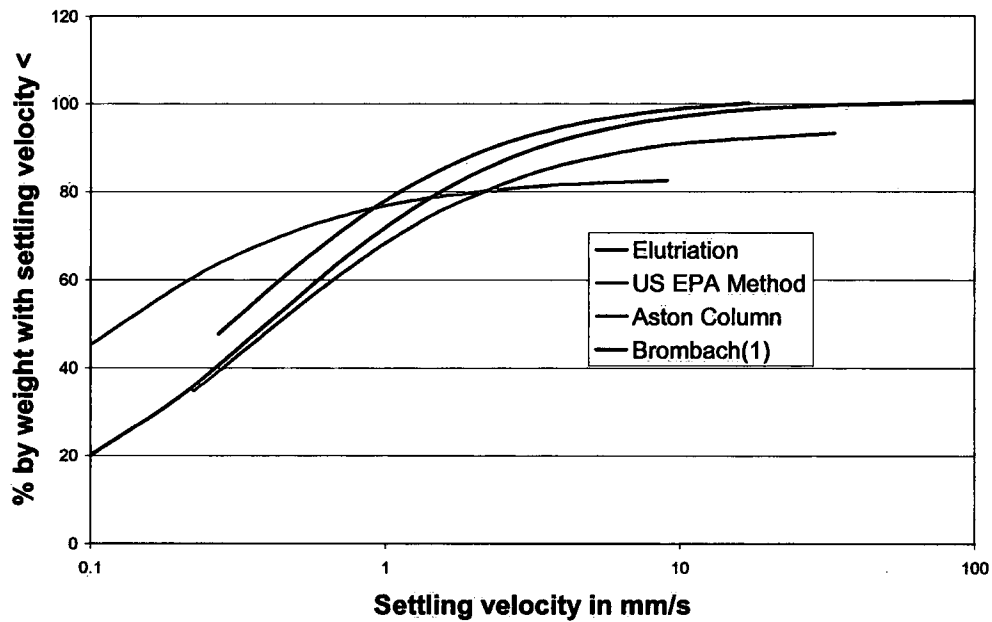


Fig. 5.14: Comparison of settling velocity distributions from various methods for dry-weather sample: February 2, 2004.

Comparison of settling velocity distributions from various methods

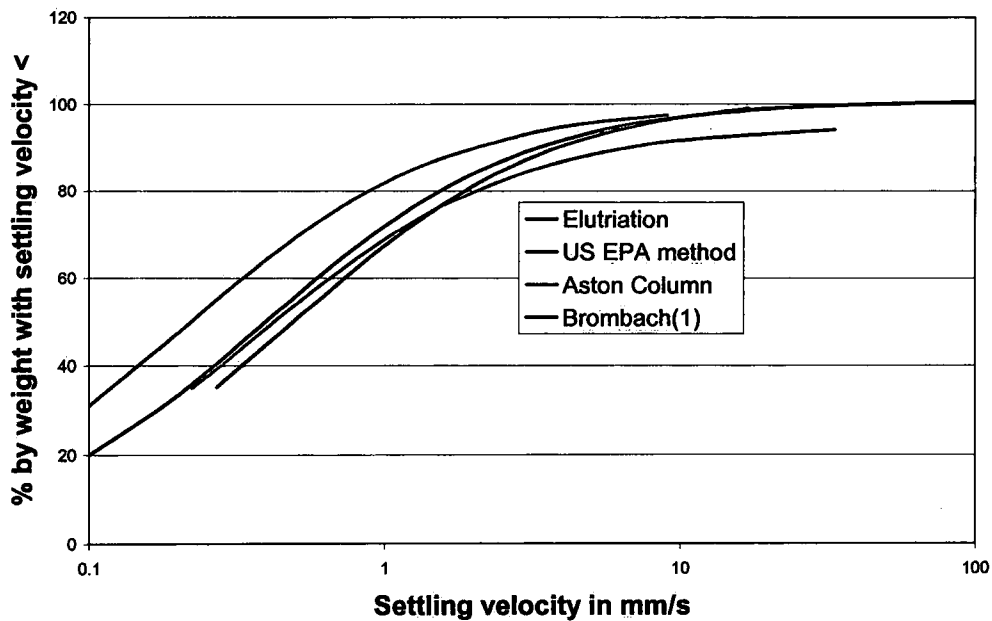


Fig. 5.15: Comparison of settling velocity distributions from various methods for wet-weather sample: October 1, 2003

Comparison of settling velocity distributions from various methods

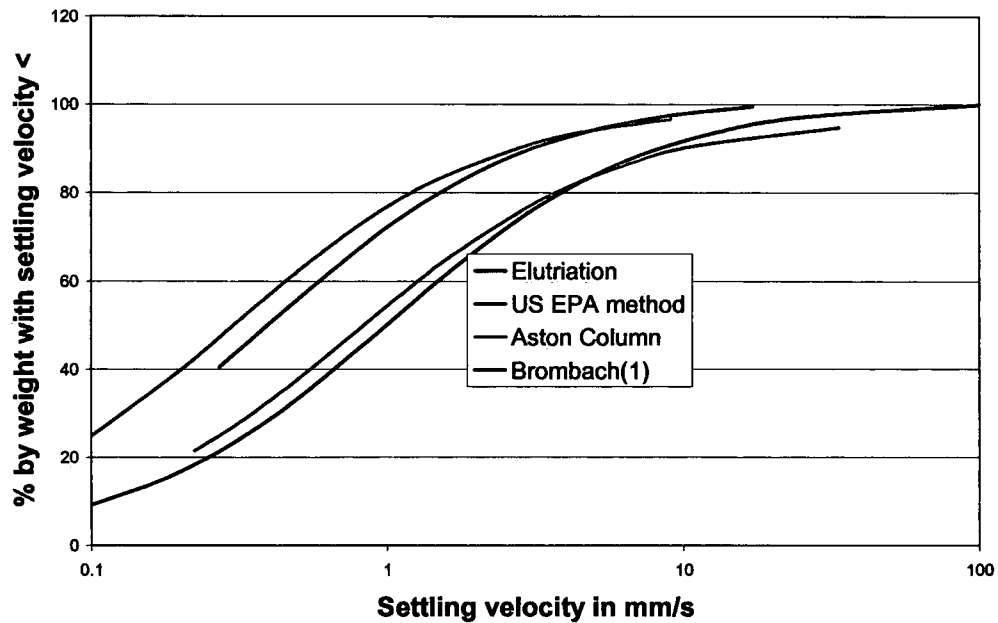


Fig. 5.16: Comparison of settling velocity distributions from various methods for wet-weather sample: October 15, 2003

Comparison of settling velocity distributions from various methods

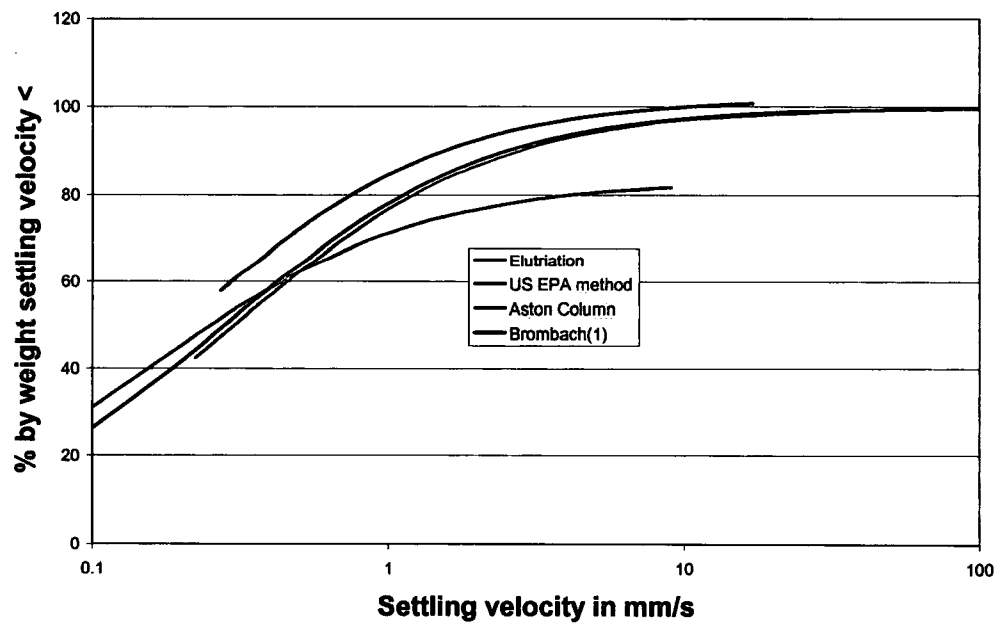


Fig. 5.17: Comparison of settling velocity distributions from various methods for wet-weather sample: October 26, 2003.

Comparison of settling velocity distributions from various methods

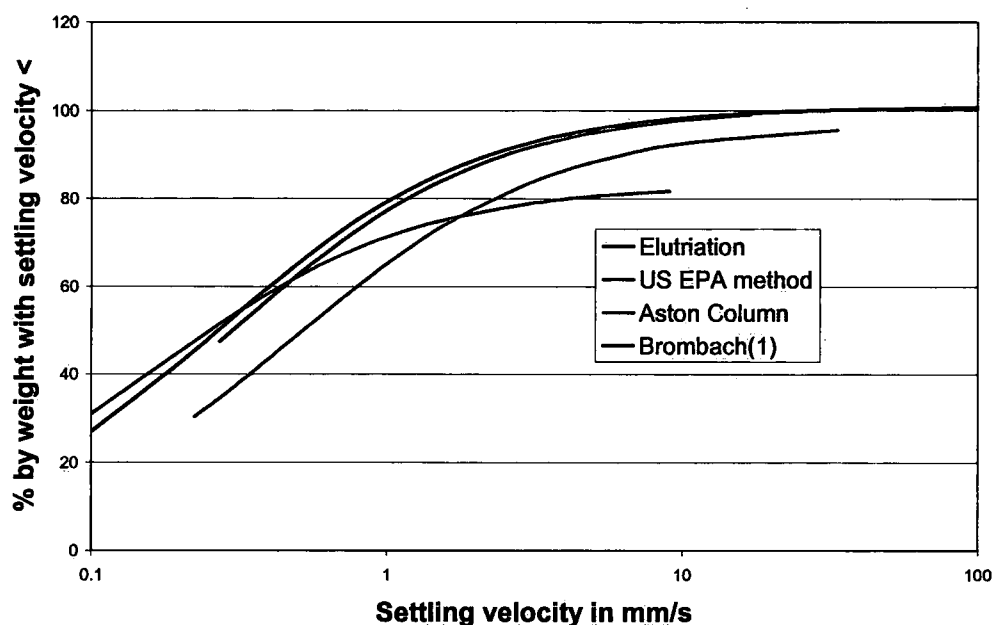


Fig. 5.18: Comparison of settling velocity distributions from various methods for wet-weather sample: November 20, 2003.

Comparison of settling velocity distributions from various methods

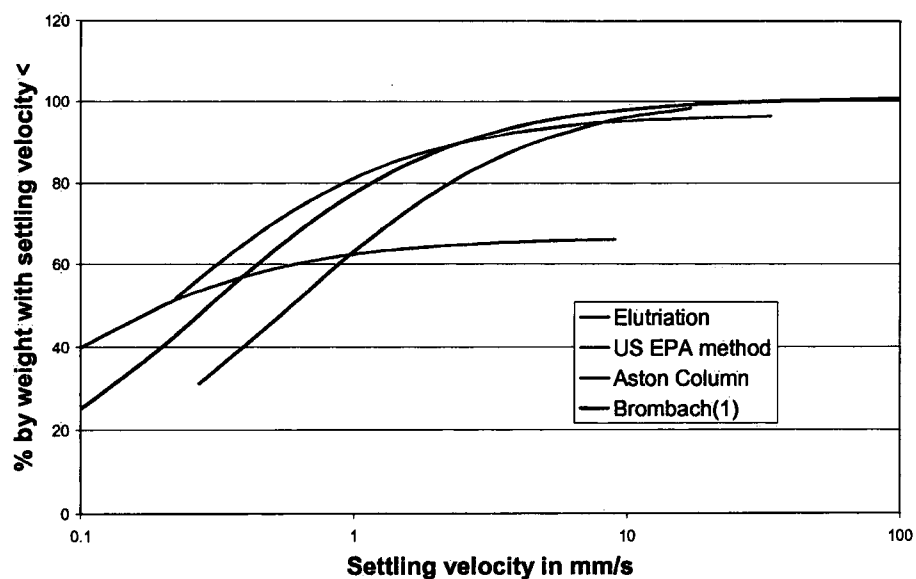


Fig. 5.19: Comparison of settling velocity distributions from various methods for wet-weather sample: November 28, 2003.

Comparison of settling velocity distributions from various methods

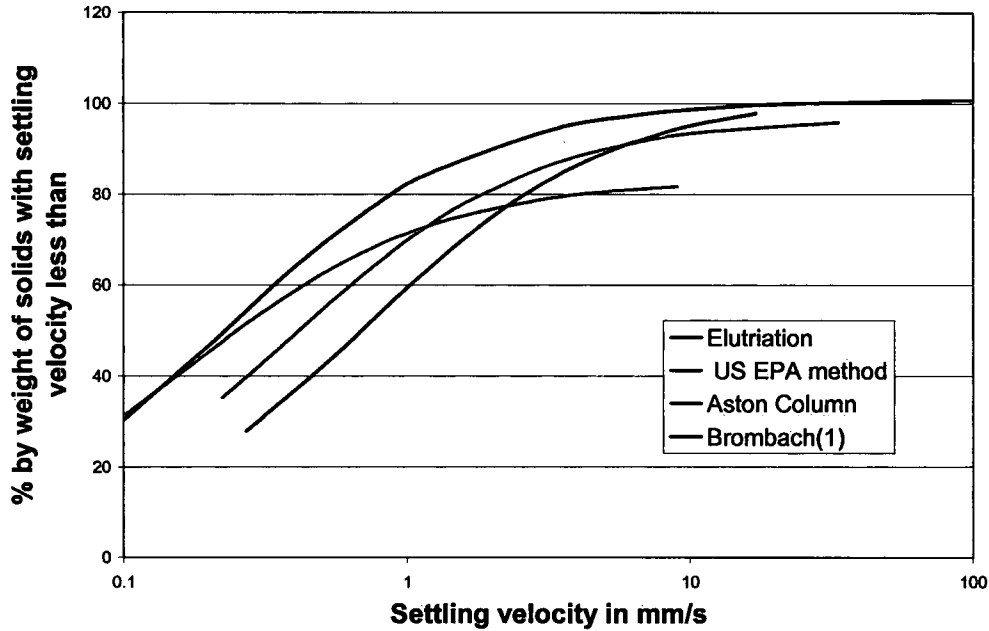


Fig. 5.20: Comparison of settling velocity distributions from various methods for wet-weather sample: March 9, 2004.

