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Flocculation/Aggregation of Cohesive Sediments in the Urban Continuum: Implications for Stormwater Management

By:
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00-095 - FLOCCULATION/AGGREGATION OF COHESIVE SEDIMENTS IN THE URBAN CONTINUUM: IMPLICATIONS FOR STORMWATER MANAGEMENT

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Abstract

The urban continuum, as it applies to sediments and associated contaminants, represents the area over/through which sediments are conveyed from a depositional or eroded surface to a treatment system and/or receiving water body. This study has focused on the changing physical characteristics of the sediment, with an emphasis on flocculation/aggregation, as it progresses through the urban continuum. The sediments of the urban continuum are found to change from an unflocculated state on the street, to a flocculated state in the surface runoff to a very large floc form in the sewer system. The high organic content in the sewers contributes to the large floc size. The structure of the flocs and the flow regime of the receiving water will dictate the fate of the sediment following a combined sewer overflow. Probability distributions fitted to the distributions of each sediment type (compartment) confirmed significant differences in the sediment population sizes. Bulk and individual particle settling velocity experiments also revealed substantial differences between compartments. Sewer flocs were found to be of low density, with high porosity, water and organic content and with settling velocities which increase with floc size.

Management Perspective

This study focused on the changing physical characteristics of the sediment, with an emphasis on flocculation/aggregation, as it progresses through the urban continuum (the route that the sediment/water takes as it moves from the street surface through the combined sewer system to the aquatic environment via a combined sewer overflow). Changes were observed in the sediment structure from an unflocculated state on the street, to a flocculated state in the surface runoff to a very large floc form in the sewer system. These changes in structure have implications for the transport of sediment and associated contaminants. In addition, the state and composition of a floc will also have profound effects on the contaminant uptake, transformation and fate. By viewing the sewer system as the conveyance pathway and observing the changes in floc structure with regards to the changing flow regimes within this pathway, this study illustrates the importance of understanding particle structure to better assess the source, fate and effect of contaminated sediments within the urban environment.

FLOCULATION ET AGRÉGATION DES SÉDIMENTS COHÉSIFS DANS LE CONTINUUM URBAIN : CONSÉQUENCES POUR LA GESTION DES EAUX PLUVIALES

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Résumé

Dans le contexte des sédiments et des contaminants qui leur sont associés, le continuum urbain désigne la zone dans laquelle ou à travers laquelle les sédiments sont transportés d'une surface érodée ou sédimentaire vers un système de traitement et/ou un plan d'eau récepteur. La présente étude a porté sur le changement des propriétés physiques des sédiments et plus particulièrement sur leur floculation et leur agrégation à mesure qu'ils migrent dans le continuum urbain. Les sédiments passent d'un état non floculé sur la chaussée à un état floculé dans l'eau de ruissellement, puis forment des flocs très volumineux dans les égouts. La teneur élevée en matières organiques des eaux d'égout favorise la formation de flocs de grandes dimensions. La structure des flocs et le régime d'écoulement des eaux réceptrices influent sur le devenir des sédiments après le débordement des égouts unitaires. Des distributions de probabilité ajustées à la distribution de chaque type de sédiments (compartiment) ont confirmé que la taille des populations de sédiments varie de façon significative. Des analyses de la vitesse de dépôt de particules individuelles ou groupées ont également révélé des différences appréciables entre les compartiments. Dans les égouts, les flocs ont une faible densité, une forte porosité et une teneur élevée en eau et en matières organiques et la vitesse de dépôt augmente proportionnellement à leur taille.

Gestion

Cette étude a porté sur le changement des propriétés physiques des sédiments, et plus particulièrement sur leur floculation et leur agrégation à mesure qu'ils migrent dans le continuum urbain (route empruntée par les sédiments et l'eau, depuis la chaussée jusqu'au réseau d'égout unitaire et le milieu aquatique, via un déversoir d'orage). On a constaté que la structure des sédiments se modifie, passant d'un état non floculé sur la chaussée à un état floculé dans l'eau de ruissellement, puis que des flocs très volumineux se forment dans les égouts. Ces modifications de la structure se répercutent sur le transport des sédiments et des contaminants qui leur sont associés. Par ailleurs, l'état et la composition des flocs influent considérablement sur la biomobilisation, la transformation et le devenir des contaminants. En considérant que le réseau d'égout constitue une voie de transport et que la structure des flocs se modifie selon le régime d'écoulement, la présente étude démontre l'importance de bien comprendre la structure des particules afin de mieux évaluer la source, le devenir et les effets des sédiments contaminés dans le milieu urbain.

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FLOCCULATION/AGGREGATION OF COHESIVE SEDIMENTS IN THE URBAN CONTINUUM: IMPLICATIONS FOR STORMWATER MANAGEMENT

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ABSTRACT

The urban continuum, as it applies to sediments and associated contaminants, represents the area over/through which sediments are conveyed from a depositional or eroded surface to a treatment system and/or receiving water body. This study has focused on the changing physical characteristics of the sediment, with an emphasis on flocculation/aggregation, as it progresses through the urban continuum. The sediments of the urban continuum are found to change from an unflocculated state on the street, to a flocculated state in the surface runoff to a very large floc form in the sewer system. The high organic content in the sewers contributes to the large floc size. The structure of the flocs and the flow regime of the receiving water will dictate the fate of the sediment following a combined sewer overflow. Probability distributions fitted to the distributions of each sediment type (compartment) confirmed significant differences in the sediment population sizes. Bulk and individual particle settling velocity experiments also revealed substantial differences between compartments. Sewer flocs were found to be of low density, with high porosity, water and organic content and with settling velocities which increase with floc size.

Keywords: Urban continuum, sediment, flocculation, sewer, stormwater

INTRODUCTION

Like natural fluvial systems, the urban environment has many components and pathways for the conveyance of water, sediment and contaminants through its watershed (sewershed). The sewershed of an urban environment is analogous to a river basin, each having their own sub-basins (with localized effects of surface runoff, erosion, atmospheric and groundwater inputs) feeding larger basins with an eventual output (river mouth, storm sewer or combined sewer outfall) to a receiving water body or sewage treatment plant (STP). Because of the strong association of contaminants to sediments [the majority of the USEPA priority pollutants (nutrients, heavy metals and organic pollutants) are primarily or exclusively associated with sediment and biota [1]], sediment erosion and conveyance within urban storm runoff can represent an important potential pollutant source. Particulate matter in urban areas has been shown to have potentially strong health risks to humans with associated socio-economic implications [2]. In addition to environmental concerns, the deposition of sediments in sewer systems results in the reduction of pipe capacity and gradient, increasing the probability of surcharging, flooding and overflows [3, 4].

