

A Water Elutriation Apparatus for Measuring Settling Velocity Distribution of Suspended Solids in Combined Sewer Overflows

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An elutriation apparatus has been proposed for determining the settling velocity distributions of suspended solids in combined sewer overflows (CSOs). The apparatus consisted of a series of interconnected cylindrical settling chambers, through which the sample was drawn using a peristaltic pump attached to the outlet of the last settling chamber. 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. The apparatus was tested using samples from a CSO outfall in Hamilton, Ontario, Canada. The test results showed that the apparatus performed well for determining settling characteristics of suspended solids and chemical distribution in different settling fractions. The effectiveness of polymer addition to enhance flocculation and settling of CSOs was also tested in this apparatus. The elutriation apparatus proposed here offers several advantages over the traditional methods (i.e., settling columns) of measurements of settling velocity distributions. The main advantage is its ability to measure the distributions under dynamic conditions, i.e., in the presence of flow. Consequently, the elutriation apparatus reproduces flow conditions in actual settling tanks better than conventional settling columns.

Key words: elutriation, settling velocity, suspended solids, combined sewer overflows

Introduction

The settling velocity distribution of suspended solids in combined sewer overflows is an important parameter for assessing the feasibility of effective CSO treatment by settling. The settling velocity distributions are usually obtained by direct measurements using experimental settling columns of various designs (e.g., Michelbach and Wöhrle 1993; Andoh and Smisson 1996; Pisano 1996; Rasmussen and Larsen 1996). Settling columns can be divided into two categories, (a) columns with quiescent settling (no turbulence) and (b) a turbulent settling column. Examples of columns belonging to the first group include the U.S. EPA Column (Dalrymple et al. 1975; O'Connor et al. 2002), Aston Column of the Aston University in the U.K. (Tyack et al. 1996), Umwelt-und Fluid-Technik Apparatus, Germany (also known as the Brombach column; Michelbach and Wöhrle 1993), and the Cergrene apparatus (Chebbo 1992; Aiguier et al. 1996). While the individual columns differ in their design and operational procedures (Aiguier et al. 1996, 1998), all suffer from a limitation of quiescent settling, which is not typical for actual CSO settling tanks. The need to account for settling under flow turbulence led to the development of a more complex apparatus incorporating an oscillating grid (Rasmussen and Larsen 1996).

This proliferation of testing methods raises the question of how similar the settling velocity characterizations produced by these methods are, and consequently, a number of researchers conducted comparative studies (Aiguier et al. 1996, 1998; Tyack et al. 1996; O'Connor et al. 2002). Aiguier et al. (1996) compared four columns (i.e., Aston Column, UFT column, Andreasen pipette and the Cergrene settling column) and observed that for the same sample, the different columns indicated different settling velocity distributions. They attributed this result to the differences among the test methods employed by the various columns. A similar conclusion was reported by O'Connor et al. (2002), who compared the U.S. EPA column and the Aston column. In both of the above studies, the authors also have highlighted some of the practical difficulties associated with the settling column measurements, including the difficulty in establishing a uniform concentration of the particles in the settling column at the start of a test and the inability to measure the fast settling fraction of the sediment in the initial phase of the test (Aiguier et al. 1996, 1998; O'Connor et al. 2002). Furthermore, a major drawback of the settling column measurement is particle settling under quiescent conditions; in full-scale, on-line settling tanks, particles undergo dynamic settling in the presence of flow. For these reasons, there is a need for a settling velocity measurement system that will overcome the above difficulties and drawbacks, however, without the

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complexity of devices involving mechanical generation of turbulence (Rasmussen and Larsen 1996). To fulfill this need, a water elutriation apparatus is proposed in this paper for measuring CSO settleability, with or without chemical addition, under dynamic conditions.