From these figures, we can see that the US EPA method gives flatter distributions for some samples. The other three methods give fairly similar distributions for all 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:

$$x = -\frac{y}{\frac{\beta}{\alpha}y - \frac{1}{\alpha}} \quad (6)$$

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 Welland samples as shown in Figs. 5.21 to 5.32.

Comparison of surface loading rate given by various methods

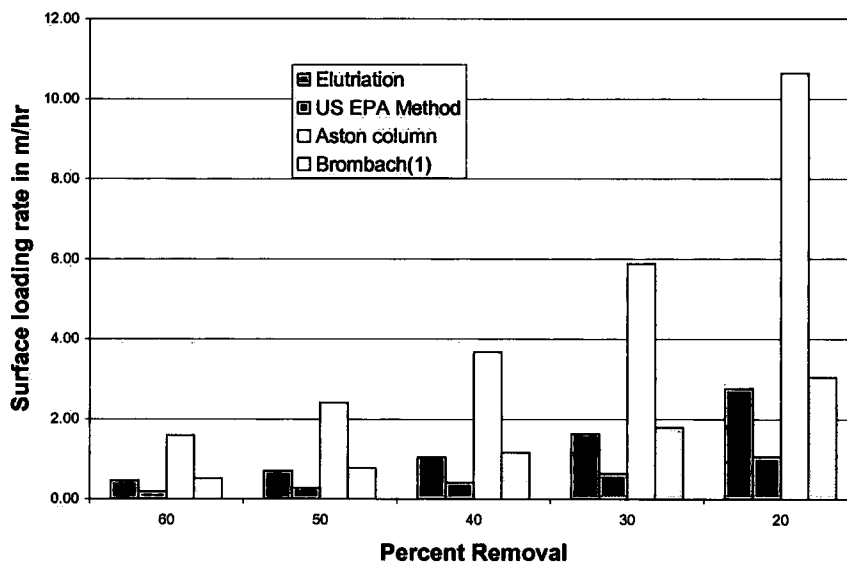


Fig. 5.21. Comparison of surface loading rates given by different methods for dry-weather sample: July 7, 2003.

Comparison of surface loading rates given by various methods

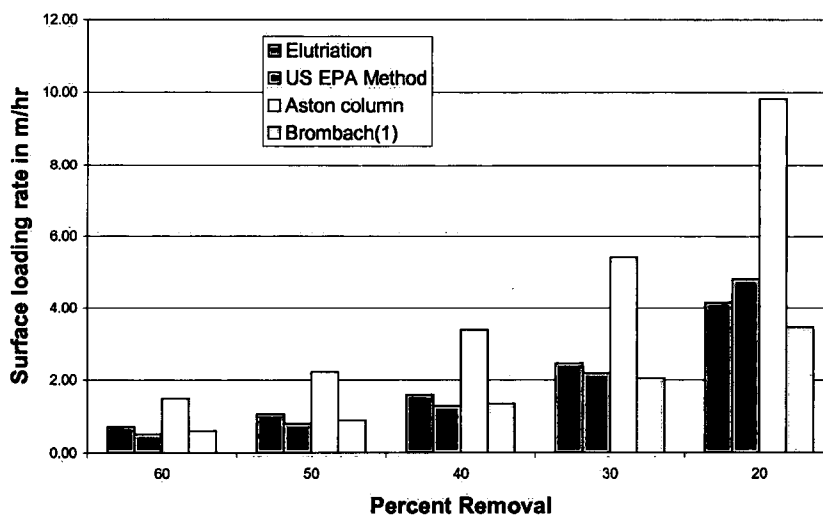


Fig. 5.22 Comparison of surface loading rates given by different methods for dry-weather sample: Aug 28, 2003.

Comparison of surface loading rates given by various methods

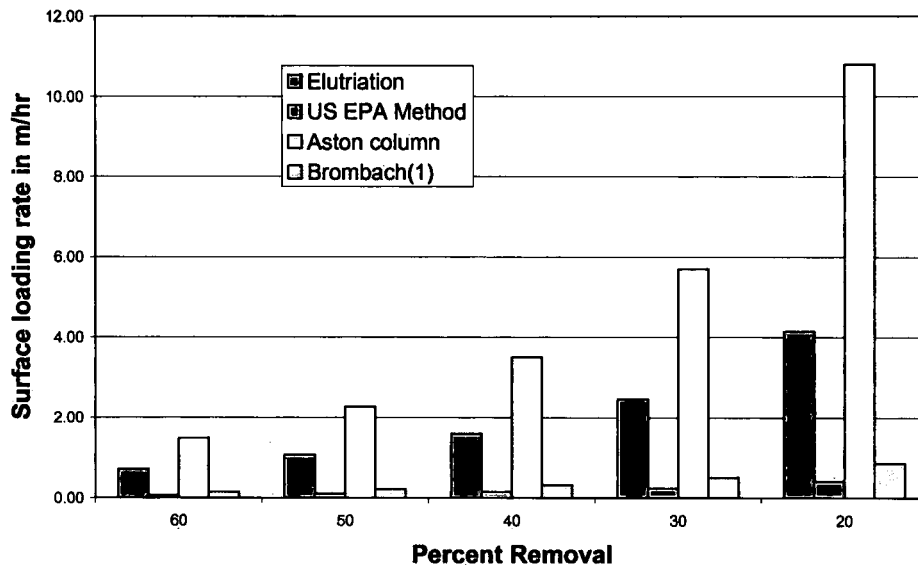


Fig. 5.23 Comparison of surface loading rates given by different methods for dry-weather sample: September 23, 2003.

Comparison of surface loading rates given by various methods

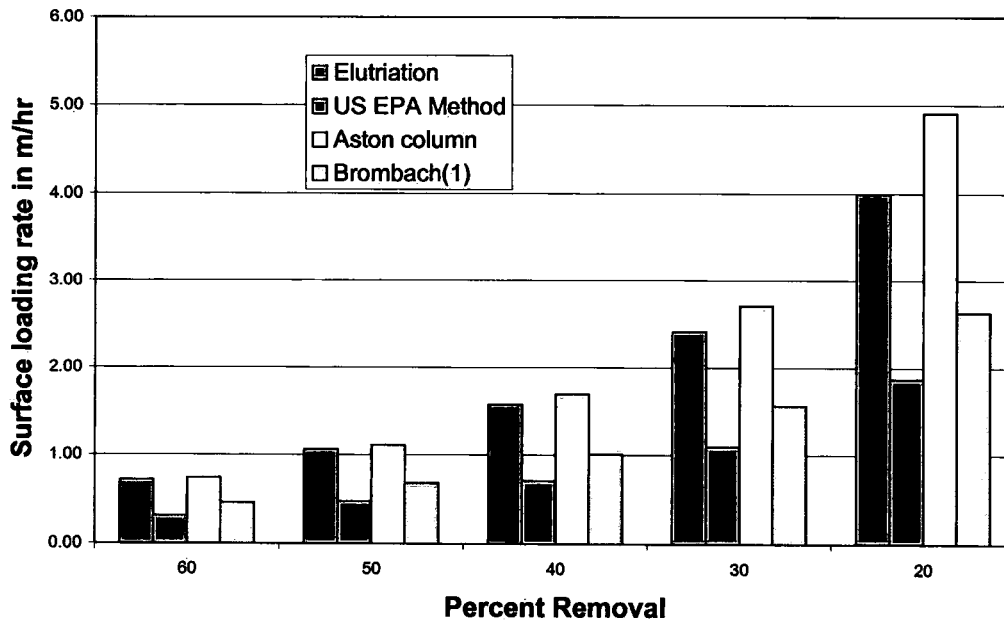


Fig. 5.24. Comparison of surface loading rates given by various methods for dry-weather sample: October 29, 2003.

Comparison of surface loading rates by various methods

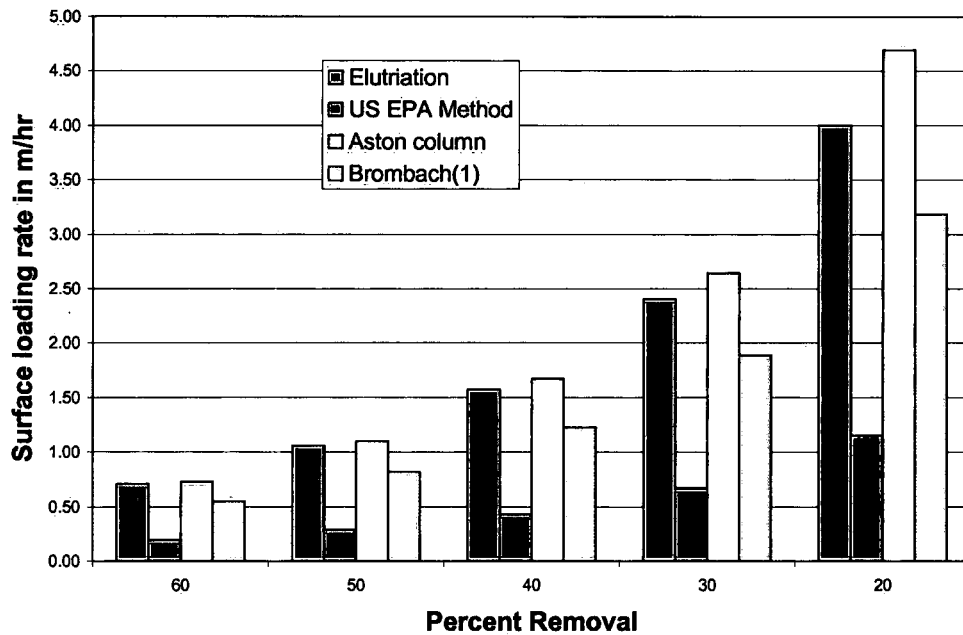


Fig. 5.25: Comparison of surface loading rates given by various methods for dry-weather sample: January 21, 2004.

Comparison of surface loading rates by various methods

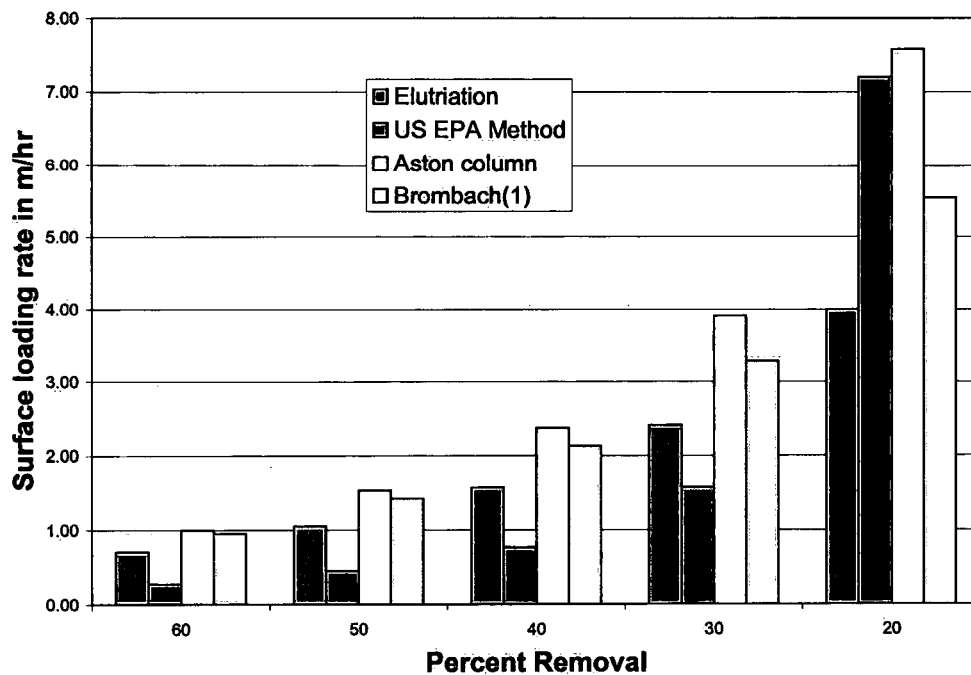


Fig. 5.26: Comparison of surface loading rates given by various methods for dry-weather sample: February 2, 2004.

Comparison of surface loading rates given by various methods

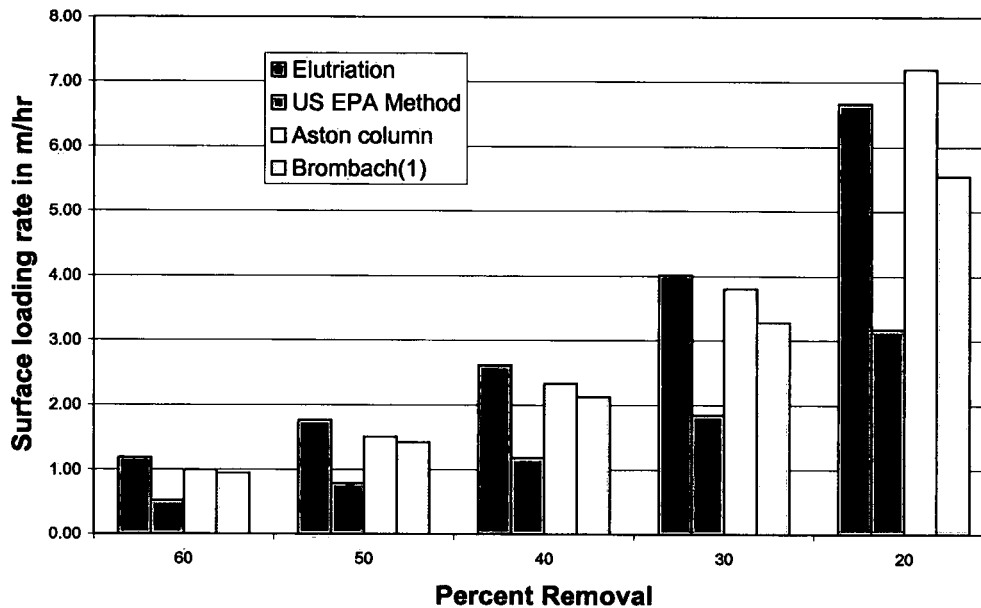


Fig. 5.27: Comparison of surface loading rates given by various methods for wet-weather sample: October 1, 2003.