The *urban continuum*, as it applies to sediments and associated contaminants, represents the area over/through which sediments are conveyed from a depositional or eroded surface to a treatment system or receiving water body. It comprises four linked pathways or compartments (Figure 1); 1) dry surface materials deposited on, or contained in, pervious or impervious surfaces, which is then 2), eroded from the surface and transported in surface washoff during storm events (comparatively little sediment is moved out of the urban system via ground water flow), to 3), sewers (combined and/or storm) which, 4), transport the sediment to a sewage treatment plant and/or receiving water body via a sewer system (combined or storm). As the sediment moves through and between these pathways, it undergoes physical, chemical and biological modifications which influence subsequent movements and impacts within the urban and receiving water systems. In each of these pathways the sediment takes on unique characteristics in terms of structure and potential chemical and biological

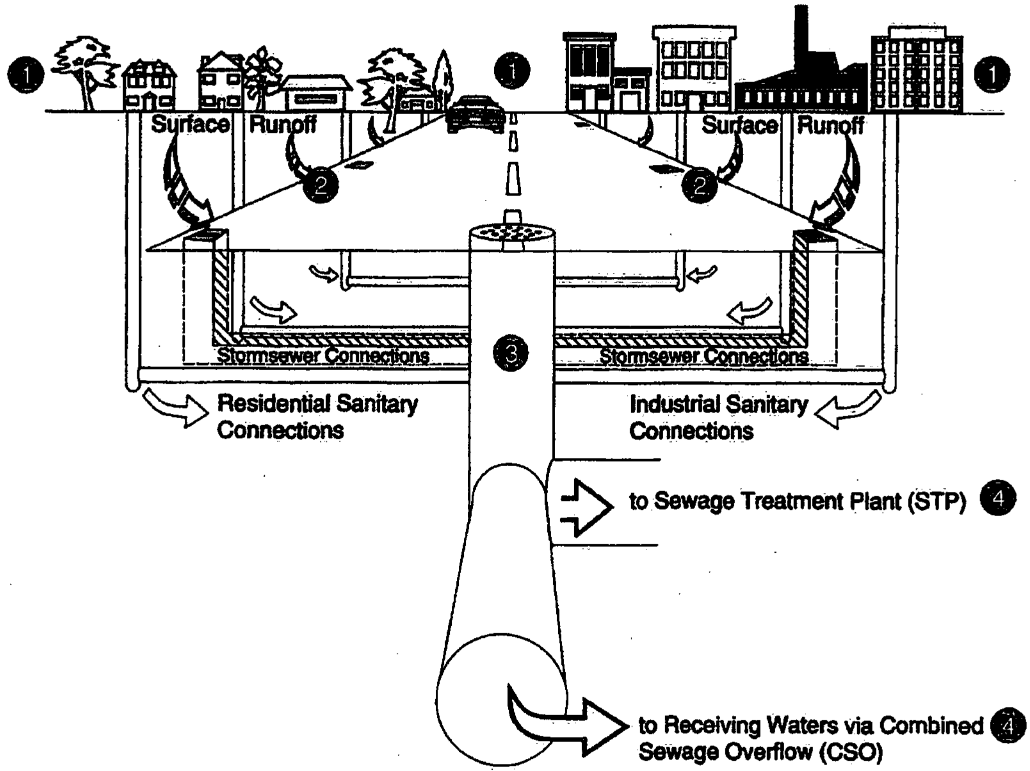


Figure 1. Schematic of the urban sediment continuum with a combined sewer system.

characteristics/functions. For the purposes of this paper, we define an aggregate as any dry composite particle (i.e. those contained in dry street sediment) and a floc as any composite particle formed or transported within a water column (susceptible to greater chemical and biological flocculation processes).

The surface runoff dynamics of urbanized areas are very complex due to the nature of the surface, and land use. Urban surfaces can be characterized as pervious or impervious with concomitant effects on surface runoff and infiltration. Land use (industrial, commercial or residential), also influences runoff dynamics by varying the relative proportions and characteristics of these surface types. Such a diversity in land use and land types combined with long and short range atmospheric deposition results in a wide variation in particulate types and sizes available for transport through the urban continuum [4, 5]. Surface washoff, and often a proportion of groundwater (through infiltration), is generally collected within stormwater sewers or within combined sewer systems. In older urban environments, generally the combined sewer system, plagued with combined sewer overflows (CSOs), is the norm. Unlike fluvial systems, combined sewer system flows are dependent on human use of water (i.e. sanitary flow) and surface runoff during storm events, while storm sewer flows are dependent primarily on stormwater runoff. In addition, sewers are subject to sudden variations in both water and sediment supply [6].

Research into sediment transport in sewer systems generally focuses around three types of sediment; suspended transport, dissolved (colloidal), and bed load [7]. A substantial amount of engineering research has been undertaken in relation to sediment (mostly grit) deposition and erosion within sewers [7-9]. This research has generally been centered around the need to maintain maximum sewer volume capacities and because this sediment type represents the majority of the mass transported in a sewer system [3, 4, 10, 11].

While an extensive amount of information has been published in relation to the contaminants associated with stormwater runoff and their impacts on receiving waters [12-18], relatively little information is available on the flocculated structure of suspended/eroded particles during storm flow [19, 20]. Some recent modeling efforts have attempted to consider flocculation effects, although most open water and sewer models assume that particles behave as primary particles [21-25]. The general lack of consideration of flocculation effects in models is due to a substantial knowledge and methodology gap related to floc structure and behaviour and how this influences sediment and contaminant transport, and to a lack of data characterizing the flocculated state of fine-grain particulates derived from urban surfaces and transported in sewer systems. As the performance of many best management practices (BMPs) are related to particle characteristics (e.g. ultraviolet treatment, artificial wetlands, swirl separators and holding tanks), such a lack of information, severely limits our ability to evaluate and improve these management options.

Combined sewer systems in most older cities of North America represent the main conveyance network within the urban continuum and can be thought of as a transient link or interface between the urban surface and the natural aquatic environment. Given the lack of information available on the state of sediment in urban sewersheds, this paper focuses on a mixed land use sewershed [industrial (primarily steel manufacturing), commercial and residential] which discharges into Hamilton Harbour, Lake Ontario via a CSO, to evaluate the structural characteristics of urban sediments and how they change as they move through the urban continuum. Understanding the structure of urban sediments will assist in elucidating the source, fate and effect of the sediment and associated contaminants within the various components of the urban continuum. Improving our knowledge in such an area will further assist in improving the performance reliability of numerous stormwater management models and BMPs. Such improvements will lead to improvements in the management of urban stormwater impacted systems.

MATERIALS AND METHODS

Study Site

The Kenilworth sewershed (Figure 2) is serviced by a combined sewer system which discharges into Hamilton Harbour, Lake Ontario via a single combined sewer outfall during storm events with a minimum of 5 mm of rainfall distributed over two hours [26]. The sewershed has a contributing area of 265.5 ha, and a surface slope of between 1 and 1.2%, and drains a variety of pervious and impervious surfaces. The upper portion of the sewershed contains approximately 52% impervious land and is dominated by older residential, single family dwellings, with commercial ribbons along major streets. The majority of residential units have their down pipes directly connected to the sewer system. The lower portion of the sewershed (approximately 9% of the contributing area) has mixed industrial practices with steel manufacturing being the dominant industry. Many of the industrial lots are semi-pervious and unpaved. Approximately 66% of the industrial area can be considered impervious. It is estimated that the total overflow volume from the sewershed for a typical rainfall year (considered to be 1986) is 311,000 m^3 with a total sediment load of greater than 6 x 10^4 kg of sediment [14].