Description of the Water Elutriation Apparatus

The water elutriation apparatus that is proposed in the present study is a modified version of a system proposed by Walling and Woodward (1993) for measuring size distribution of suspended sediment in rivers. The Walling and Woodward system consisted of four cylindrical settling chambers interconnected in series by glass and PVC tubing as shown schematically in Fig. 1. The sediment-water mixture was drawn from the river or from the flume through the series of settling chambers by a peristaltic pump. The pump was positioned on the downstream side of the settling chambers so that it did not disrupt the sediment flocs as they passed through the apparatus. The inlet and outlet positions in each settling chamber were such that the sediment suspension entered the chambers near the bottom and exited near the top. Such an arrangement allowed the sediment flocs that had settling velocities higher than the upward suspension velocity to settle in the respective chambers. The diameters of the chambers increased progressively from 25 to 200 mm with successive chambers doubling in size. The upward velocities of the suspension, therefore, decreased progressively in successive chambers by a factor of four. The suspension discharging out of the peristaltic pump, which was operated at a flow rate of 0.1 L/min, contained the sediment fraction whose settling velocity was lower than the suspension velocity in the fourth chamber. This fraction was collected and included in the calculation of the settling velocity distribution of the particles and in checking mass balance of the experiments.

In adapting this water elutriation system to CSO testing, a number of modifications were implemented. The

flow rate was increased from 0.1 to 0.5 L/min to maintain a turbulent flow regime in the PVC tube leading to the first chamber. A turbulent flow regime is also beneficial for mixing a coagulant/flocculant solution with the sample when the apparatus is used for testing chemically aided settling. The mixing was also aided by a static mixer installed in the feed tube. Complete and rapid mixing of the coagulant and the sample is required to quickly disperse the coagulant throughout the sample, in order to maximize the contact between the coagulant and the particles for effective chemical coagulation (Metcalf and Eddy 2003). In this study, a commercially available polymer was used as the flocculant of choice. The sample and the polymer solution were drawn from two separate containers and mixed in the tube leading to the first chamber.

The second modification involved eliminating the 25-mm settling chamber and using only three settling chambers. With the flow rate of 0.5 L/min, the upward velocities generated in the three settling chambers were 4.24, 1.06 and 0.265 mm/s, in the first, second and third chamber, respectively. The particles discharging from the peristaltic pump have settling velocities lower than 0.265 mm/s and hence are denoted by a settling velocity designation of <0.265 mm/s. These settling velocities (1.0–15.2 m/h) cover well the range of typical overflow rates used in practice for design of primary clarifiers (2.5–4.2 m/h; Metcalf and Eddy 2003), which would be applicable to plain settling of CSOs. The volumes of the chambers were 1.0, 3.30 and 9.50 litres, respectively. The modified water elutriation system is shown schematically in Fig. 2. This system was then tested using CSO samples from Hamilton, Ontario, Canada. Details of the testing procedure and the results are presented in this paper.

Materials and Methods

CSO samples were collected from a combined sewer outfall in Hamilton by pumping out the samples into large containers (65-litre capacity). Six such containers were

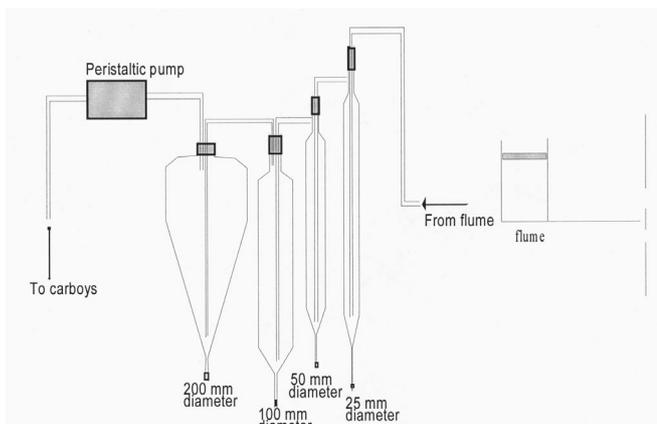


Fig. 1. Schematic view of the water elutriation system of Walling and Woodward (1993).

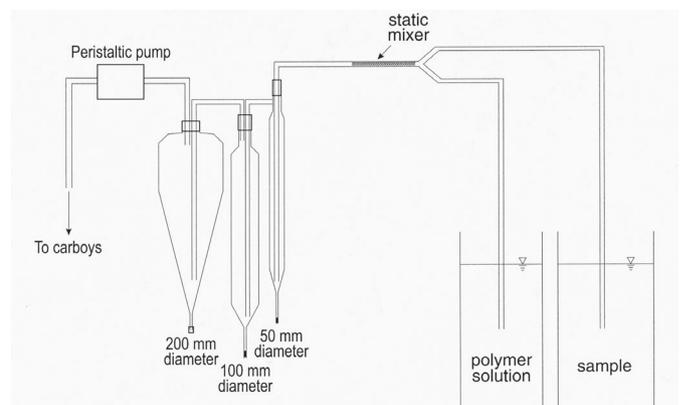


Fig. 2. Modified water elutriation system proposed for testing settleability of CSOs.