Comparison of surface loading rates given by various methods

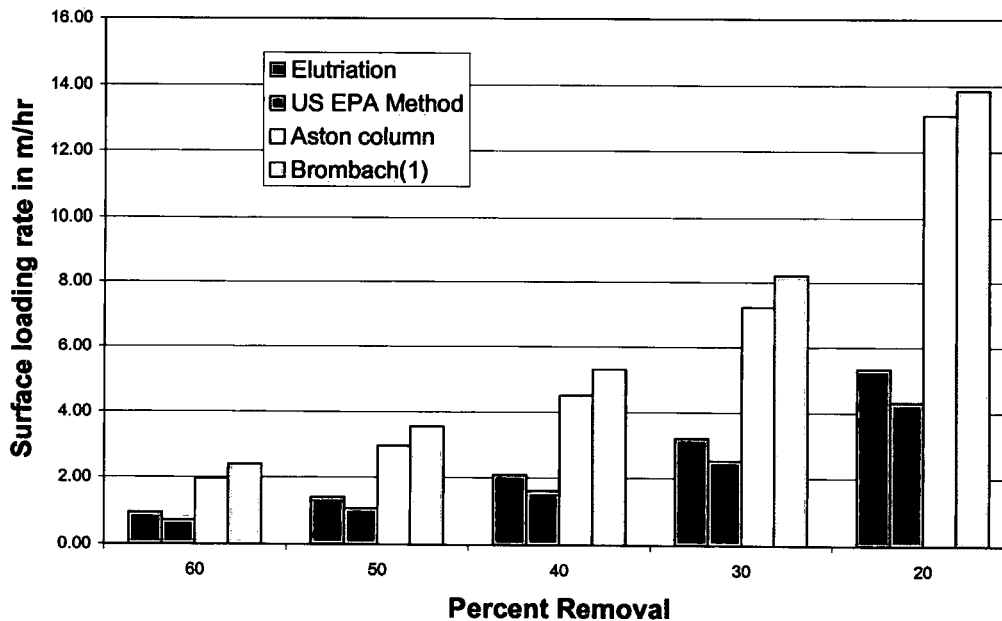


Fig. 5.28: Comparison of surface loading rates given by various methods for wet-weather sample: October 15, 2003.

Comparison of surface loading rate given by various methods

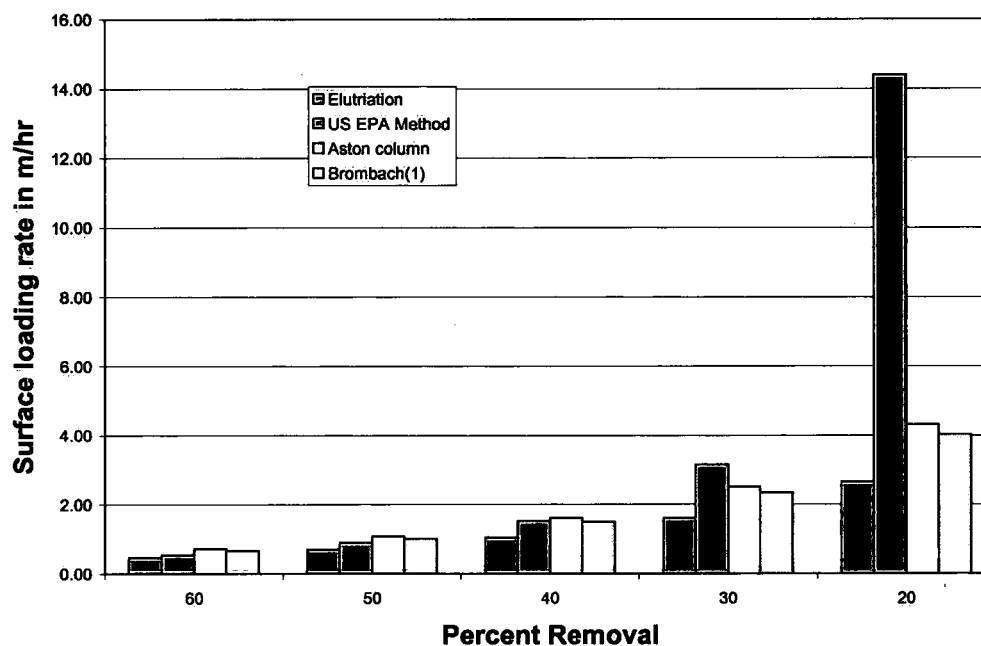


Fig. 5.29: Comparison of surface loading rates given by various methods for wet-weather sample: October 26, 2003.

Comparison of surface loading rates given by various methods

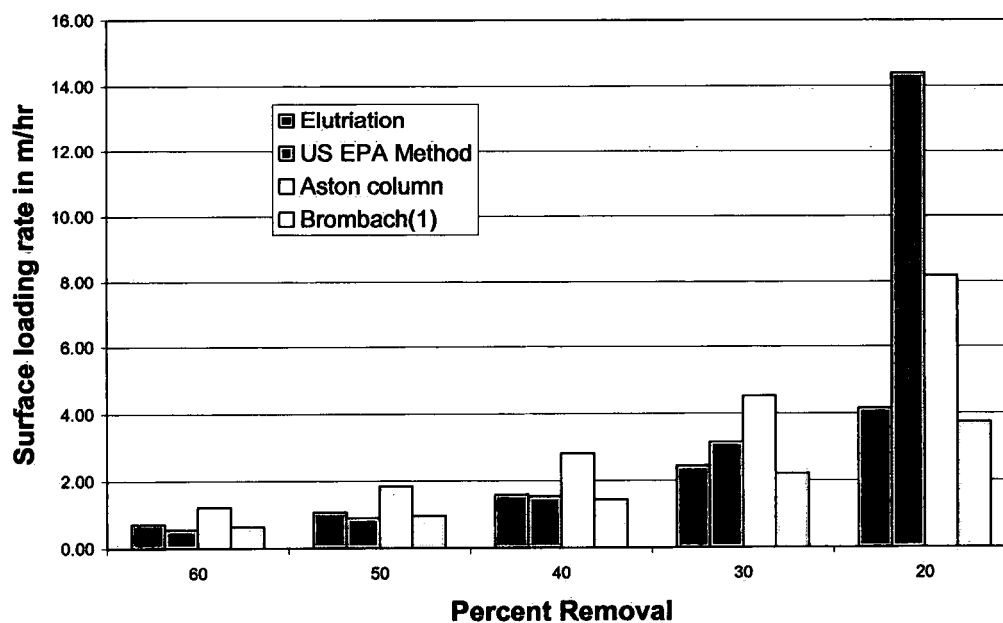


Fig. 5.30: Comparison of surface loading rates given by various methods for wet-weather sample: November 20, 2003.

Comparison of surface loading rates by various methods

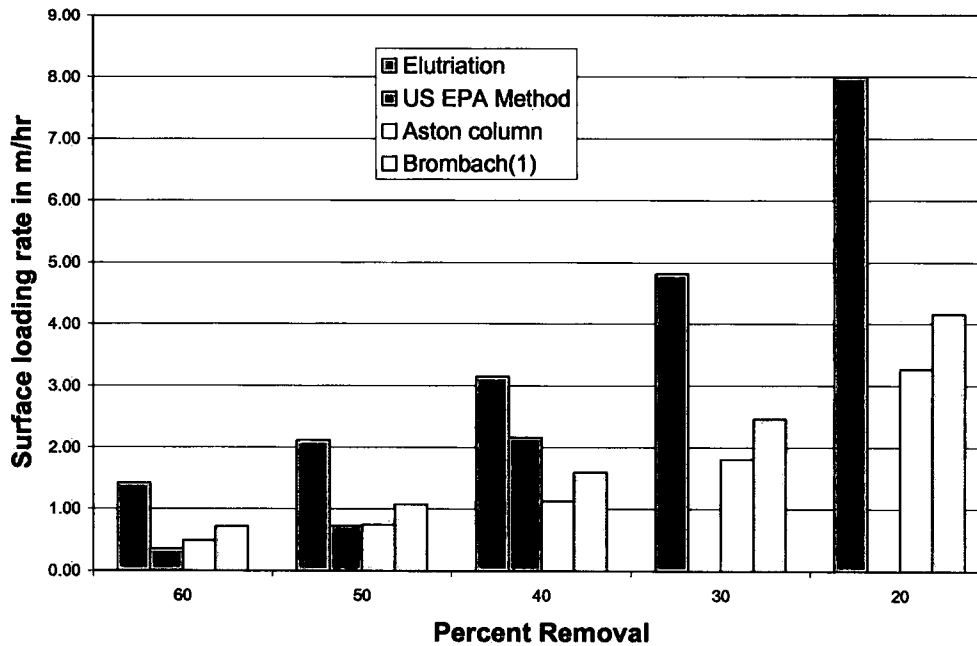


Fig. 5.31: Comparison of surface loading rates given by various methods for wet-weather sample: November 28, 2003.

Comparison of surface loading rates by various methods

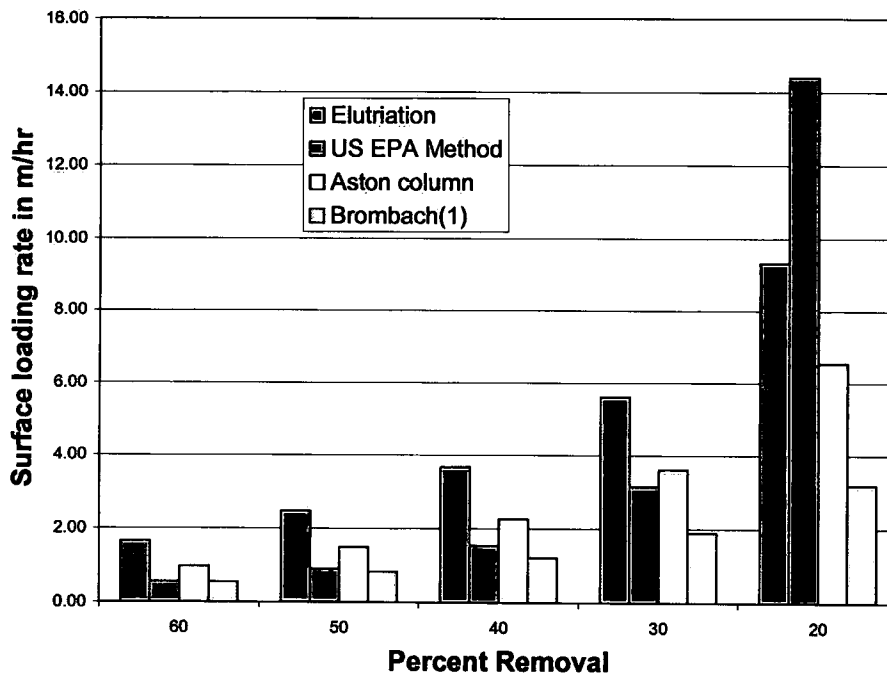


Fig. 5.32: Comparison of surface loading rates given by various methods for wet-weather sample: March 9, 2004.

These figures indicate that for 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 50% removal, the surface loading rates given by different methods for different samples are around 1 m/hr.

To examine the variability in the cumulative settling velocity distributions among samples, these distributions were plotted for each method as shown in Figs. 5.33 to 5.40. In addition, the surface loading rates for various percent removals calculated from the various methods are shown in Figs. 5.41 to 5.48. A comparison of these figures show that the distributions given by the Elutriation apparatus yields least variability from sample to sample. Elutriation also shows smaller variations for the dry-weather samples than for the wet-weather samples.

Settling velocity distributions- Elutriation- Dry weather samples

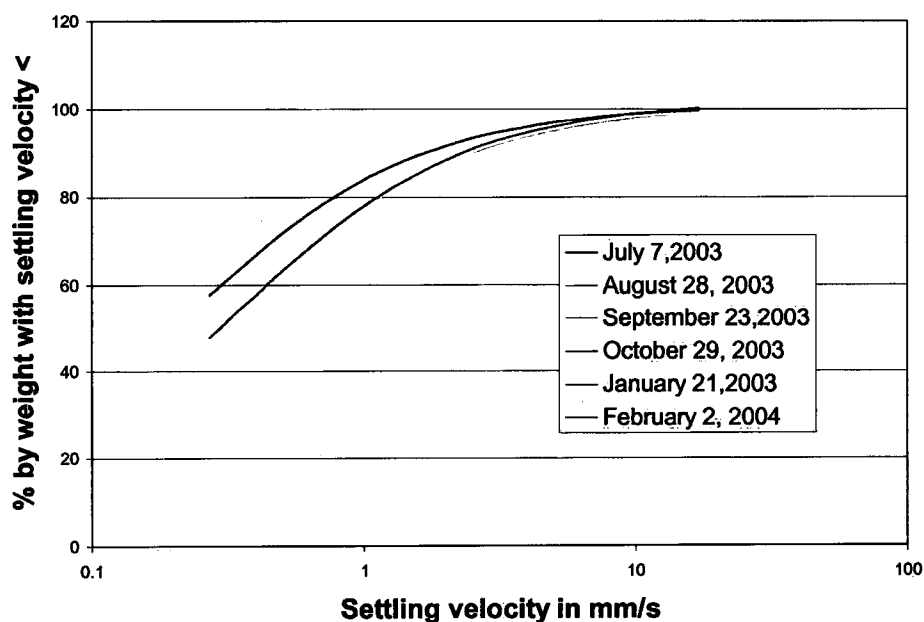


Fig. 5.33: Settling velocity distributions given by the Elutriation apparatus for dry-weather samples. (Note: multiple curves coincide.)

Settling velocity distributions- Elutriation- wet weather samples

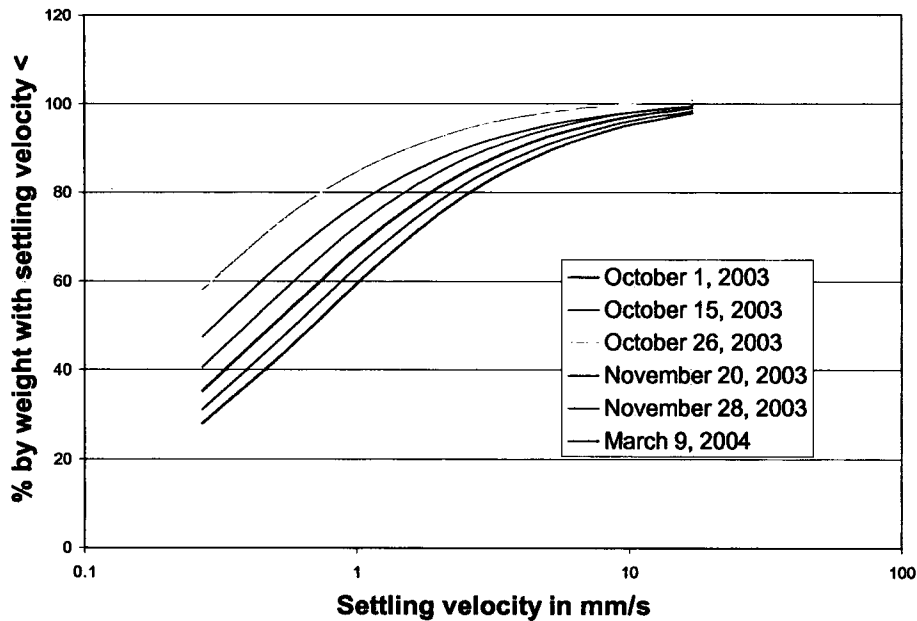


Fig. 5.34: Settling velocity distributions given by the Elutriation apparatus for wet-weather samples.