Sample Collection

Dry surface street sediment samples were collected from the gutters at 12 sites located throughout the sewershed (Figure 2) on March 18, 1997. All samples were gathered with a stainless steel scoop which was washed with acetone and distilled water prior to each sample collection and placed in a 500 ml polyethylene container. No post sampling sieving was performed (i.e. samples remained as original bulk samples).

Surface washoff samples were collected within an industrial (Site 1) (August 15, 1997; April 16, 1999) and residential area (Site 8) (August 15, 1997) (Figure 2). Combined sewer samples were also collected at the same sites, dates and times as above with an additional 19 CSO samples also collected from August 15, 1997 to April 16, 1999 (Site 1, Figure 2). Where possible more than one sample was collected for each date to characterize a storm event. Sewer grab samples were collected using a long-handled sampler fit with a 500 ml polyethylene wide-mouth sampling bottle, while surface washoff was collected during selected storm events by holding the sample bottle below street level within the sewer catch basin (gully pots). Floc subsamples were then immediately taken with a wide mouth pipette (3.74 mm) and transferred into a 25 ml plankton chamber partially filled with tap water (surrogate for particle-free sewer water). Such a pipetting procedure has been demonstrated not to be destructive to natural marine flocs [27]. Phillips and Walling [28] also demonstrated that the sampling of flocs in a bottle provided representative floc size populations, provided the sediment was sized immediately. Given that the flocs immediately settle within the plankton chamber where they are sized following the image analysis method of Droppo *et al.* [29], it is assumed that representative floc sizes are obtained. This method [29], allows for structural observations and determination of floc (effective) grain size distributions contained in the plankton chambers by employing an inverted microscope interfaced with a CCD video camera and computer image analysis system. Distributions of the primary (absolute) particles were obtained by sonication of the previously measured floc population, followed by resettling in the plankton chamber with subsequent sizing. Bulk samples (dry street sediment and sediment trap sediments) were sized using a SediGraph (Model 5100).

Distribution Analysis

The probability distributions which best fit the dry street sediment, surface washoff, and sewer sediments particle size distribution were determined using BestFit [30]. BestFit software is an Excel spreadsheet add-in which compared the sample data with 25 theoretical probability distributions, using a maximum-likelihood estimator approach. Subsequently, Chi-square and Kolmogorov-Smirnov test statistics are calculated to evaluate goodness-of-fit and BestFit ranked the fit of each distribution based on the test statistic results.

Settling Experiments

Settling experiments were performed following the methods of Droppo *et al.* [29]. A drop of sediment collected with a wide mouth pipette (3.74 mm) from a gently

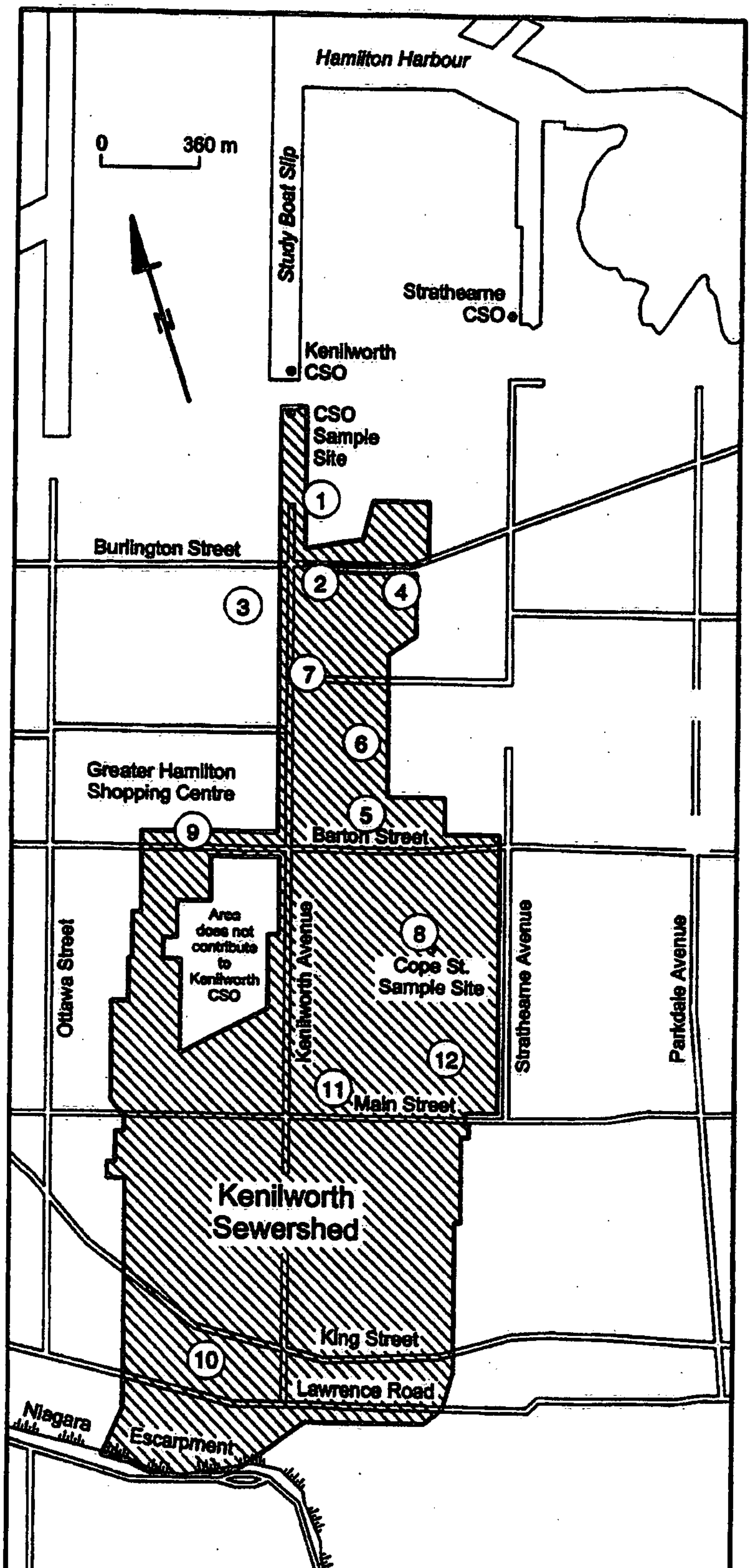


Figure 2. 1997 Sampling locations within the Kenilworth Sewershed (Note that Site 1 is referred to as the Kenilworth Street industrial Site, while Site 8 is referred to as the Cope Street residential Site).

homogenized sample bottle was introduced into an insulated 2.5 l capacity settling column (water at room temperature). As the flocs pass through the field of view of the microscope they are video taped on a SVHS VCR through a CCD camera interface. Using Northern Exposure™, the settling velocity was derived by digitally overlaying two video frames separated by a known time interval. In this way the same particle appears twice on the newly combined image and the distance of settling (over a known time), particle size, and settling orientation can be digitized.

The density and porosity of a floc was estimated using Stokes' Law [31]. As Stokes' Law is based on the settling of single impermeable spherical particles in a laminar region (Reynolds number < 0.2), it is not ideal for the determination of floc density due to the heterogeneous structure and irregular shape of flocs [32]. Nevertheless Stokes' Law or a modification thereof has often been used to determine the wet density and porosity of singular flocs [29, 31], and does provide an indication of how aggregate settling velocity, density, and porosity are related to aggregate size.