filled and transported to the laboratory, where they were stored in a cold room prior to testing. During this time, the bulk of the solids settled to the bottom of the containers. At the time of testing, the sample in each container was split into two parts. Part 1 was the supernatant water, which was used to fill the three settling chambers and a 25-litre plastic bottle. Part 2 was the rest of the sample, which was well mixed and then poured into a second 25-litre plastic bottle. For polymer aided settling tests, a known volume of 0.1% solution by weight of Zetag 7873 flocculant (Ciba Specialty Chemicals) was added to the bottle containing the supernatant water and mixed thoroughly using a propeller type mixer. The Zetag 7873 flocculant is a cationic polyelectrolyte having relatively high molecular weight and low charge density. The dose range for the polymer addition was determined using standard jar tests. The sample in the second bottle was also mixed thoroughly with the help of a second mixer.

To begin a test, the peristaltic pump was started and the sample and the supernatant water were drawn from the two bottles into the settling chambers. The discharge from the peristaltic pump was collected in an effluent plastic bottle. As the sample and the polymer dosed supernatant water flowed into the tube leading to the first settling chamber through a Y connector, the two streams mixed due to their impingement and turbulence in the tube. A static mixer installed in the tube also ensured that the two streams mixed completely. As the mixture flowed through the settling chambers, flocs of different settling velocities settled in different settling chambers. The flocs that did not settle in the settling chambers were transported through the peristaltic pump and were collected in a separate container for counting as the fraction with settling velocity less than 0.265 mm/s.

The peristaltic pump was run for 90 min. During this time, the flow rate through the pump was monitored to ensure that it remained fairly steady at 0.5 L/min. The tube leading to the first settling chamber had to be cleared of flocs sticking to the static mixer by occasionally tapping the tube gently with a plastic rod. At the end of the test, the peristaltic pump was switched off and the materials collected in different settling chambers were quantified. This was done by mixing the contents of the

chambers uniformly and measuring the solids concentration in the homogenous mixture. The solids mass concentration in the mixture was then multiplied by the total volume of the chamber to calculate the mass of the solid particles settled in each chamber. In addition, uniformly mixed samples of sediment water mixture were collected from each of the chambers for chemical analyses.

Results and Discussion

Settling Tests

Altogether six tests were carried out using the modified water elutriation system. The main characteristics of these tests (including the mass balance check for these tests), are summarized in Table 1. In this table, the weights of the solids collected in different chambers are listed together with the weight of the solids pumped through the system during the test period. In the last column a recovery ratio is calculated which is the ratio of the solids collected and the solids pumped (i.e., the mass in). On average, solids recovery (mass balance) was $98.1 \pm 5.6\%$. The data in Table 1 were used to calculate the settling velocity distributions for the six tests and the results are plotted as bar charts in Fig. 3 to 5. In Fig. 3, the results from Test #1 and #2, without chemical settling aid, are plotted. In Fig. 4, the results from Test #3 and #4 with a polymer dose of 4 mg/L are illustrated. Finally, in Fig. 5, the results from Test #5 and #6 with a polymer dose of 8 mg/L are shown. The test results shown in Fig. 3 (without polymer) serve as reference tests for comparing the effect of polymer dose on settling velocity of solids in CSOs.

Figure 3 shows that in polymer-free (un-aided) settling, only a small percentage of solids (~2.5% by weight) had settling velocities greater than or equal to 4.24 mm/s (15.3 m/h), and the bulk of solids (~65% by weight) were in the settling velocity class of <0.265 mm/s (0.95 m/h). This figure also shows that the results from Test #1 and #2 were fairly close to each other even though the initial concentrations of the solids in these tests were very different (95 mg/L in Test #1 and 143 mg/L in Test #2). This is an indication that the particles may have undergone discrete particle settling; floc-

TABLE 1. Main characteristics of the settleability tests carried out in the water elutriation apparatus