Settling velocity distributions- US EPA Method-Dry weather samples

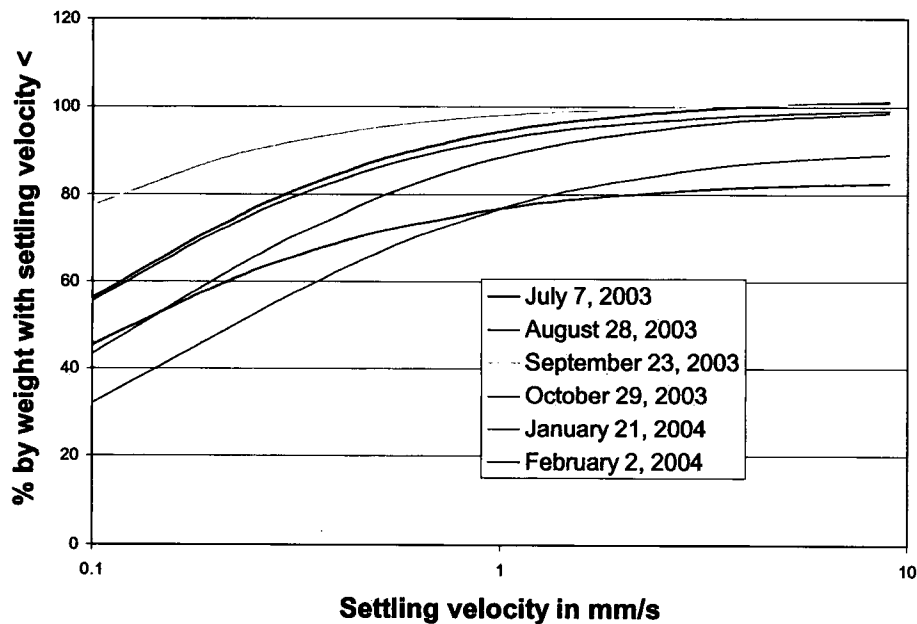


Fig. 5.35: Settling velocity distributions given by the U.S. EPA column for dry-weather samples.

Settling velocity distributions-US EPA method- Wet weather samples

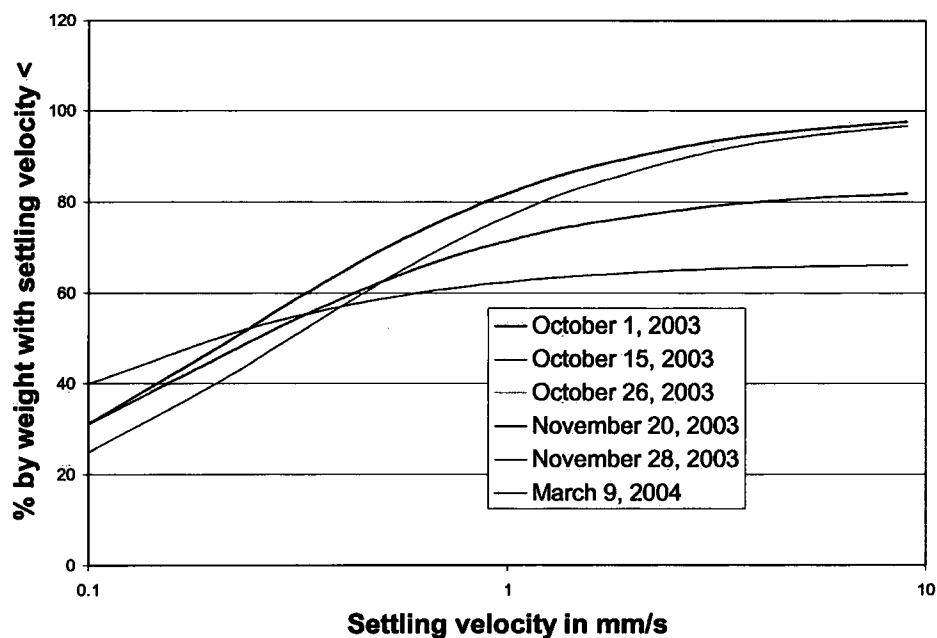


Fig. 5.36: Settling velocity distributions given by the U.S. EPA column for wet-weather samples.

Settling velocity distributions - Aston Column- Dry weather samples

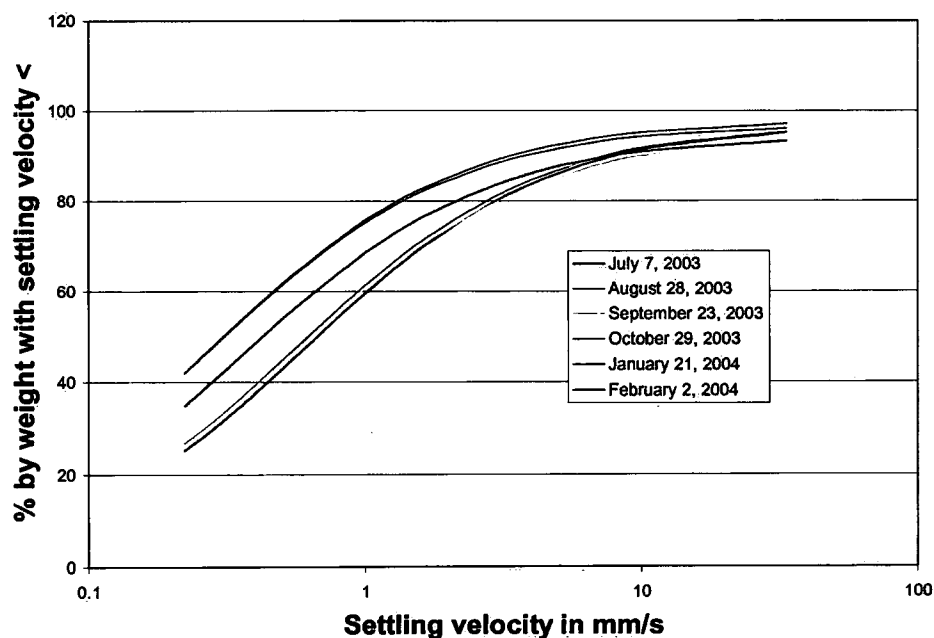


Fig. 5.37: Settling velocity distributions given by the Aston column for dry-weather samples.

Settling velocity distributions - Aston Column- Wet weather samples

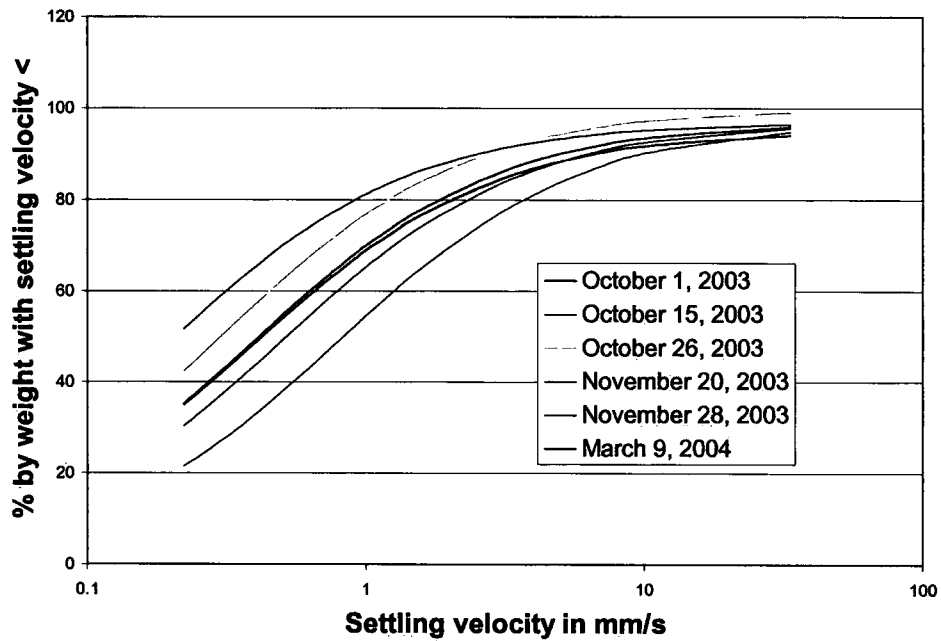


Fig. 5.38: Settling velocity distributions given by Aston column for wet-weather samples.

Settling velocity distributions-Brombach (1) - Dry weather samples

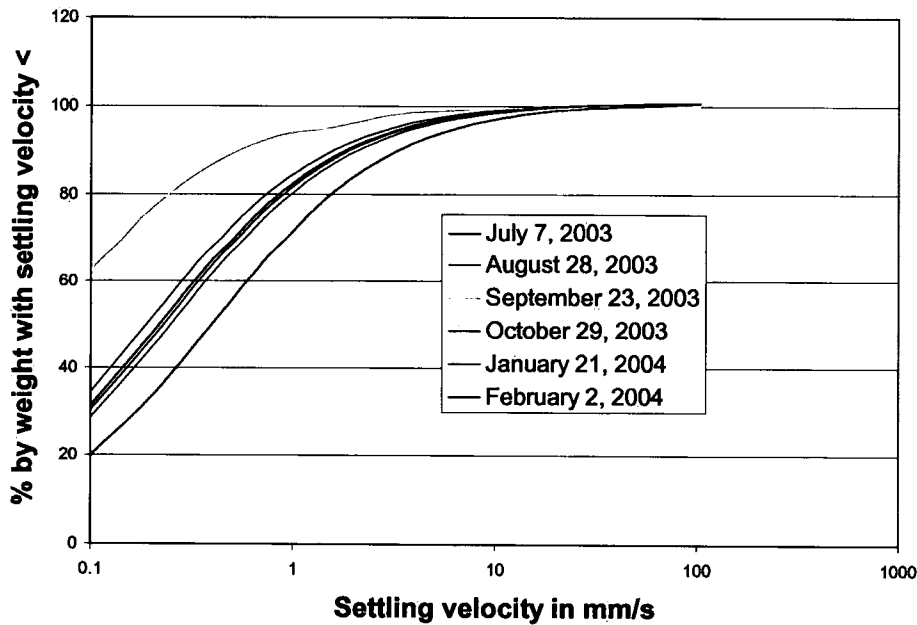


Fig. 5.39: Settling velocity distributions given by the Brombach column for dry-weather samples.

Settling velocity distributions - Brombach -Wet weather samples

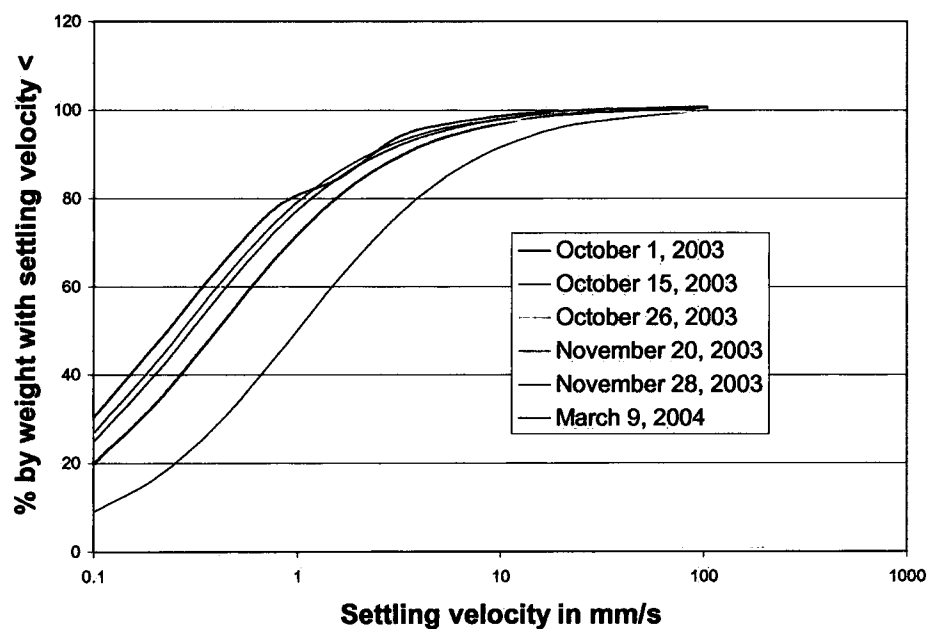


Fig. 5.40: Settling velocity distributions given by the Brombach column for wet-weather samples.

Surface loading rates given by Elutriation apparatus-Dry weather samples

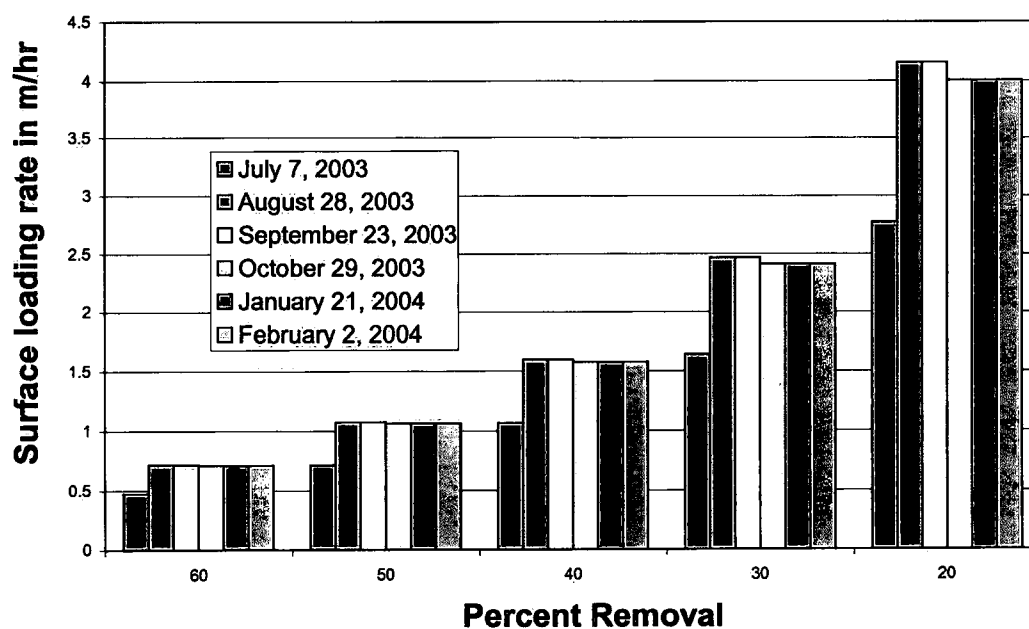


Fig. 5.41: Surface loading rates given by the Elutriation apparatus for dry-weather samples.