Modified Imhoff Cone

Bulk settling of three CSO and three industrial street sediment samples (Site 1) were analysed using a Modified Imhoff Cone manufactured by UFT, Germany [33]. In this method, sediment is introduced at the top of the apparatus and samples of settled sediment are collected at the bottom of the Imhoff cone at specific time intervals and their volumes measured. The relative proportion of each volume to the total sample is then calculated. The result is a percent solids settled in relation to a settling velocity (determined by the time required to settle over a known distance). The organic content, water content and wet bulk density of each fraction was then determined following the standard methods of Environment Canada [34].

Sedimentation Trap

A sedimentation trap was moored approximately 3 m out from the outfall and 1 m up from the bed (approximately 2 m below the surface) to collect sediments discharged during a CSO. The sedimentation trap consisted of four 500 ml polyethylene bottles attached to the bottom of 1 m long acrylic tubes (internal diameter 15 cm). The traps were collected on a monthly basis between 25 June and 1 October, 1996. Although the sediment trap sample dates did not correspond with the street and sewer sample times, the grain size distributions obtained are believed to be a good representation of the CSO sediments deposited in the receiving water due to the averaging effects of long term sampling (1 month).

RESULTS AND DISCUSSION

Figure 3 illustrates the change in sediment structure from representative pathways (compartment) of the urban continuum (not including receiving water body - sediment traps), while Figure 4 provides the range of size distributions measured for each of the four continuum compartments. Figure 4 illustrates distinct size bands for each of the compartments with a general fining from the initial dry surface sediments to the final end point of Hamilton Harbour (sediment traps). The observed changes in particle structure and distributions will be discussed below in order of their conveyance through the urban continuum.

Street Sediment

Samples of dry street sediment (Figure 3a and b) illustrated the dominance of larger solid mineral particles with minimal to no aggregation. It is likely that the more angular particles in the micrographs of Figure 3a and b are derived from newer areas where recent weathering has occurred (e.g. coal piles, high use industrial roads), whereas the more rounded particles may be derived from older areas where significant abrasion has occurred during transport and parent material weathering [4]. Grain size distributions of the 12 street sediment samples revealed a modal range of 0.12 and 1.4 mm and a median (d_{50}) range of 0.08 to 0.42 mm. BestFit analysis revealed that the top three probability distributions to describe the street sediment were Pareto, Weibull, and Pearson VI. Similar sizes for urban street sediment have been found by other researchers [5, 35, 36], although Klemetson [35] found that most street sediments were best fitted with a log-normal distribution. All of the street sediment samples were very poorly to poorly sorted and positively skewed, demonstrating the importance of the coarser fraction in the distributions. From a contaminant viewpoint, the dominance of the larger single-grained particles will facilitate a dilution of bulk samples as the larger particles will generally contain lower associated contaminant concentrations [37].

Determination of settling velocity for individual grains of street sediment was not possible, due to the larger grained material settling too fast for reliable imaging. As a result, Figure 5 illustrates the bulk sediment settling analysis in conjunction with the bulk density, water and organic content data (analysis performed by Hofmann [38]). The median settling velocity of the bulk street sediment ranged from 25 to 60 mm s^{-1} for the three samples. These results are reasonable, given that the Stokes' settling velocity derived from the d_{50} values of the dry sediment (SediGraph analysis - 176, 195 and 210 µm) would range from 28 to 40 mm s^{-1} and that the majority of the particles are single grained inorganic particles (Figure 3a, b). The wet bulk density of the street sediment was estimated to range between 2.65 and 2.0 g cm^{-3} (Figure 5a) which corresponds well with the average specific gravity range of 2.10 to 2.51 found by Butler *et al.* [39] for street sediment in London, England. As would be expected, the percent organic content and the percent water content (mostly measures the amount of water absorbed during settling as the

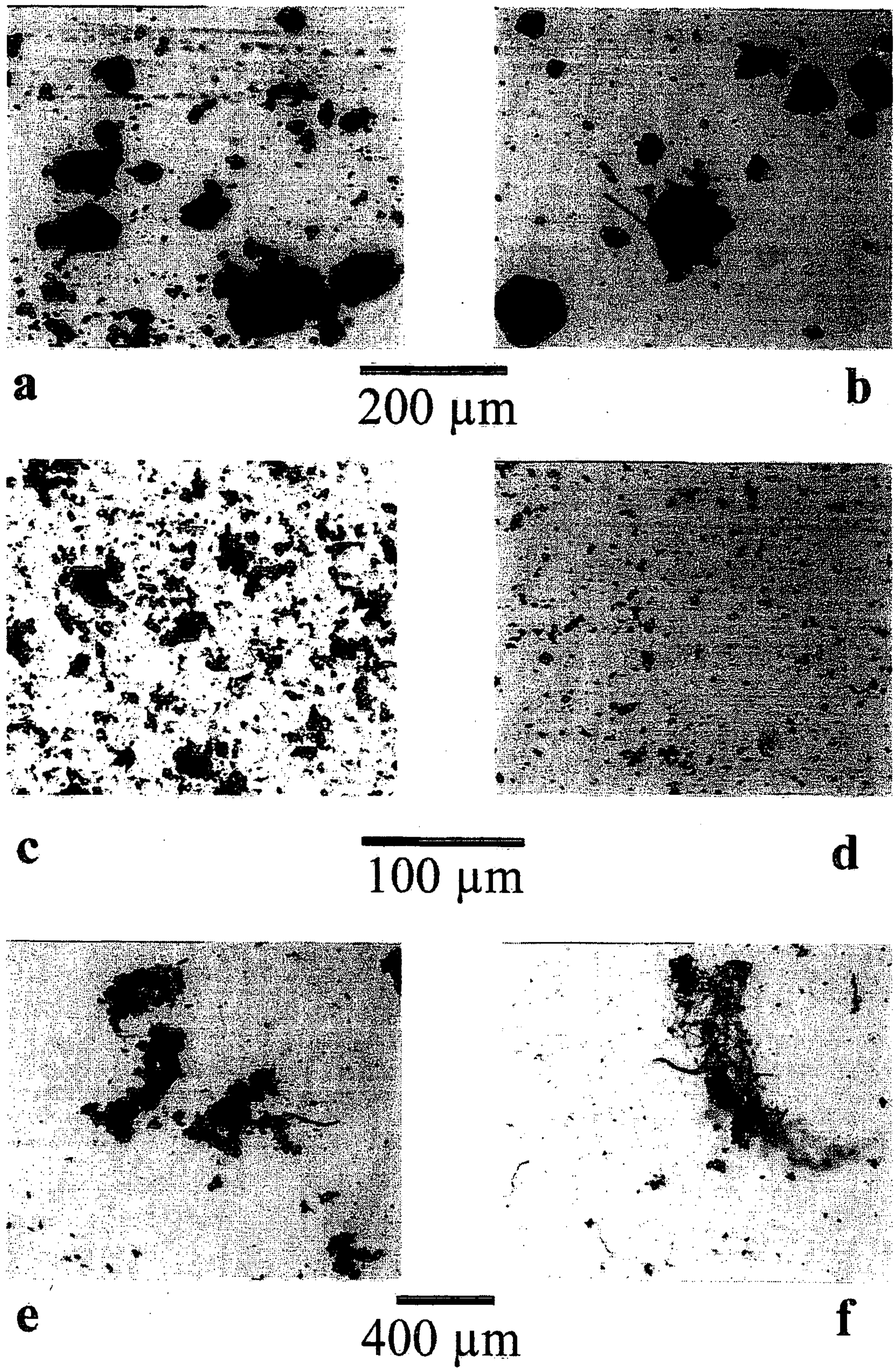


Figure 3. Representative micrographs of aggregates/flocs from dry surface street sediment (a and b), surface washoff (c and d), and CSO samples (e and f).