Test no.	Polymer dose (mg/L)	Mass of particles pumped (mg)	Mass in 50-mm chamber (mg)	Mass in 100-mm chamber (mg)	Mass in 200-mm chamber (mg)	Mass passing pump (mg)	Total mass accounted for (mg)	Recovery ratio (%)
1	0	4287	107.1	356.5	966.5	2954	4384	102.3
2	0	6419	157.5	670.3	1416	3969	6214	96.8
3	4	6016	3182	1065	451.6	510.6	5210	90.6
4	4	9060	4390	961.9	2136	2150	9639	106.4
5	8	4780	1407	848.9	735.5	1691	4682	97.9
6	8	5879	1547	914.9	1085	1994	5541	94.3

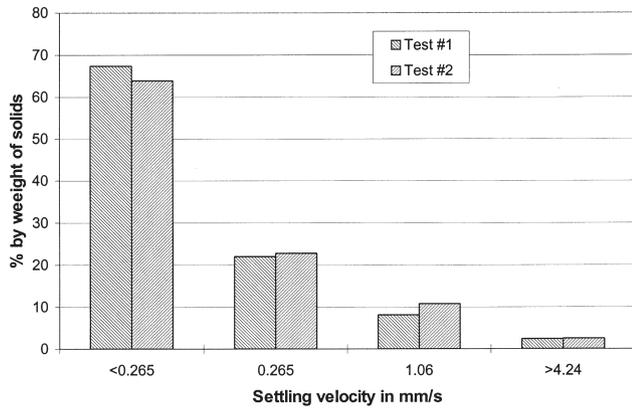


Fig. 3. Settling velocity distribution of Hamilton CSO samples (without polymer).

culent settling with particle interaction would be affected by the concentration of suspended solids.

In Fig. 4, where the results from Test #3 and #4 are displayed, the distributions are very much different from those shown in Fig. 3. In these tests, settling was aided by 4 mg/L of polymer and hence due to flocculation, the bulk of the sediment had settled in the first chamber with settling velocities greater than or equal to 4.24 mm/s (15.3 m/h). Only a small fraction (10–20% by weight) of solids had passed through the peristaltic pump (i.e., had a settling velocity of <0.265 mm/s [0.95 m/h]). The differences in results between Tests #3 and #4 are more pronounced than those between Tests #1 and #2. This can be attributed to the difference in the initial concentrations of solids in these tests (134 mg/L in Test #3 and 201 mg/L in Test #4) because of the dominant flocculent settling, and the differences in relative doses of polymer per mg TSS.

Figure 5 shows the results for Test #5 and #6 in which the polymer dose was 8 mg/L. Doubling the polymer dose had not increased the settleability of the solids as the fraction of the solids settling in the first chamber

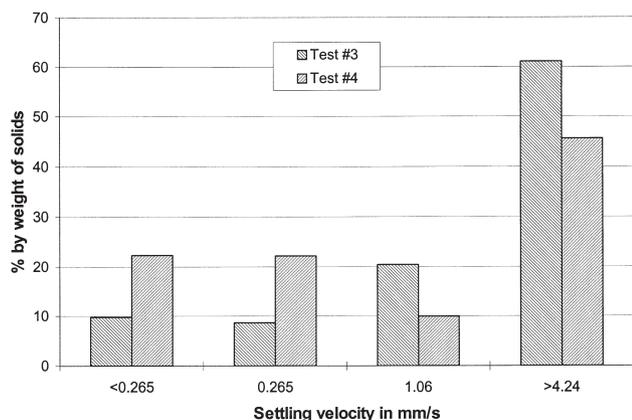


Fig. 4. Settling velocity distribution of Hamilton CSO samples with polymer addition: dose = 4 mg/L.

dropped to about 30% and the solid fraction with settling velocity less than 0.265 mm/s (0.95 m/h) increased to about 35%. The polymer dose of 8 mg/L appears to be an overdose, which has a negative effect on the flocculation process by particle restabilization (Amirtharajah and O’Melia 1990; Metcalf and Eddy 2003). The differences between the results of the two tests shown in this figure were also insignificant because the difference in the solid concentrations of the samples for these tests was comparatively small (106 mg/L for Test #5 and 131 mg/L for Test #6) and the flocculation process was not as dominant.