Surface loading rates given by Elutriation-Wet weather samples

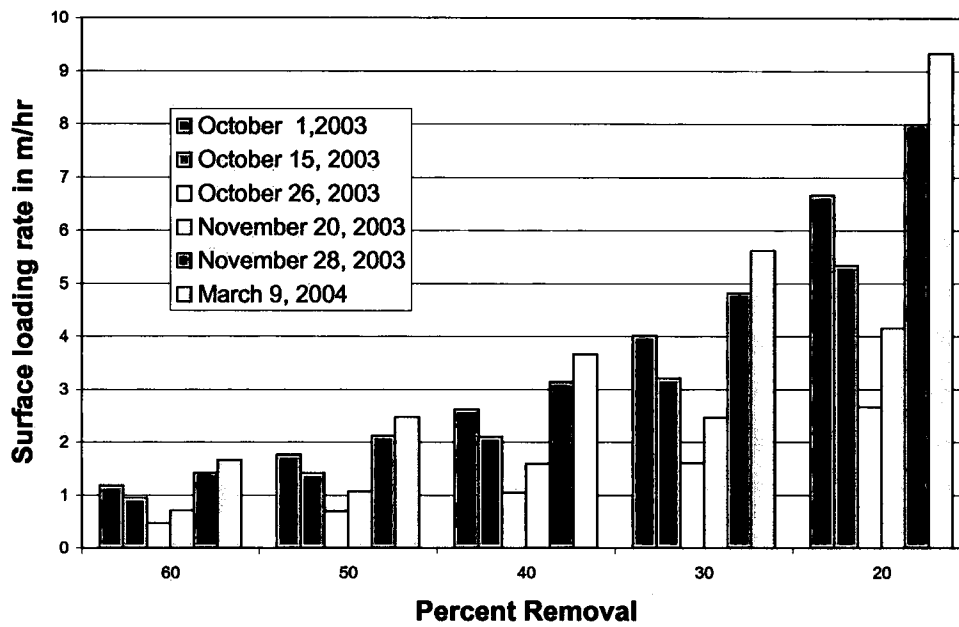


Fig. 5.42: Surface loading rates given by the Elutriation apparatus for wet-weather samples.

Surface loading rates given by US EPA method-Dry weather samples

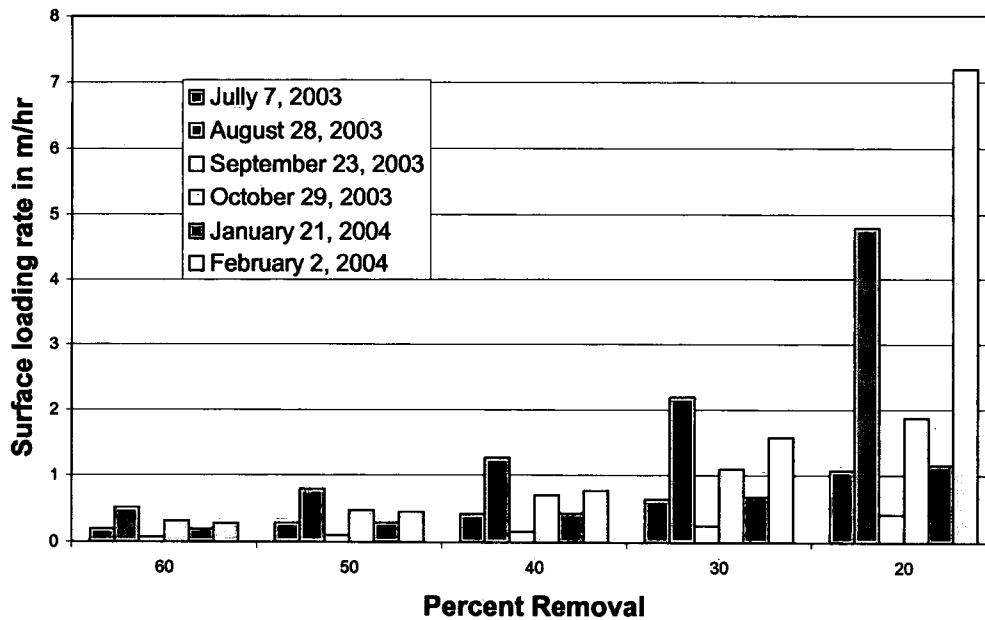


Fig. 5.43: Surface loading rates given by the U.S. EPA column for dry-weather samples.

Surface loading rates given by US EPA Method-Wet weather samples

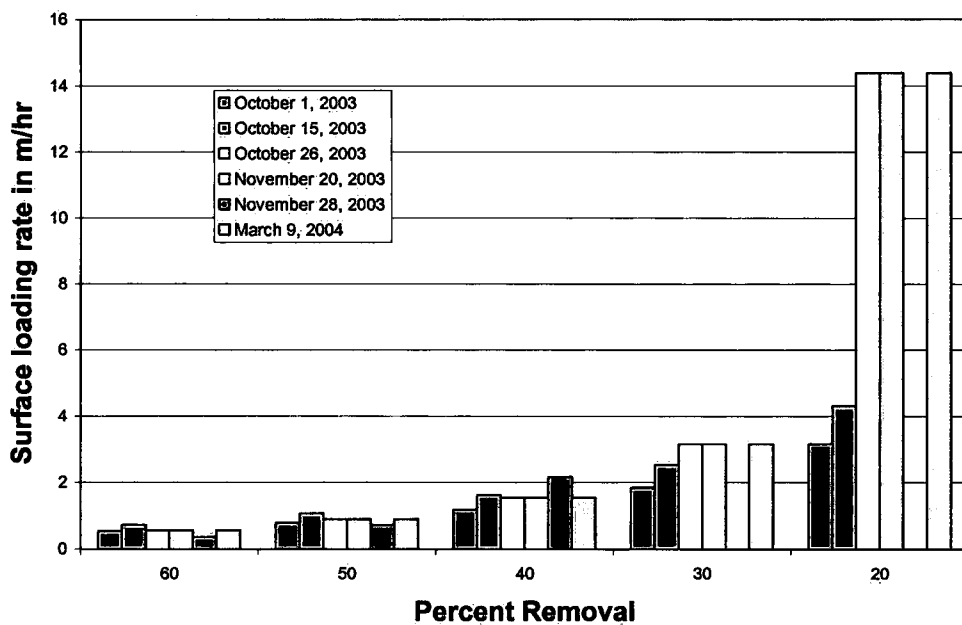


Fig. 5.44: Surface loading rates given by the U.S. EPA column for wet-weather samples.

Surface loading rates given by Aston Column- Dry weather samples

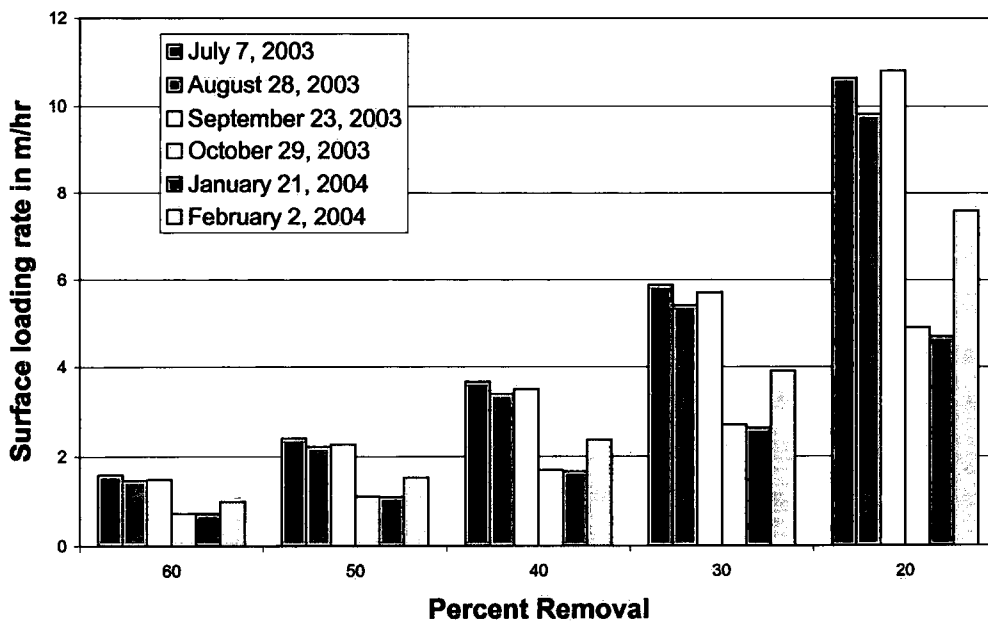


Fig. 5.45: Surface loading rates given by the Aston column for dry-weather samples.

Surface loading rates given by Aston Column- Wet weather samples

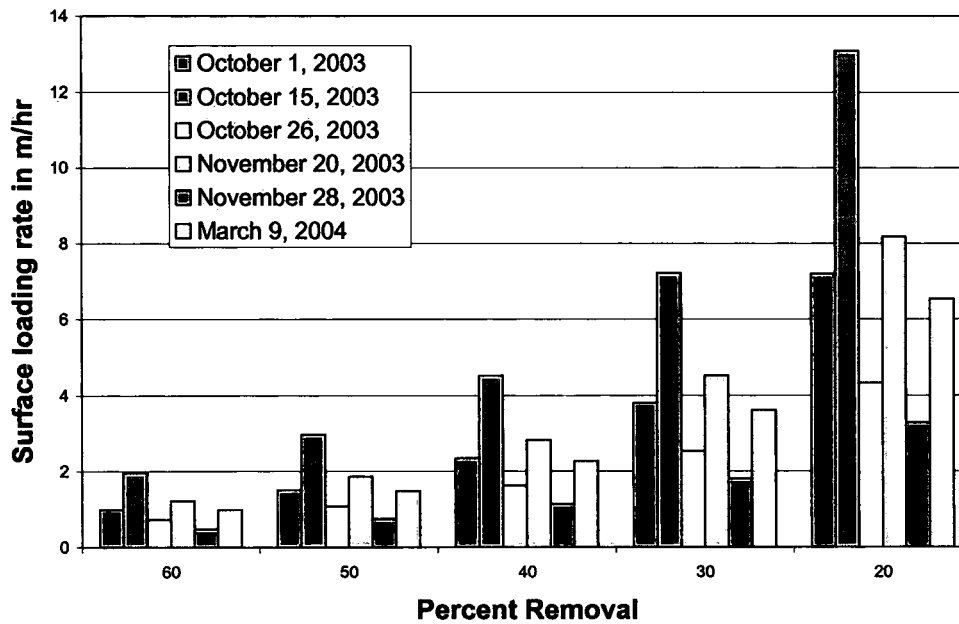


Fig. 5.46: Surface loading rates given by the Aston column for wet-weather samples.

Surface loading rates given by Brombach-Dry weather samples

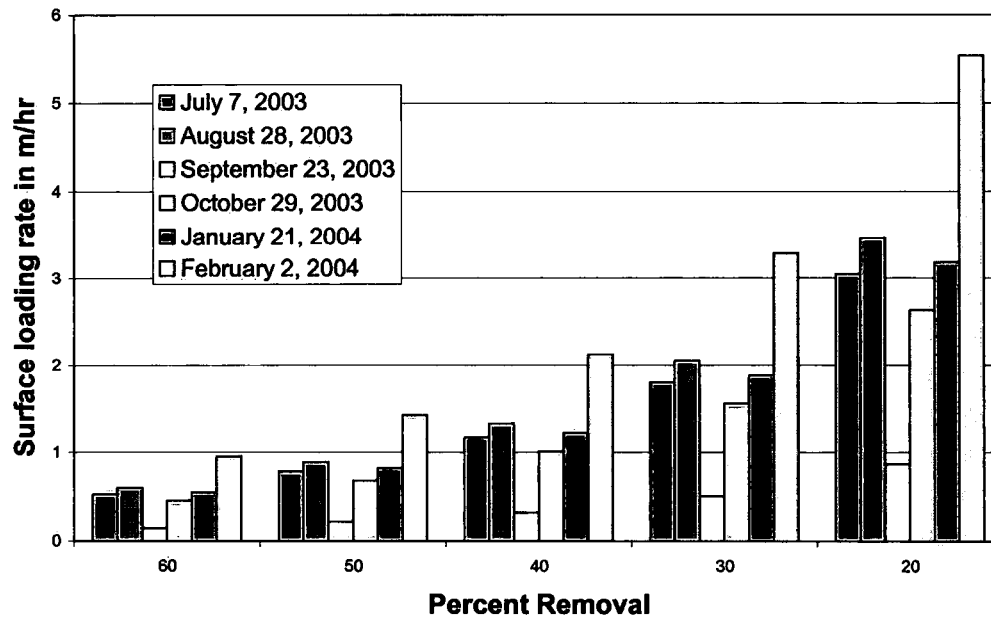


Fig. 5.47: Surface loading rates given by the Brombach column for dry-weather samples.

Surface loading rates given by Brombach- Wet weather samples

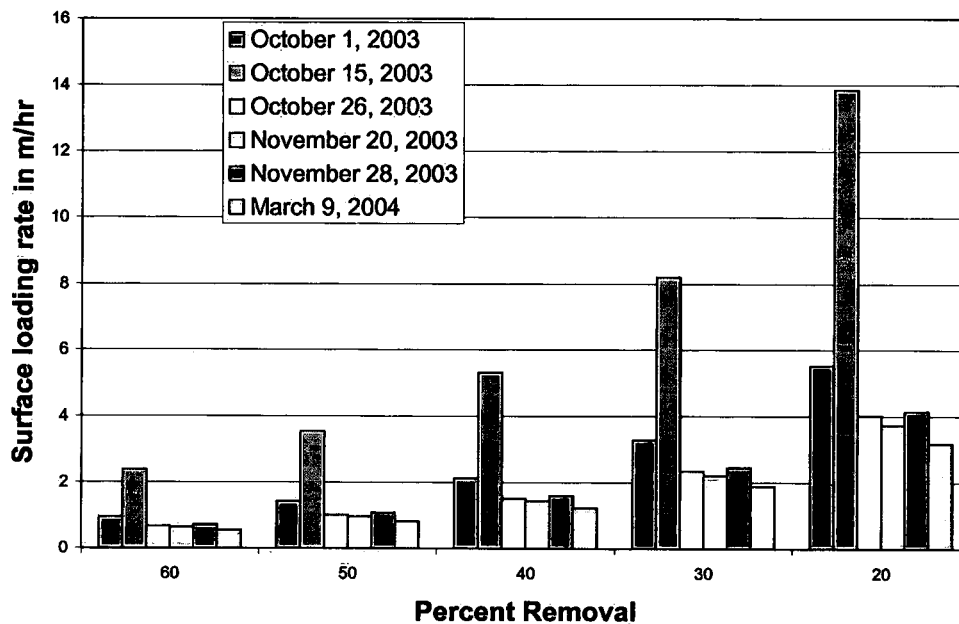


Fig. 5.48: Surface loading rates given by the Brombach column for wet-weather samples.