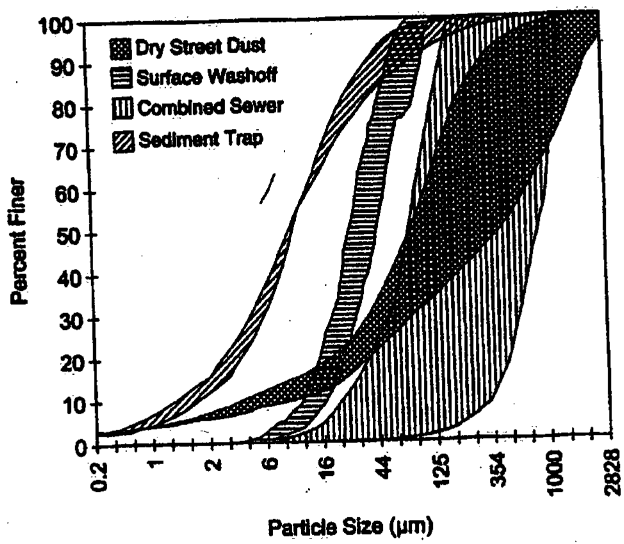


Figure 4. Range in particle size distributions for each of the 4 urban continuum compartments. Although the street sediment and the sediment trap sediments were sized by Sedigraph and the surface washoff and CSO samples were sized by image analysis respectively, this graph illustrates the large range of sizes possible in the urban continuum.

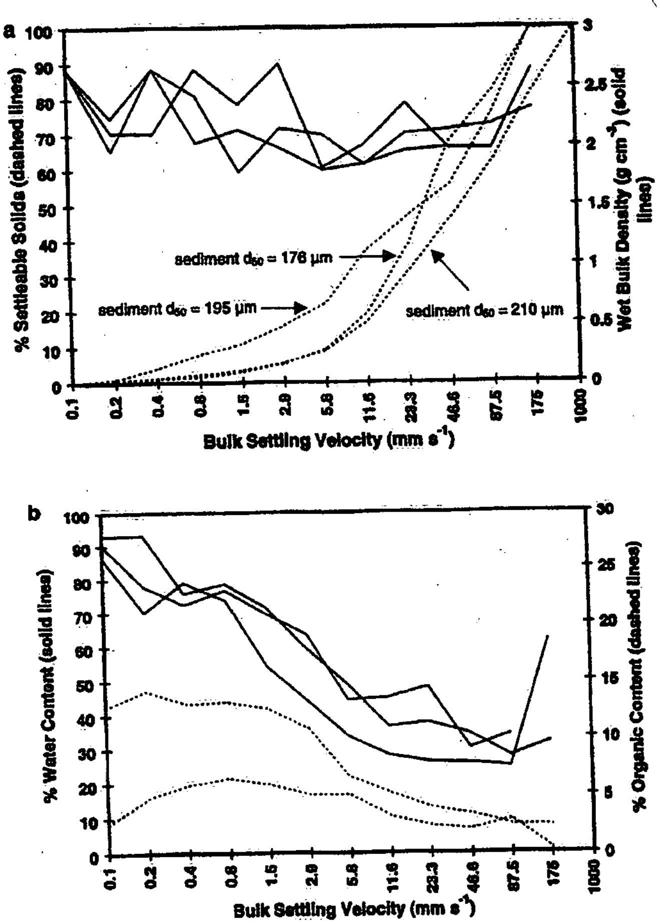


Figure 5. Bulk settling velocity of street sediment as related to (a) % settled and wet bulk density, and (b) % organic content (2 samples only) and % water content.

sediment was initially dry before being made into a slurry) were higher for the slower settling particles and lower for the faster settling particles (Figure 5b). This is consistent with the relationship observed by Liss *et al.* [40] and Droppo *et al.* [13, 29] between floc composition/structure and floc behaviour.

Surface Washoff Sediment

During a storm, hydraulic sorting results in winnowing of fines from bulk street sediments (Figure 3c and d). Generally there is an order of magnitude decrease in d_{50} from the dry street sediment (Figure 4) and a change in the probability distributions representing the washoff sediment. BestFit analysis of the distributions revealed the top three probability distributions which best describe the washoff sediment changed to Pearson V, Pearson VI and Log-normal. Adapting numerical models for these probability distributions will improve the prediction of sediment and contaminant transport within this component of the urban continuum. During the runoff event, the size characteristics of the sediment transported in the surface flow will vary due to changes in 1) flow characteristics (e.g., velocity, runoff depth), 2) rainfall intensity, 3) duration between rain events, 4) source area contributions and 5) potential flocculation and/or deflocculation. The effect of flow on the size of particles entrained is visually seen in Figure 3c and d which illustrates storm runoff samples from the same industrial site, but represent 2 different discharges at the time of sampling (3 and 0.35 l min.$^{-1}$ respectively). Figure 6 illustrates the coarsening of the washoff particle size distribution with time for the August 15, 1997 storm event. The d_{50} was observed to increase up to the peak flow (16:20). Comparison of the average distribution of the first duplicate samples (15:45) with that of the last sample for the Kenilworth site (16:20) showed a significant difference between the distributions for the two sampling times (modified Kolmogorov-Smirnov test, α = 0.05). The exact reason for this increase in size cannot be determined, however, it may be related to 1) the winnowing of street sediment fines by hydraulic sorting (i.e. over time the amount of fine material available for resuspension is reduced), 2) the increase in street discharge and velocity between the two sampling times resulting in a greater flow competence, 3) larger particles being introduced to the flow from source areas other than the street, 4) the activation of "rainflow transport" (the movement of large particles due to the interaction of rainfall and a thin film of water) [41-43], 5) flocculation of the sediment, and/or 6) sample error/bias due to limited samples.