Figures 3 to 5 give the histograms of the settling velocity distributions of solids. For computing the fraction of the solids that can be removed in a primary sedimentation tank, a cumulative settling velocity distribution is required. Such distributions were constructed for all the tests and are shown in Fig. 6. Knowing the cumulative settling velocity distribution of solids, the fraction of the solids that would settle in a primary sedimentation tank for a given overflow rate can be calculated using the following expression (Metcalf and Eddy 2003):

$$\text{Fraction Removed} = (1 - X_c) + \int_0^{X_c} \frac{V_p}{V_c} dx \quad (1)$$

where V_p is the settling velocity distribution of the solids and V_c is the surface loading rate for the sedimentation tank expressed in mm/s. X_c is the fraction of the solids that has settling velocity greater than V_c . Applying the above equation for the size distribution resulting from Test #1, the fraction removed in a sedimentation tank with a surface loading of 100 m³/m²-day (i.e., 4.2 m/h, a typical value for peak flows in primary sedimentation tanks; Metcalf and Eddy 2003) was calculated as 12.5%. A similar value for Test #3 was calculated as 73.5% and for Test #5 as 43%. From these values, and the Ontario Ministry of the Environment regulatory requirement of 50% of solids removal in CSO treatment (OMOE, undated) one can conclude that the

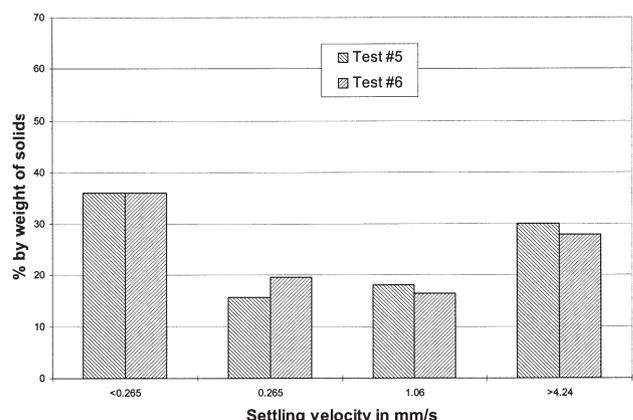


Fig. 5. Settling velocity distribution of Hamilton CSO samples with polymer addition: dose = 8 mg/L.

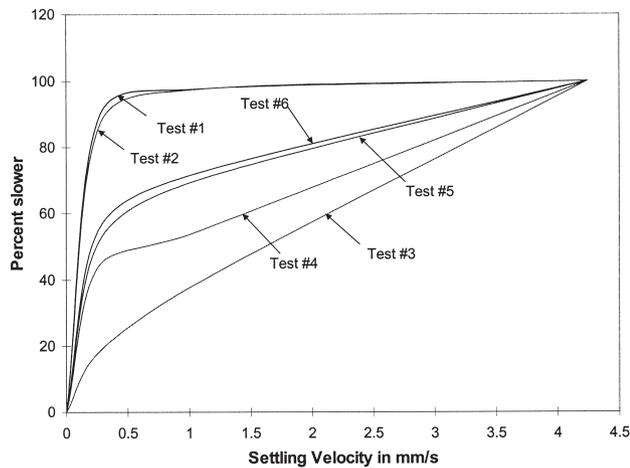


Fig. 6. Cumulative settling velocity distributions of solids in Hamilton CSO samples.

treatment of CSOs in a primary sedimentation tank is a viable option with a polymer addition of 4 mg/L.

Chemical Analyses

Settling removes not only solids, but also other constituents associated with solids. To obtain some general

indication of association of various constituents with specific settling fractions, the samples collected from the settling columns and the raw CSO were analyzed for selected trace metals (cadmium, chromium, copper, manganese, lead and zinc), nutrients (total phosphorus [TP], ammonia and total Kjeldahl nitrogen [TKN]) and constituents relating to the organic content and oxygen demand (chemical oxygen demand [COD], total and dissolved organic carbon [TOC and DOC, respectively]). The measured concentrations of these analytes are listed in Tables 2 to 4 for Tests #1, #3 and #5, respectively. The data for Tests #2, #4 and #6 were similar to Tests #1, #3 and #5, respectively, and hence are not listed. The concentrations of cadmium, chromium and ammonia were all below detection limits. For all the other chemicals, the concentrations were higher. High concentrations of these chemicals were found in samples collected from the 50-mm chamber, especially in Test #3 and Test #5 in which the polymer was used. It should be pointed out, however, that the concentrations reported here were total concentrations, which represent the sum of the constituent concentrations in the particulate and dissolved phases. Therefore, it is not possible to draw a definite conclusion about the fraction of the chemicals that are associated with