5.1.6 Differences between the XCG and NWRI Welland CSO settleability curves

The initial comparison of the XCG and NWRI settleability curves for Welland CSOs, obtained by the Brombach method, indicated significant discrepancies. Specifically, the NWRI data indicated lower settleabilities, with greater presence of finer fractions. Subsequent investigations of these discrepancies revealed that they were largely caused by differences in data analysis/presentation and by inherent experimental variability. Concerning the former point, the XCG plots refer to the samples, which were pre-settled for 1 hour (the mass of particulate remaining in suspension after 1 hour settling is not accounted for). On the other hand, the NWRI results were obtained by following the original Brombach procedure, with pre-settling for two hours, but when plotting the settleability curves, the need for consistency with other testing methods led to accounting for the entire mass of solids contained in the raw sewage sample (i.e., before pre-settling). If the NWRI results were replotted by retaining only the mass of pre-settled solids (however, pre-settled for two hours rather than one), the mean NWRI settleability curve falls within the XCG envelope of the data collected in several Canadian cities (Figure 5.49).

Thus, this particular difference is caused mostly by different presentation of observed data. The second source of discrepancies, variability in the sub-sampled media tested, is caused by sub-sampling of large (volume) CSO samples delivered to the XCG lab. Such samples were divided into two sub-samples, the first one retained by XCG and the second one delivered to NWRI. The sample splitting process is likely to produce sub-samples of somewhat different characteristics. Thus, recognizing the above sources of uncertainties and procedural differences, both sets of data appear to be comparable.

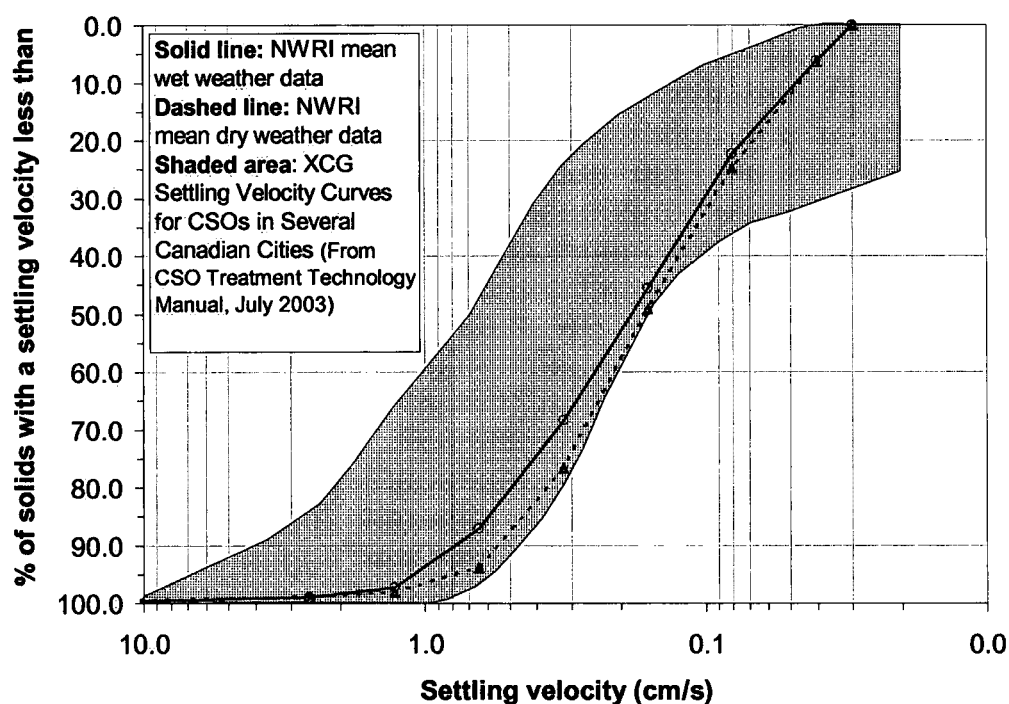


Fig. 5.49: Cumulative Distribution of Settling Velocity: Settleable Solids in Pre-Settled Sample - NWRI Data

5.2 Jar testing

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 two dates, 28-Nov-03 and 03-Mar-04, no replicates could be obtained using the

polymer, and results reflect only a single test. The results of the jar tests with Zetag 7873 are summarized for wet-weather samples in Table 5.7; the results for dry-weather samples are included in Table 5.8.

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

Sample date	Initial SS (mg / L)	SS remaining at specified polymer dosage (mg / L)				
		0	1	2	4	6
16-Jul-03	223	58.0	23.5	20.0	13.2	11.5
30-Sep-03	292	34.5	21.5	21.3	20.3	17.3
26-Oct-03	192	30.0	13.6	14.0	14.0	12.8
20-Nov-03	270	57.5	24.0	22.0	19.0	18.7
28-Nov-03	265	34.0	16.0	14.7	16.0	14.7
03-Mar-04	65.9	30.9	24.0	25.7	21.2	20.0
05-Mar-04	125	46.9	25.5	21.4	19.2	17.0
24-Mar-04	147	44.2	30.5	27.6	26.8	24.1
Mean	197	42.0	22.3	20.8	18.7	17.0
SD	80	11.4	5.4	4.7	4.4	4.1

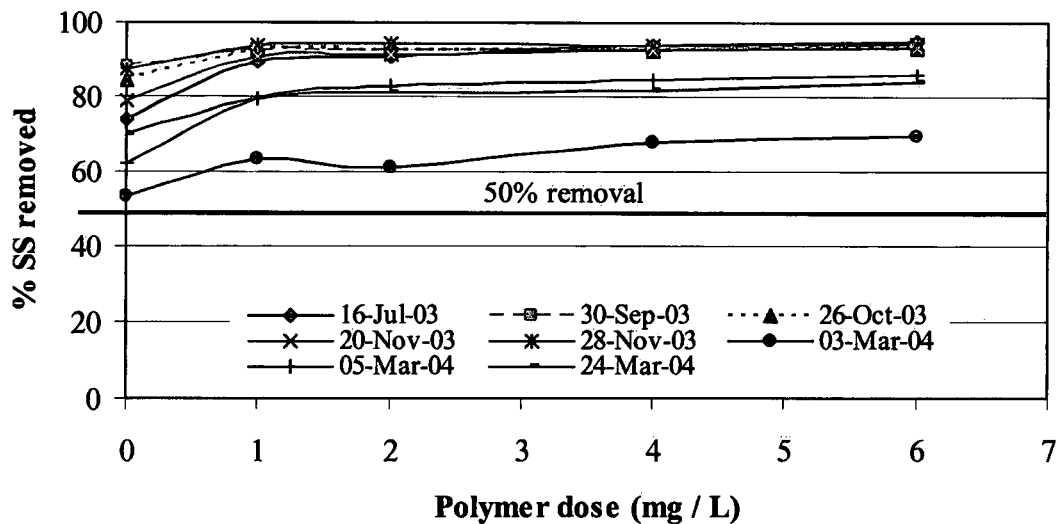


Fig. 5.50: Relative SS removal during jar tests of Welland wet-weather samples treated with Zetag 7873.

Table 5.8: Summary of jar test results for dry-weather samples treated with Zetag 7873.

Sample date	Initial SS (mg / L)	SS remaining at specified polymer dosage (mg / L)				
		0	1	2	4	6
07-Jul-03	232	45.5	24.0	21.2	18.4	16.5
28-Aug-03	54	26.3	21.2	20.5	21.0	18.0
23-Sep-03	121	40.2	31.1	28.7	26.2	22.0
29-Oct-03	115	34.5	22.7	20.5	18.0	17.0
21-Jan-04	126	27.4	21.1	21.0	20.3	21.0
Mean	130	34.8	24.0	22.4	20.8	18.9
SD	64	8.2	4.1	3.5	3.3	2.5

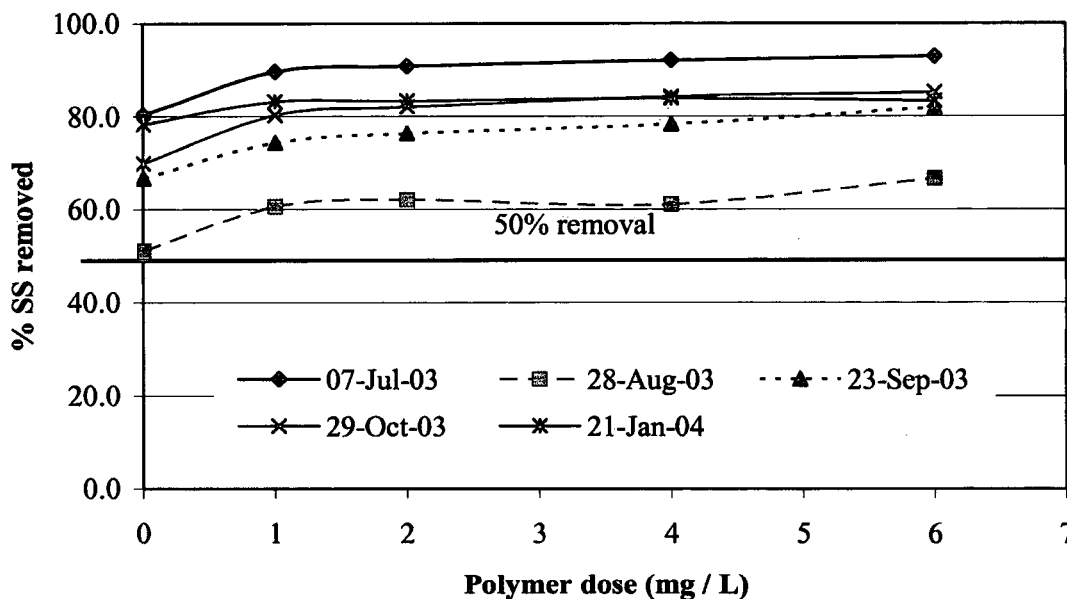


Fig. 5.51: Relative SS removal during jar tests of Welland dry-weather samples treated with Zetag 7873.

In all cases, very good SS removals were observed even in the absence of polymer; on average, 75% of suspended solids in wet-weather samples were removed by settling during the jar tests, and 69% of SS in dry-weather samples. The final SS concentrations were typically below 50 mg/L, so both TSS reduction criteria in the Ontario Ministry of Environment Procedure F-5-5, 50% removal and an average effluent TSS of ≤ 90 mg/L, could be met under these settling conditions. Previous studies have reported average settleable solids fractions of ~60-70% in wet-

weather samples, although this varies with both the sample and surface loading rate (Li *et al.* 2003, Averill *et al.* 1997). 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. A dosage of 1.0 mg/L of polymer (expressed as product as supplied) resulted in average TSS values after settling of 22-24 mg/L, or TSS removals of 78-85%. Overdosing (i.e. impairment of suspended solids removal at high flocculant doses) was only observed in a few samples at a dose of 8.0 or 10.0 mg / L (not shown). Qualitative observations were also recorded during each jar test; in general, floc size and settling rate increased with polymer dose. Further experiments will utilize the elutriation apparatus for assessment of floc settling rates in samples treated with polymer. Four dry-weather samples and three wet-weather samples were also tested with alum. Results for the dry-weather samples treated with alum are shown in Figs. 5.52 and 5.53; similar results were seen for wet-weather samples.

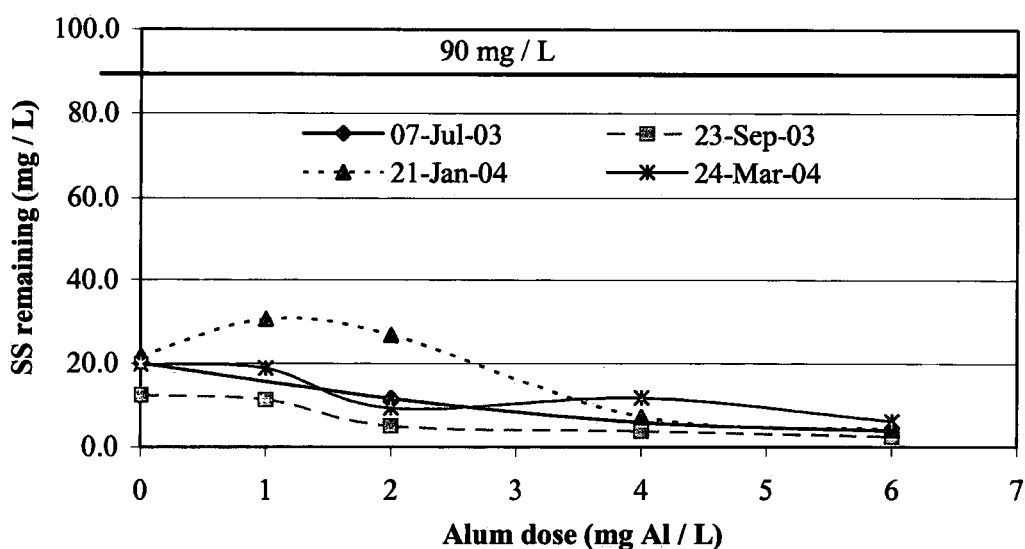


Fig. 5.52: SS remaining during jar tests of Welland dry-weather samples treated with alum.

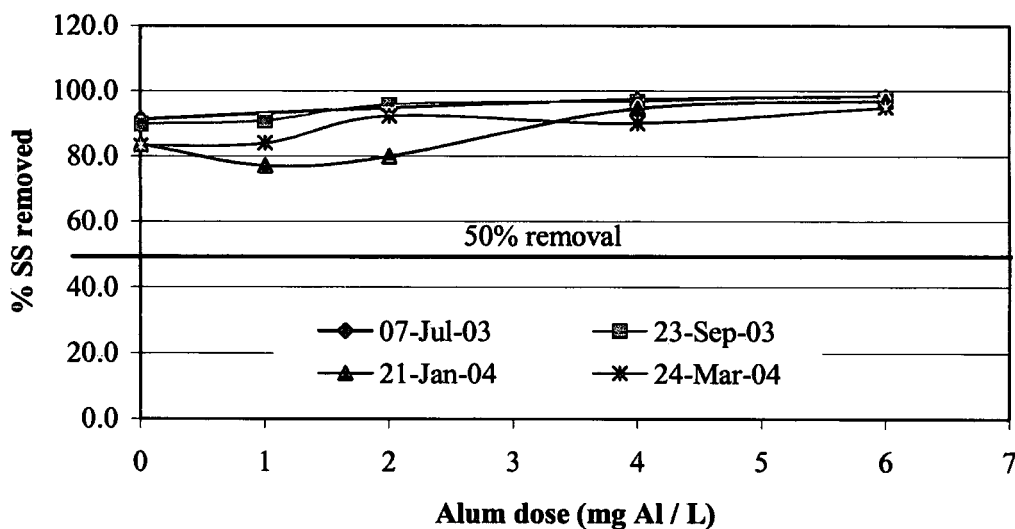


Fig. 5.53: Relative SS removal during jar tests of Welland dry-weather samples treated with alum.