Size ranges of surface washoff particles (Figure 4) were similar to Chebbo *et al.* [44], Chebbo and Bachoc [19], and Verbanck *et al.* [45] who found that about 75% of the stormwater sediment mass was finer than 100 µm with a median diameter between 25 and 44 µm. The transport of finer sediments will translate into a higher contaminant concentration entering the sewer system (relative to bulk concentrations) due to the enrichment of the runoff by the higher contaminant containing fine particles [13, 46, 47]. Droppo *et al.* [13] found a dilution factor of 5 times if the bulk sediment was used to estimate washoff concentrations of metals while Irvine *et al.* [46] found an enrichment factor of 2

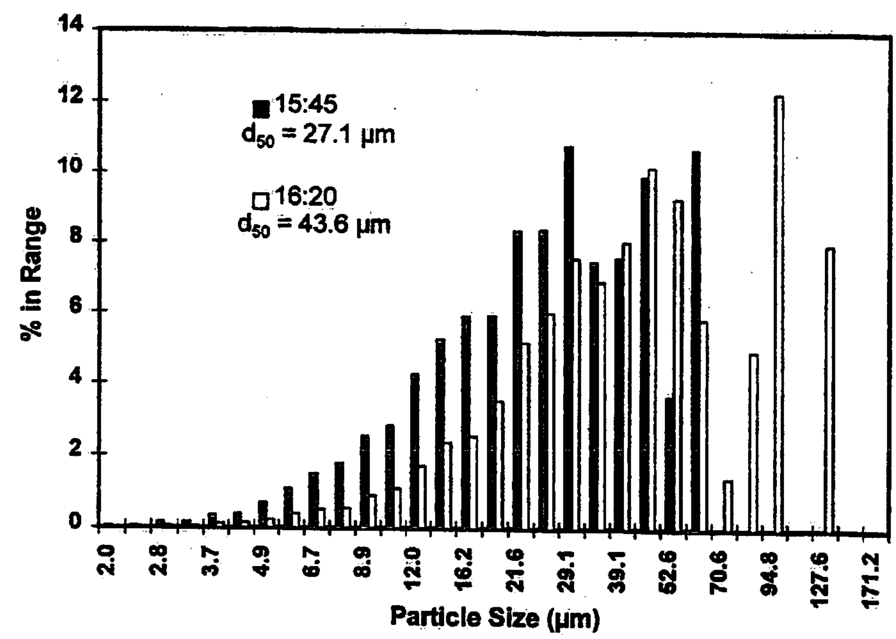


Figure 6. Comparison of street washoff distributions (by volume) with time (Kenilworth Site 1) (August 15, 1997). Initial distribution (15:45 - single sample) is finer than sample taken 35 minutes later in the event.

to 4 times between parent material and particulates transported within surface runoff. As such, sewer transport models which utilize grab sample contaminant concentrations as input variables, are likely to underestimate the loadings of contaminants to the sewer system.

Combined Sewer Overflow Sediment

Particulate surface washoff can represent a significant proportion of the sediment load for combined sewer systems [35, 48, 49]. Once street washoff enters the sewer system it is combined with a variety of materials including raw sewage, bacteria, a variety of chemicals/pollutants including oil and grease, surfactants, and additional particulate matter from up-sewer. As such, the street sediment is mixed within this new medium, and a new "representative" particle composition and particle size distribution is developed. The size, structure and function of such particles are dependent on the composition of the sediment matrix and on the shear stress imposed within the sewer environment. Figure 3e and f illustrate this substantial change in sediment structure within the sewer system. The CSO flocs are seen to be large and very porous with a substantially higher organic content (see also organic content plots of Figure 5b and 8b).

Table 1 provides a summary of 19 grab samples collected during 13 overflow (CSO) events. A strong degree of flocculation within the sewer sediments is evidenced by the high ratios of average effective to absolute particle sizes. Significant variation is present in the effective particle size d_{50} values (this is particularly true for the volume measurements which are more highly influenced by larger particles), while the variation is limited for the absolute d_{50} values. The minimal variation in the absolute particle sizes is reflective of consistent particle size inputs from the various source areas within the sewershed. This does not, however, preclude that the composition of these particles may be different over time or from source areas. Once these constituent particles are flocculated, their variation in size can be the result of two factors; 1) a change in the physical/biological/chemical composition of the sewer suspension with time, or 2) a change in the flow conditions with time. The physical (sediment type), chemical and biological characteristics of the sediment

Table 1. Medium (d_{50}) values (µm) by number and volume for the effective and absolute size distributions of CSO samples.

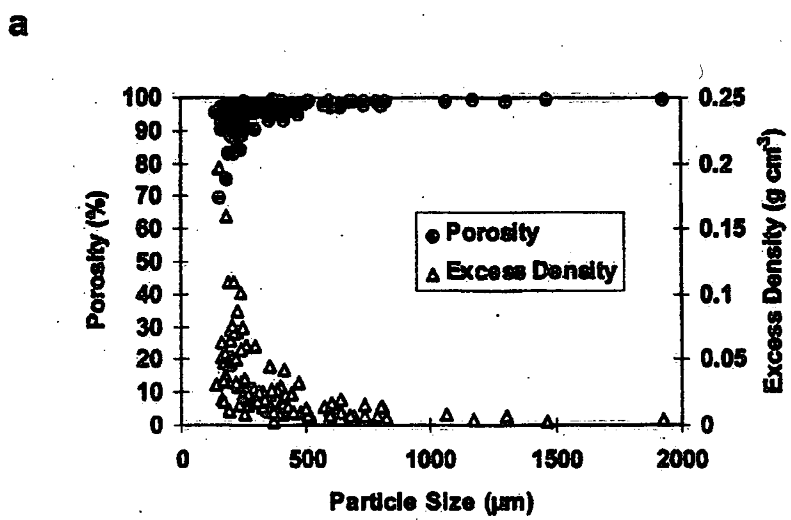
Date	Time	d_{50} By Number		d_{50} By Volume	
		Effective (Flocculated)	Absolute (Sonicated)	Effective (Flocculated)	Absolute (Sonicated)
Aug 15/97	16:30	4.88	—	81.2	—
Jan 6/98	14:18	16.9	—	460	—
Jan 8/98	9:00	15.6	—	873	—
Jun 25/98	14:15	15.1	3.23	492	6.65
Aug11/98	9:15	14.7	3.49	531	10.5
Aug 18/98	9:42	13.6	3.36	447	10.0
Aug 22/98	**	14.7	3.76	642	11.5
Oct 7/98-1	14:35	13.4	3.08	738	6.43
Oct 7/98-2	14:36	12.3	—	383	—
Nov 10/98	**	12.8	3.13	215	7.28
Nov 10/98	**	12.1	—	143	—
Nov 26/98	**	12.8	3.38	528	7.60
Nov 26/98	**	14.0	—	474	—
Nov 30/98	21:30	15.9	3.26	256	9.03
Nov 30/98	21:31	15.9	—	246	—
Feb. 12/99	10:00	13.9	3.52	272	9.22
Feb. 12/99	10:01	13.8	—	219	—
Apr. 16/99	9:15	13.4	2.98	296	9.70
Apr. 16/99	9:45	15.6	3.38	160	8.14
MEAN		13.8	3.32	392	8.73
SD		2.53	0.22	212	1.64
Ratio of Effective to Absolute d_{50}		4.15		44.9	

** = no time stamp in data

within sewers changes many times over a day due to temporal variations in inputs from residential, commercial and industrial users. The flow patterns of a combined sewer also vary frequently due to different storm intensities and daily temporal variations in sanitary flow volumes as related to water usage. The effect of shear on flocs in general is well known (e.g. [50]), however, this cannot be viewed simplistically here, due to the changing suspended solid concentration, chemical and biological conditions with time. In addition, the Kenilworth CSO is a complicated system due to changing backwater conditions as a result of changes in the level of Lake Ontario. As such, the turbulent structure of flow changes throughout the year and results in poor correlations of floc size to flow velocity and discharge.