TABLE 2. Summary of concentration data for Test #1 (without polymer)

Sample description	Total Cu ($\mu\text{g/L}$)	Total Mn ($\mu\text{g/L}$)	Total Zn ($\mu\text{g/L}$)	Total Pb ($\mu\text{g/L}$)	Total P (mg/L)	TKN (mg/L)	COD (mg/L)	DOC (mg/L)	TOC (mg/L)
Whole sample	41.05	23.0	172.3	13.65	0.48	1.12	35.0	9.38	13.8
50-mm chamber	115.0	138.0	206.0	26.10	0.45	1.16	33.0	10.2	13.2
100-mm chamber	48.50	132.0	179.0	11.70	0.45	1.02	19.0	8.92	13.0
200-mm chamber	44.20	121.0	170.0	12.30	0.45	1.05	14.0	8.56	12.0
Pumped discharge	59.16	72.29	123.5	20.46	0.37	0.85	24.6	10.2	10.9

TABLE 3. Summary of concentration data for Test #3 (with polymer, dose = 4.0 mg/L)

Sample description	Total Cu ($\mu\text{g/L}$)	Total Mn ($\mu\text{g/L}$)	Total Zn ($\mu\text{g/L}$)	Total Pb ($\mu\text{g/L}$)	Total P (mg/L)	TKN (mg/L)	COD (mg/L)	DOC (mg/L)	TOC (mg/L)
Whole sample	36.30	57.8	218.9	19.13	0.57	1.80	52.5	9.10	13.5
50-mm chamber	306.0	2370	2390	128.0	8.09	30.4	839	11.5	91.1
100-mm chamber	46.50	221.0	273.0	16.10	0.79	2.84	73.0	8.11	9.47
200-mm chamber	21.40	18.00	71.50	23.90	0.36	0.99	25.0	8.31	8.52
Pumped discharge	18.90	7.300	44.50	21.97	0.35	0.78	21.4	7.63	8.84

TABLE 4. Summary of concentration data for Test #5 (with polymer, dose = 8.0 mg/L)

Sample description	Total Cu ($\mu\text{g/L}$)	Total Mn ($\mu\text{g/L}$)	Total Zn ($\mu\text{g/L}$)	Total Pb ($\mu\text{g/L}$)	Total P (mg/L)	TKN (mg/L)	COD (mg/L)	DOC (mg/L)	TOC (mg/L)
Whole sample	15.38	174.9	90.80	25.10	0.64	1.58	54.0	4.87	10.5
50-mm chamber	157.0	2290	909.0	72.30	2.92	9.63	297	4.18	22.0
100-mm chamber	24.20	304.0	133.0	29.30	0.96	2.28	60.0	5.09	5.24
200-mm chamber	10.70	93.90	55.30	40.10	0.62	1.32	36.0	4.35	6.50
Pumped discharge	13.57	37.29	35.03	40.20	0.46	1.17	34.7	3.64	4.79

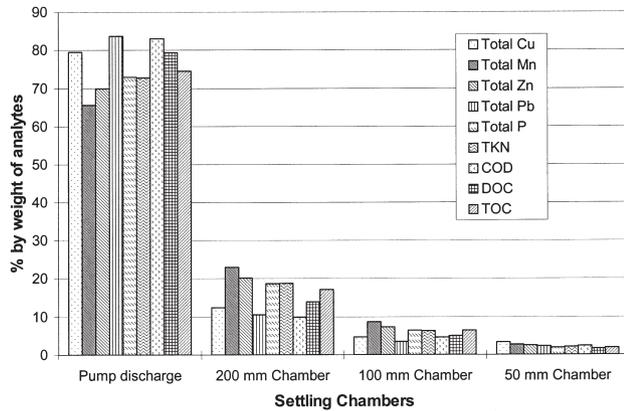


Fig. 7. Constituent distribution in different settling fractions in Test #1.

solids of different settling velocity classes. However, the chemical data can be used to determine the changes in the distribution of chemicals in different chambers for different tests. For this, a mass balance calculation was carried out, and the percentage of mass associated with different chambers is plotted in Fig. 7 to 9 for Tests #1, #3 and #5. Results for Tests #2, #4 and #6 were similar to Tests #1, #3 and #5, respectively, and hence are not shown.