The jar tests with alum included a flocculation (slow mixing) step, which further improved SS removal in the control jars over that seen in jar tests with Zetag 7873. It has been shown through jar tests that coagulation with polymers can be effective without the slow mixing step (Li *et al.* 2003, Young *et al.* 2003). When alum is added, the slow mix, or flocculation, step is necessary to allow the growth of settleable flocs (Amirtharajah and O'Melia 1990). The added mixing time likely allowed natural floc growth in the control jar (no coagulant added) through an increased frequency of interparticle collisions, resulting in lower TSS concentrations after settling.

The addition of alum also enhanced SS removal, once the coagulant demand had been met. As shown by the 21-Jan-04 sample in Fig. 5.52, dosages below this required concentration resulted in SS levels equal to or higher than in the control jar; above this dosage, the concentrations of SS remaining were extremely low.

5.3 Chemical characterization

5.3.1. Chemical characterization of CSO samples (raw water)

Analysis of TSS and VSS are performed on all samples in house; additional aliquots of raw water are sent to WTC Analytical Laboratories for analysis of TOC, DOC, COD, TP, TKN,

ammonia, and both dissolved and total Cu and Zn. All samples after July 16, 2003 were measured for BOD, as well. The first four samples of 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), the analyses were adjusted to focus on measurable analytes. 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.

Analytical data are available for samples up to and including March 9, 2004; data for the remaining two wet-weather and two dry-weather samples are yet to come. The results are summarized in Tables 5.9 to 5.12, below.

Table 5.9: Chemical analysis results for wet-weather flow samples

Collection Date		16-Jul-03	30-Sep-03	15-Oct-03	26-Oct-03	20-Nov-03
Analysis	Units					
TSS	mg/L	292	174	287	199	303
VSS	mg/L	129	79	161	117	147
TOC	mg/L as C	47.4	67.0	59.1	29.4	80.2
DOC	mg/L as C	12.3	10.5	15.4	15.3	9.3
Total COD	mg/L	254	179	346	246	251
Total BOD	mg/L	N/A	57	110	66	99
NH ₃	mg/L as N	2.63	4.43	4.58	5.84	7.53
TKN	mg/L as N	10.0	10.5	15.1	15.5	16.5
TP	mg/L as P	2.30	1.76	2.84	2.52	2.55
Chloride	mg/L	N/A	N/A	N/A	N/A	N/A
Cadmium, dissolved	µg/L	ND	ND	<1.8	ND	N/A
Cadmium, total	µg/L	9.00	<1.8	ND	5.04	N/A
Copper, dissolved	µg/L	<9	10.8	ND	ND	ND
Copper, total	µg/L	83.5	51.2	104	48.1	61.6
Lead, dissolved	µg/L	ND	ND	ND	ND	N/A
Lead, total	µg/L	<25.6	ND	ND	ND	N/A
Nickel, dissolved	µg/L	ND	ND	<7.3	20.1	N/A
Nickel, total	µg/L	17.5	ND	23.9	17.6	N/A
Zinc, dissolved	µg/L	31.3	20.6	24.0	17.4	15.1
Zinc, total	µg/L	233	143	183	110	166

N/A - Data not available

ND – Below detection limit

Table 5.9 continued: Chemical analysis results for wet-weather flow samples

Collection Date		28-Nov-03	03-Mar-04	05-Mar-04	09-Mar-04
Analysis	Units				
TSS	mg/L	259	60	112	161
VSS	mg/L	139	39	45	82
TOC	mg/L as C	60.4	28.2	32.0	42.3
DOC	mg/L as C	8.9	10.5	7.9	13.1
Total COD	mg/L	280	87	88	187
Total BOD	mg/L	120	37	27	70
NH ₃	mg/L as N	5.35	20.6	8.91	8.04
TKN	mg/L as N	16.0	13.1	15.1	15.7
TP	mg/L as P	2.98	1.38	1.09	2.17
Chloride	mg/L	N/A	141	119	116
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	ND	ND	<9	ND
Copper, total	µg/L	80.1	14.5	22.8	45.6
Lead, dissolved	µg/L	N/A	N/A	N/A	N/A
Lead, total	µg/L	N/A	N/A	N/A	N/A
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	19.7	12.2	19.5	6.46
Zinc, total	µg/L	143	32.7	82.5	88.1

N/A - Data not available

ND – Below detection limit

Table 5.10: Statistical summary of chemical analyses for wet-weather flow samples.

			Wet-weather samples			
Analysis	Units	MDL	n [†]	Median	Mean	SD
TSS	mg/L		9	199	205	86
VSS	mg/L		9	117	104	45
TOC	mg/L as C	0.50	9	47.4	49.6	18.3
DOC	mg/L as C	0.50	9	10.5	11.5	2.7
Total COD	mg/L	4.811	9	246	213	86.4
Total BOD	mg/L	1.118	8	67.9	73.2	33.8
NH ₃	mg/L as N	0.02	9	5.84	7.55	5.28
TKN	mg/L as N	0.157	9	15.1	14.2	2.4
TP	mg/L as P	0.082	9	2.30	2.18	0.65
Chloride	mg/L	0.51	3	119	125	13.7
Cadmium, dissolved	µg/L	1.80	0	N/A	N/A	N/A
Cadmium, total	µg/L	1.80	2	7.02	7.02	N/A
Copper, dissolved	µg/L	9.00	1	10.8	N/A	N/A
Copper, total	µg/L	9.00	9	51.2	56.8	28.9
Lead, dissolved	µg/L	25.6	0	N/A	N/A	N/A
Lead, total	µg/L	25.6	0	N/A	N/A	N/A
Nickel, dissolved	µg/L	7.30	1	20.1	N/A	N/A
Nickel, total	µg/L	7.30	3	17.6	19.7	3.67
Zinc, dissolved	µg/L	1.90	9	19.5	18.5	7.06
Zinc, total	µg/L	1.90	9	143	131	60.1

[†] n = number of results above the MDL

N/A - Data not available

Table 5.11: Chemical analysis results for dry-weather flow samples

Collection Date		07-Jul-03	28-Aug-03	23-Sep-03	29-Oct-03
Analysis	Units				
TSS	mg/L	231	59	119	123
VSS	mg/L	161	41	52	95
TOC	mg/L as C	28.2	28.8	17.9	63.6
DOC	mg/L as C	24.3	10.5	11.3	18.8
Total COD	mg/L	357	107	133	211
Total BOD	mg/L	N/A	75	66	26
NH ₃	mg/L as N	20.4	13.4	9.3	12.2
TKN	mg/L as N	28.0	20.3	14.8	28.7
TP	mg/L as P	4.33	2.25	1.37	0.57
Chloride	mg/L	N/A	N/A	N/A	N/A
Cadmium, dissolved	µg/L	<1.8	ND	ND	ND
Cadmium, total	µg/L	2.71	<1.8	ND	ND
Copper, dissolved	µg/L	56.2	15.5	18.3	<9
Copper, total	µg/L	72.4	30.6	18.1	16.0
Lead, dissolved	µg/L	ND	ND	<25.6	ND
Lead, total	µg/L	ND	ND	ND	ND
Nickel, dissolved	µg/L	<7.3	65.1	<7.3	20.2
Nickel, total	µg/L	7.49	8.47	<7.3	26.1
Zinc, dissolved	µg/L	191	21.4	28.7	13.9
Zinc, total	µg/L	196	53.9	48.2	46.0

N/A - Data not available

ND – Below detection limit

Table 5.11 continued: Chemical analysis results for dry-weather flow samples.

Collection Date		21-Jan-04	02-Feb-04
Analysis	Units		
TSS	mg/L	126	191
VSS	mg/L	100	162
TOC	mg/L as C	53.1	86.8
DOC	mg/L as C	17.9	17.2
Total COD	mg/L	387	276
Total BOD	mg/L	143	146
NH ₃	mg/L as N	15.5	28.1
TKN	mg/L as N	25.4	40.3
TP	mg/L as P	3.22	4.65
Chloride	mg/L	79.5	89.6
Cadmium, dissolved	µg/L	N/A	N/A
Cadmium, total	µg/L	N/A	N/A
Copper, dissolved	µg/L	<9	<9
Copper, total	µg/L	53.2	58.5
Lead, dissolved	µg/L	N/A	N/A
Lead, total	µg/L	N/A	N/A
Nickel, dissolved	µg/L	N/A	N/A
Nickel, total	µg/L	N/A	N/A
Zinc, dissolved	µg/L	37.2	3.48
Zinc, total	µg/L	71.2	75.7

N/A - Data not available

ND – Below detection limit

Table 5.12: Statistical summary of chemical analyses for dry-weather flow samples.

Analysis	Units	MDL	Dry-weather samples			
			n [†]	Median	Mean	SD
TSS	mg/L		6	125	141	60.5
VSS	mg/L		6	97	102	52
TOC	mg/L as C	0.50	6	41.0	46.4	26.2
DOC	mg/L as C	0.50	6	17.6	16.7	5.1
Total COD	mg/L	4.811	6	244	245	115
Total BOD	mg/L	1.118	5	75.0	91.2	52.0
NH ₃	mg/L as N	0.02	6	14.5	16.5	6.8
TKN	mg/L as N	0.157	6	26.7	26.3	8.6
TP	mg/L as P	0.082	6	2.74	2.73	1.63
Chloride	mg/L	0.51	2	84.6	84.6	N/A
Cadmium, dissolved	µg/L	1.80	0	N/A	N/A	N/A
Cadmium, total	µg/L	1.80	1	2.71	2.71	N/A
Copper, dissolved	µg/L	9.00	3	18.3	30.0	22.7
Copper, total	µg/L	9.00	6	41.9	41.5	23.2
Lead, dissolved	µg/L	25.6	0	N/A	N/A	N/A
Lead, total	µg/L	25.6	0	N/A	N/A	N/A
Nickel, dissolved	µg/L	7.30	1*	20.2	N/A	N/A
Nickel, total	µg/L	7.30	2*	16.8	16.8	N/A
Zinc, dissolved	µg/L	1.90	5**	21.4	20.9	13.0
Zinc, total	µg/L	1.90	5**	53.9	59.0	13.6

[†] n = number of results above the MDL

N/A - Data not available

* Dissolved and total nickel data rejected for 28-Aug-03 due to obvious error (i.e. concentration of dissolved nickel >> concentration of total nickel).

** Dissolved and total zinc data for 07-Jul-03 rejected as outliers by Q-tests, supported by the results of analyses of elutriation apparatus fractions.

Taking the minimum level of quantitation as 3.18 times the MDL (US EPA 2003), it can be seen that organics and nutrients (TOC, DOC, COD, BOD, TP, TKN, and ammonia) are regularly present at quantifiable levels. Similarly, chloride, total copper, and both total and dissolved zinc can be properly quantified in the samples listed; as noted above, concentrations of Cd, Pb and Ni were typically near or below the MDL and are not properly quantifiable.

The results for the quantifiable analytes in wet- and dry-weather samples were generally comparable; the differences under the two conditions are not statistically significant for most analytes. The mean values of TSS (205 mg/L wet and 141 mg/L dry) and total Zn (131 µg/L wet and 59 µg/L dry) appear to be much higher in wet-weather than in dry-weather samples, yet both displayed a great deal of variability with a coefficient of variation (CV, or relative standard deviation) of ~0.42 for the TSS measurements and 0.46-0.70 for Zn, so the differences are not significant at the 95% confidence interval. Only ammonia, TKN and DOC were significantly lower in wet weather than in dry weather, as might be expected when sewage is diluted with urban runoff. From the small number of analyses to date, chloride concentrations appear to be higher in wet-weather than dry-weather samples. These results are to be expected, as chloride concentration has thus far only been recorded during the winter months, when the application of road salts would likely contribute to chloride concentrations in surface runoff. Continued evaluation of chloride concentrations in both wet-weather and dry-weather samples will provide a baseline value for this ion in Welland wastewater through the rest of the year.

Typical concentrations of various constituents in weak, medium and strong wastewater are listed in Table 5.13. The dry-weather samples taken at Welland (Table 5.12) can be characterized as relatively 'weak' in terms of the concentrations of TSS, VSS, TOC, COD, BOD, ammonia, TKN, and TP. However, the samples in which chloride was measured proved to be 'strong' in chloride concentration.

Table 5.13: Typical concentrations of various analytes in wastewater of various strengths
(adapted from Metcalf and Eddy, 2003)

Analyte	Units	Wastewater		
		Weak	Medium	Strong
TSS	mg/L	120	210	400
VSS	mg/L	95	160	315
TOC	mg/L	80	140	260
COD	mg/L	250	430	800
BOD	mg/L	110	190	350
Ammonia	mg/L	12	25	45
TKN	mg/L	20	40	70
Total P	mg/L	4	7	12
Chloride	mg/L	30	50	90

Typical concentrations of a number of constituents of stormwater and CSOs are listed for various studies in Table 5.14. It should be noted that the values listed for lead in Ontario (Marsalek and Ng 1989) and under NURP (US 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 Welland's wet-weather flows.

Table 5.14: 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
TSS	mg/L	170 ¹	100	58	190	270-550
COD	mg/L	N/A	65	53	N/A	260-480
BOD	mg/L	14 ¹	9	8.6	41	60-220
Total N	mg/L	3.5 ¹	N/A	N/A	8.3	N/A
Ammonia	mg/L	0.30-0.75 ²	N/A	0.44	N/A	N/A
TKN		N/A	1.5	1.4	N/A	N/A
Total P	mg/L	0.35 ¹	0.33	0.27	1.4	1.2-2.8
Chloride	mg/L	230-340 ²	N/A	N/A	N/A	N/A
Copper	µg/L	43.4-47.2 ²	34	16	N/A	N/A
Lead	µg/L	97-233 ²	144	16	N/A	N/A
Zinc	µg/L	234-307 ²	160	116	N/A	N/A

N/A - Data not available

Sources of data:

1 Waller and Novak, 1981

2 Marsalek and Ng, 1989

3 US 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 Welland during this study were present at typical concentrations for such samples. At 205 mg/L, the mean TSS concentration was somewhat lower than the typical 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 (73.2 mg/L) and TP (2.18 mg/L) concentrations were somewhat higher than seen in the Ontario study, but were within the range reported as typical for CSOs. While zinc was present at a somewhat lower concentration (131 µg/L) than seen in Ontario stormwater (Marsalek and Ng 1989), the concentration of copper (57 µg/L) was higher than reported in any of the stormwater studies. Ammonia, TKN, and chloride were present at concentrations between typical values for stormwater and wastewater, at 7.6, 14.2, and 125 mg/L, respectively.