The observed large floc sizes combined with a high porosity also results in a high water content which translates into a low density (Figure 7a). The low density does not, however, translate into a low settling velocity as seen in Figure 7b. Although porosity approaches 100% and, as such, the density approaches the density of water (Figure 7a), settling velocity still increases with an increase in CSO floc size (Figure 7b). This is suggestive of flow through macro pores during settling which through a reduction in drag may result in an increase in settling velocity [51].

In examining the bulk settling characteristics of three of the CSO samples (August 15, 18 and 22, 1998) (analysis by Hofmann, [38]), it was found that the median settling rate of the sediment was between 3 and 7 mm s^{-1} (Figure 8a). This



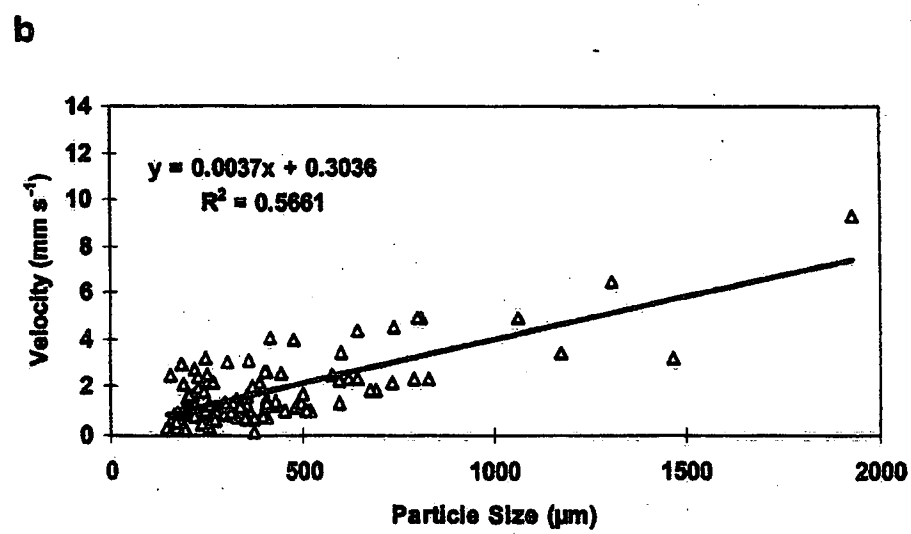


Figure 7. The relationship between CSO floc size and (a) excess density (wet density of floc minus density of water) and porosity and (b) settling velocity for an August 22, 1998 sample.

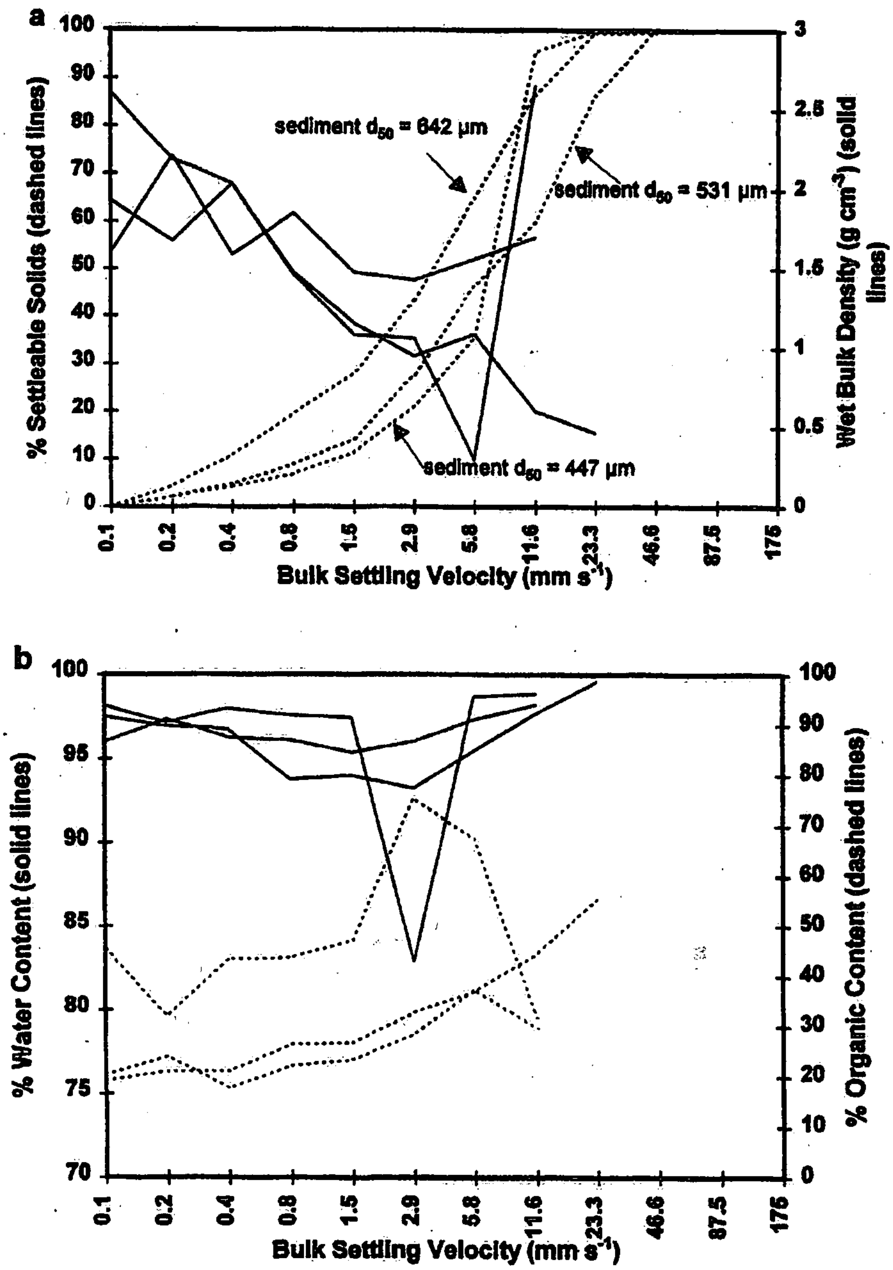


Figure 8. Bulk settling velocity of 3 CSO samples (August 15, 18, 22, 1998) as related to (a) % settled and wet bulk density, and (b) % organic content and % water content.

bulk settling velocity range is within the range of the settling velocities measured for individual flocs of the CSO samples (Figure 7b). The majority of individual flocs measured were, however, below 3 mm s^{-1}. The fact that many of the individually measured settling velocities do not fall within the above bulk settling velocity range is likely to be related to the hydrodynamics of bulk particle settling. It has been shown that such methods of measuring bulk sediment settling velocities can be biased by the particles settling en masse and not as discrete particles [52].