From Fig. 7 corresponding to Test #1, one can see that much of the contaminants are associated with the pump discharge (solids having low settling velocity and the water). In this test, the settling was not aided by polymer and only a small fraction of solids was trapped in the settling chambers. In the case of polymer-aided settling with a polymer dose of 4 mg/L (i.e., in Test #3 shown in Fig. 8), a significant portion of the chemicals is captured in the 50-mm chamber. This can be attributed to the flocculation process by which the finer particles with higher chemical concentrations are incorporated into the floc structures that have much higher settling

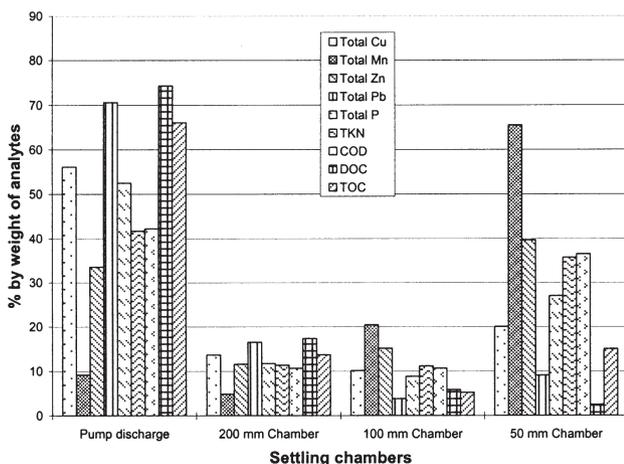


Fig. 8. Constituent distributions in different settling fractions in Test #3.

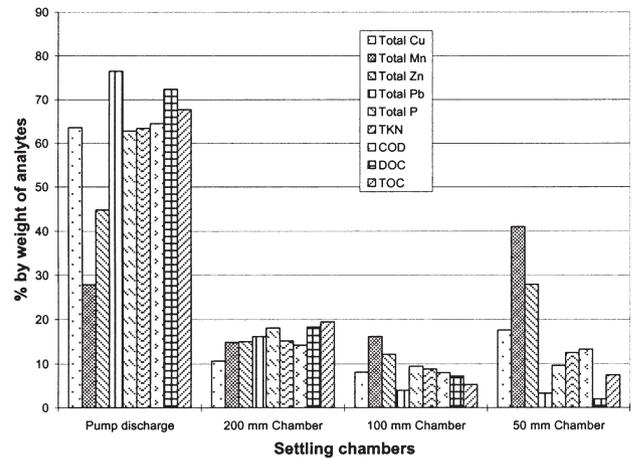


Fig. 9. Constituent distributions in different settling fractions in Test #5.

velocities. This effect was particularly strong for Mn, Zn, TKN and COD. Note that the distribution of DOC exhibited little change on addition of the polymer, indicating that the dissolved material was not affected by the flocculation. With a further increase in the polymer dose, i.e., 8 mg/L, overdosing of the flocculant causes the flocculation process to become less effective in transferring the finer fractions into coarser floc structures and hence the chemical transfer to the 50-mm chamber is comparatively lower as can be seen in Fig. 9.

Summary and Conclusions

A modified water elutriation apparatus is proposed for determining the settling velocity distribution of suspended solids present in combined sewer overflows. The apparatus allows the use of polymers to enhance the settling through the flocculation process. The system was tested using samples from a CSO outfall in Hamilton, Ontario, Canada. The test results show that the proposed apparatus performed well for determining settling characteristics of suspended solids. The apparatus is amenable to collecting samples for chemical analyses for the determination of chemical distributions in different settling fractions. The testing procedure demonstrated the use of polymers for enhancing settling and trapping of sediment and associated chemical contaminants. Compared to the conventional settling columns, the elutriation apparatus offers two main advantages—it mimics better dynamic (turbulent) settling in actual settling tanks and allows evaluation of chemically aided settling.

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