5.2.2. 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 five wet-weather and three dry-weather samples. Typical results are shown for a wet-weather sample in Fig. 5.54. The distributions of most of the contaminants by settling velocity fraction quite closely follow that of the TSS, emphasizing the importance of solids removal in reducing the contaminant load of an event.

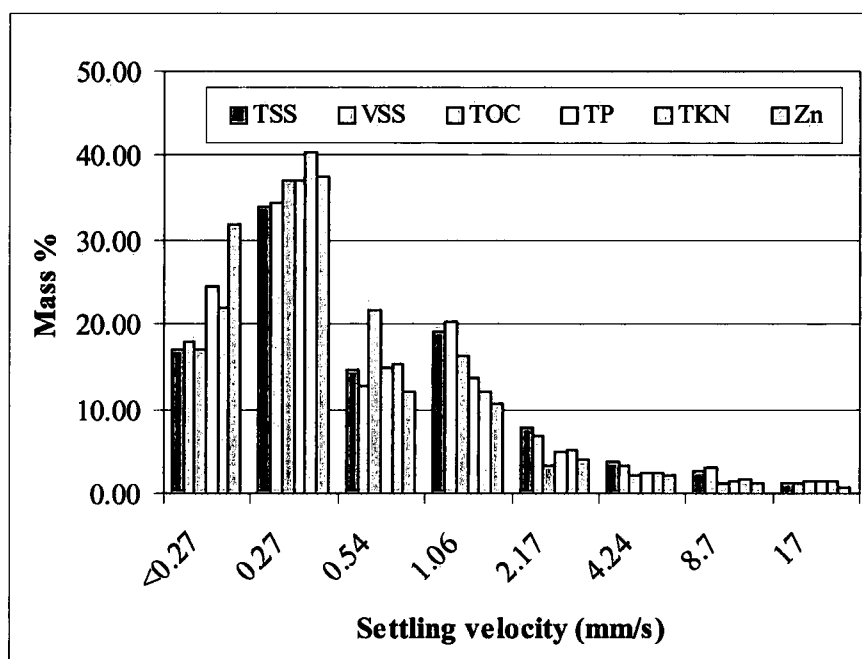


Fig. 5.54: Distribution of selected analytes in elutriation apparatus fractions for 01-Oct-03 wet-weather sample.

The mean and standard deviation results are summarized for each collected fraction of selected analytes for the wet-weather samples in Table 5.15: As the columns increase in size and volume from Column 1 to 7, the measured concentration of an analyte may decrease, but the total mass of that analyte collected in the column typically increases. In general, only a small portion of each analyte 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 TOC, typical recoveries are very good.

Table 5.15: Elutriation fraction chemistry results: wet-weather summary

	Analyte MDL Conc. units	TSS 2.3 mg / L		VSS 2.3 mg / L		TOC 0.5 mg / L		COD 4.811 mg / L	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Raw CSO	Concentration	245	44	127	27	59	19	260	60
	Mass (mg)	10761	2087	5583	1222	2597	853	11405	2642
Column 1 17 mm/s	Concentration	533	442	307	340	61	6.8	325	73
	Mass (mg)	172	142	100	111	20	3.0	105	29
	Mass %	1.64	1.20	1.73	1.54	0.65	0.38	1.05	0.47
Column 2 8.7 mm/s	Concentration	328	96	175	49	63.1	16.6	369	267
	Mass (mg)	172	50	91.4	24.7	33.01	8.92	191	133
	Mass %	1.77	0.54	1.86	0.71	0.96	0.18	1.72	0.90
Column 3 4.24 mm/s	Concentration	330	81	171	50	64	14	330	101
	Mass (mg)	275	68	142	42	53	12	275	83
	Mass %	2.82	0.54	2.78	0.44	1.60	0.39	2.59	0.73
Column 4 2.17 mm/s	Concentration	438	237	255	191	70	23	481	270
	Mass (mg)	727	401	424	323	116	38	799	458
	Mass %	7.20	2.86	7.74	4.01	3.32	0.41	7.20	2.85
Column 5 1.06 mm/s	Concentration	425	119	231	54	75	22	421	99
	Mass (mg)	1451	424	790	200	254	76	1439	363
	Mass %	14.85	3.14	15.68	3.09	8.12	4.68	13.81	3.43
Column 6 0.54 mm/s	Concentration	240	47	119	28	59	16	240	47
	Mass (mg)	1383	267	687	160	340	88	1388	274
	Mass %	14.21	0.81	13.43	1.18	10.88	6.16	13.08	0.65
Column 7/8 0.27 mm/s	Concentration	158	30	81	15	51	17	179	34
	Mass (mg)	3463	695	1780	374	1128	405	3941	902
	Mass %	36.84	5.29	35.13	4.56	32.18	4.18	37.05	3.76
Unsettled <0.27 mm/s	Concentration	48	13	25	7.8	35	16	57	19
	Mass (mg)	2139	593	1120	345	1583	726	2551	836
	Mass %	21.80	3.74	21.66	3.86	42.30	14.70	23.50	2.98
	Recovery	91	13	92	12	168	132	93.8	5.4

Table 5.15 continued: Elutriation fraction results: wet-weather summary

	Analyte MDL Conc. units	TP 0.082 mg / L		Cu 9.0 µg/L		Zn 1.9 µg/L	
		Mean	SD	Mean	SD	Mean	SD
Raw CSO	Concentration	2.71	0.44	69	23	149	28
	Mass (mg or µg)	118.52	19.49	3023	1013	6528	1227
Column 1 17 mm/s	Concentration	5.09	2.52	92	30	219	76
	Mass (mg or µg)	1.63	0.79	30	11	71	26
	Mass %	1.39	0.51	1.09	0.44	0.96	0.29
Column 2 8.7 mm/s	Concentration	4.00	1.71	80	27	202	48
	Mass (mg or µg)	2.09	0.88	42	14	106	26
	Mass %	1.74	0.44	1.44	0.19	1.43	0.13
Column 3 4.24 mm/s	Concentration	2.90	0.50	105	40	207	50
	Mass (mg or µg)	2.42	0.43	88	34	172	42
	Mass %	2.10	0.10	2.98	0.64	2.34	0.22
Column 4 2.17 mm/s	Concentration	3.66	1.24	105	46	218	81
	Mass (mg or µg)	6.06	2.12	174	79	361	139
	Mass %	5.16	1.02	5.89	1.07	4.86	1.47
Column 5 1.06 mm/s	Concentration	3.44	0.77	108	32	225	59
	Mass (mg or µg)	11.73	2.74	368	115	768	215
	Mass %	10.34	2.51	13.02	3.37	10.49	2.20
Column 6 0.54 mm/s	Concentration	2.63	0.39	65	20	188	97
	Mass (mg or µg)	15.19	2.39	378	122	1075	522
	Mass %	13.22	0.87	13.04	2.33	14.30	4.66
Column 7/8 0.27 mm/s	Concentration	2.06	0.34	58	15	122	17
	Mass (mg or µg)	45.42	9.23	1279	372	2671	413
	Mass %	39.26	3.60	45.54	12.03	36.75	3.38
Unsettled <0.27 mm/s	Concentration	0.70	0.18	24	11	47	9
	Mass (mg or µg)	31.35	8.22	1075	526	2110	401
	Mass %	26.79	2.64	16.99	16.02	28.87	2.97
	Recovery	97.7	10.2	97.6	19.2	112.6	7.1

6. Conclusions

Characteristics of both wet-weather (CSOs) and dry-weather (municipal sewage) flows at the Welland sewage treatment plant were determined through laboratory testing of samples collected at the plant. Even though the sampling and testing program is still continuing, preliminary guidance for further work can be provided on the basis of the data available in late April, 2004. Specifically, the following conclusions can be drawn at this time (July 2004):

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 US EPA Column Method (EPACM), and a newly proposed elutriation apparatus (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 EAM, ACM and BCM produced similar results, with mean surface loads of 1.06, 1.25 and 0.98 m/h, respectively. The EPACM indicated a significantly lower rate of 0.4 m/h. The small number of samples prevented calculation of meaningful standard deviations, but EAM produced the least variation in results. For CSO samples, the average surface load rates for 50% TSS removal were 1.59, 1.61, 1.48 and 0.88 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, for practical design, EAM, ACM and BCM provided comparable data; but the EPACM indicated somewhat lower settleabilities. The results obtained so far indicate that any of the three comparable methods (EAM, ACM, BCM) would be acceptable and produce comparable designs. The final choice within this group would depend on other considerations. The EAM 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 so far assessed only 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 Welland CSO samples with low polymer dosages. Without any additions, 80% of TSS settled in jar tests after 20 minutes; with polymer addition of 1 mg/L, this removal increased to 90% and changed little with larger polymer dosages (2, 4, and 6 mg/L). Thus, the currently available data indicate that Welland CSOs may be well suited for chemically aided settling, with relatively inexpensive low dosages of a polymeric coagulant. Upcoming experiments employing the Elutriation apparatus to evaluate settling in polymer-treated samples will confirm the suitability of this treatment method for Welland CSOs.
3. Dry-weather flow and CSO chemical characteristics – the municipal sewage at this site is characterized by weak strength, with mean concentrations of TSS (141 mg/L), VSS (102 mg/L), TOC (46 mg/L), BOD (91 mg/L), COD (245 mg/L), TP (2.7 mg/L), TKN (26 mg/L) and NH_3 (16.5 mg/L) being comparable to those listed in common handbooks for weak sewage. Chloride concentration (85 mg/L) was elevated to the “strong sewage” value. CSO samples related well to the composition of municipal sewage; as expected, they contained higher levels of TSS (205 mg/L), chloride (125 mg/L) and some trace metals (mean total Cu = 0.057 mg/L, Ni = 0.020 mg/L and Zn = 0.131 mg/L), all associated with stormwater runoff, and lower concentrations of oxygen demanding constituents (mean concentrations TOC = 50 mg/L, DOC = 11.5 mg/L, COD = 213 mg/L, BOD = 73 mg/L) and nutrients (mean concentrations NH_3 = 7.6 mg/L, TKN = 14.2 mg/L, and TP = 2.2 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 0.45 for dry-weather samples and 0.37 for CSOs. At 95% confidence levels, there was no statistically significant difference between the dry-weather and CSO water quality data.

4. Pending completion of the originally proposed sampling program and the resulting changes in estimates of CSO characteristics, the results presented in this report provide good guidance for planning CSO storage and treatment facilities in the City of Welland.

7. Acknowledgments

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- NWRI staff providing technical assistance in sample processing and analysis.

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 Science and Technology* 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 Science and Technology* 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 C.R. O'Melia. (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 Science and Technology* Vol. 33, No. 9, pp 127-134.
- Averill, D., D. Mack-Mumford, J. Marsalek, R. Andoh and D. Weatherbe. (1997). Field facility for research and demonstration of CSO treatment technologies. *Wat. Sci. Technol.* Vol. 36, No. 8-9, pp 391-396.
- Bolto B.A., D.R. Dixon, S.R. Gray, H. Chee, P.J. Harbour, L. Ngoc and A.J. Ware. (1996). The use of soluble organic polymers in waste treatment. *Wat. Sci. Tech.* Vol. 34, No. 9, pp. 117-124.
- Hennis S., D. Brown, S.R. Vasconcellos, and J.M. Gucciardi. (2001). Polymer technology boosts wastewater treatment performance. *Chemical Processing (On-line)*. Accessed April 22, 2004 on the Internet at <<http://www.chemicalprocessing.com>>.
- Krishnappan, B.G., Marsalek, J., Stephens, R.P., Rochfort, Q., Exall, K. and Seto, P. (2004 – in press). A water elutriation system for measuring settling velocity distribution of suspended solids in combined sewer overflows. *Water Quality Research Journal of Canada* (2004 – special issue on urban water).
- Li J., S. Dhanvantari, D. Averill, and N. Biswas. (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 H.Y.F. Ng (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., C. He, Q. Rochfort, K. Exall, J. Wood, B.G. Krishnappan, P. Seto and P. Chessie (2003). 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*. Preprints, NATO Advanced Research Workshop, Nov. 5-8, 2003, Rome, Italy, pp 93-104.

- 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 Science and Technology* 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 Science and Technology* 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 Science and Technology* 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. U.S. EPA report # EPA/600/R-02/090. October 2002. CRADA # 136-96. National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio.
- Odegaard H. (1988). Coagulation as the first step in wastewater treatment. In Hahn, HH 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 Science and Technology* 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 Environment and Technology*, Vol. 8, No. 4, pp 27-33.
- Pitt, R., Maestre, A., 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 T. Larsen (1996). A method for measuring sludge settling characteristics in turbulent flows. *Wat. Res.* Vol. 30, No.10, pp 2363-2370.
- Standard Methods 19th Ed. 4500-NH₃ G Nitrogen (Ammonia): Automated Phenate Method.
- Standard Methods 20th Edition 2540 E Fixed and Volatile Solids Ignited at 550°C.
- Standard Methods 20th Edition 5310B Total Organic Carbon: Combustion-Infrared Method.
- Standard Methods 20th Edition 2540 D Total Suspended Solids Dried at 103-105°C.
- Tyack, J.N., Hedges, P.D., 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. (2003). Technical Support Document for the Assessment of Detection and Quantification Approaches. Office of Science and Technology, U.S. EPA, Washington, D.C.
- 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 Z. Novak (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 Research, Vol. 27, No. 9, pp 1413-1421.
- Wood, J., M. Yang, Q. Rochfort, P. Chessie, J. Marsalek and P. Seto (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 (in press).
- WTCAL INW3 Wastewater Technology Centre Analytical Laboratory Method INW3 Determination of Biochemical Oxygen Demand in Water.
- WTCAL INW10 Wastewater Technology Centre Analytical Laboratory Method INW10 Determination of Total Kjeldahl Nitrogen in Water, Solids and Sludges.
- WTCAL INW11 Wastewater Technology Centre Analytical Laboratory Method INW11 Determination of Total and Dissolved Phosphorus in Water and Total Phosphorus in Solids and Sludges.
- WTCAL INW13 Wastewater Technology Centre Analytical Laboratory Method INW13 Determination of Anions in Water.
- WTCAL INW14 Wastewater Technology Centre Analytical Laboratory Method INW14 Determination of Metals (Total and Dissolved) in Water by Inductively Coupled Plasma.
- WTCAL INW16 Wastewater Technology Centre Analytical Laboratory Method INW16 Determination of COD in water.
- Young S., S.J. Stanley, and D.W. Smith. (2003). Effect of mixing on the kinetics of polymer-aided flocculation. J. Water Supply. Vol. 49, pp 1-8.

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