The highly different nature of bulk CSO sediment and bulk dry street sediment is illustrated by comparing Figures 8 and 5. Note that for the bulk CSO sediment samples settled, the median particle size of the CSO samples is 2 to 3 times larger than the dry street sediment d_{50} values, and yet the CSO median settling velocities are an order of magnitude below that of the street sediment. This is a dramatic illustration of the effects of flocculation on the structure and function (settling) of sediment. The CSO samples are substantially more flocculated, possess a higher organic content (20 to 75%), and higher water content (generally greater than 95%) than the street sediment samples (Figure 8b and 3b) [38], and as such possess a substantially lower settling velocity. The bulk settling data confirms the floc relationships found for individual flocs in Figure 7 by showing that as settling velocity increases, wet bulk density decreases in conjunction with an increase in organic content. Surprisingly, the water content remained relatively constant (with the exception of one data outlier) for all of the settling velocity classes and this may reflect the high porosity of the CSO samples.

A comparison of sewer sediment distributions with the contributing street washoff distributions showed significant differences (modified Kolmogorov-Smirnov test, $\alpha = 0.01$), with the sewer floc distributions consistently being the larger of the two. Figure 4 provides an example of these differences between the CSO and street washoff sediment distributions. Comparison of the probability distributions showed a change from the street washoff sediments to the sewer sediments with the top three representative distributions now being Normal, Beta and Rayleigh. The ratio of average sewer d_{50} (Table 1) to average street washoff d_{50} [24.7 ± 12.2 μm by volume; 4.30 ± 0.46 μm by number (n=9)] was 15.8 and 3.2 for volume and number distributions respectively. Interestingly, the absolute (sonicated) particles sizes were very similar between the street washoff and the sewer samples. This is suggestive of the street washoff being a primary source of sediment to the sewer system. This is consistent with the findings of others [35, 48, 49]. Colston [48] found that 95% of the total load to receiving water bodies from an urban CSO was derived from surface washoff. While optically it is not possible to quantify the relative proportion of the CSO sediment that is composed of street sediment, Droppo *et al.* [13] demonstrated that street sediment from the Kenilworth sewershed could be an important contributing source of metals and sediment to Hamilton Harbour. They used street sediment metal concentrations as an indicator of street sediment contributions to the Kenilworth CSO. While the absolute particle sizes are similar between the two urban sediment types, the phenomenon of flocculation within the sewer system results in a substantial increase in the effective particle size.

The larger size distributions for the CSO samples relative to the street washoff are likely to be related to the higher organic matter content of the combined sewer system contributing to the incorporation of the street sediment into new or existing flocculated particles. This assumption of high organic content was confirmed using an environmental scanning electron microscope (ESEM) to image CSO flocs in their hydrated state. Figure 9 illustrates a micrograph from the ESEM and reveals the high organic content (coatings) of the CSO sediments. These coatings are likely to be

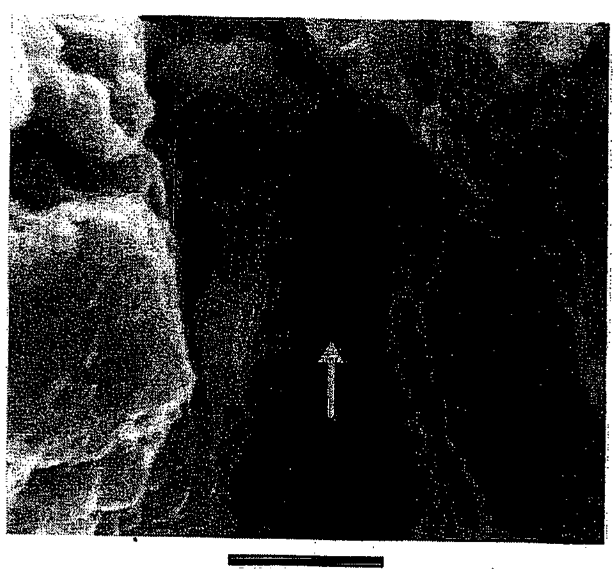


Figure 9. ESEM micrograph of CSO floc.

extracellular polymeric substances (EPS) [40]. Figure 9, in addition to having the general appearance of a complete coating over inorganic grains, also reveals a bridging of floc parts by EPS fibril bundles (see arrow).

Once the CSO sediments enter a receiving water body their fate will be dependent on the individual particle settling velocity, particle-particle interaction and on the flow regime in which they are resident. In the case of the Kenilworth boat slip, there is negligible flow and as such the sediment probably settles quickly. This is supported by comparing the distributions of the sonicated CSO sediment samples (d_{50} = 8.7 ± 1.6 μm) with those of the SediGraph measured sediment trap samples (d_{50} of 6.6 ± 1.8 μm). Assuming that the SediGraph breaks up the flocs close to their primary particles, the similarity of these distributions suggests that the sediment traps do contain a representative portion of the CSO sediment. In addition, this suggests, for the case of the Kenilworth sewershed, that the repository (barring resuspension) of the urban continuum sediment load is in close proximity to the CSO outfall within Hamilton Harbour.

CONCLUSIONS

This study has focused on the changing physical characteristics of the sediment, with an emphasis on flocculation/aggregation, as it progresses through the urban continuum. It was observed that all compartments of the continuum, with the exception of the dry street sediment, show a strong, but different, degree of flocculation/aggregation. Hydraulic sorting of the dry street sediment during storm events, resulted in the winnowing of fine sediments which possessed a higher propensity to flocculate or already exist in an aggregated state. This hydraulic sorting (i.e. a finer population of sediment entering the sewer than that of the parent street material) indicates that studies which use grab samples to estimate the sediment and contaminant loading to sewers will be in error due to the significant differences in mass and because of the dilution effect of the larger particles reducing the overall grab sample contaminant concentration (i.e. the finer population of particles possess a higher contaminant concentration relative to the larger particles remaining on the street). While such sorting occurs, street sediment still appears to be a significant source of sediment to the sewer systems. Once the surface sediment (flocs) enters the sewer system it is integrated with the existing sediment population of the sewer resulting in much larger, low density, high porosity, high organic flocs. The high organic content of this environment assists in the development of such large flocs. The characteristics of these flocs and the flow regime of the receiving water at the time of a CSO will dictate their fate in the environment. The strong difference in sediment characteristics between the urban continuum compartments is further indicated by the different measured and fitted particle size distributions (probability distributions) found for each compartment. These different distributions are indicative of the different source areas, particle structures, and transport processes operating within the urban continuum.

Although the sewer flocs represented the largest flocculated particles within the urban continuum, their settling velocities were small relative to the dry street sediment and to what would be calculated by Stokes' equation for particles of a similar size. The difference is related to the sewer flocs being porous, low density, high water and organic content flocs and not solid particles. Very large sewer flocs were found to have porosities that approach 100% and densities that approach that of water. Settling velocities still increased with floc size, however, suggesting that flow through large pores of the flocs is reducing drag during settling. Care must be taken when using bulk settling measurement methods such as the Modified Imhoff Cone as some error is introduced due to particles settling en masse and not as discrete particles. When possible, particle settling behaviour should be measured on individual particles. Understanding particle characteristics (structure and behaviour) and how they change through the urban continuum will be important for future modelling of sediment and contaminant transport and for the evaluation, modification and/or development of BMPs aimed at minimizing the impact of the urban continuum on our aquatic ecosystems.

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