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Transport Characteristics of fine sediments from an
on-stream stormwater management pond
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MANAGEMENT PERSPECTIVE

This paper is intended for researchers, environmental designers, planners and water managers concerned about planning, design and operation of stormwater management ponds serving to control stormwater pollution. As such, it supports the Departmental Business Line Nature, with respect to understanding and reducing human impacts on the ecosystems and conserving and restoring priority ecosystems.

Among the stormwater Best Management Practices used in the Great Lakes Region, stormwater ponds are particularly common, and hundreds of such facilities have been built and found effective in reducing suspended solids and attached contaminant loads in stormwater by settling. The settling of suspended solids in stormwater ponds is a complex process that is not as yet fully understood. To advance the understanding of particulate settling in stormwater ponds, transport characteristics of bottom sediments from an on-stream stormwater management pond in Kingston, Ontario, were studied in the laboratory. Deposition tests led to the determination of the critical shear stress for deposition and the mass of sediment that would stay in suspension. Erosion tests produced an estimate of the critical shear stress for erosion of the surface sediment layer. These data were then used to develop empirical relationships for estimating sediment deposition and erosion as a function of bed-shear stress. Such relationships can be used in modelling sediment transport in stormwater ponds.

Next steps – further investigations of stormwater pond sediments are planned to elucidate the properties of sediments from various sources and look for generalization of obtained results.

ABSTRACT

Transport characteristics of fine sediment deposited in an on-stream stormwater management pond were studied in a rotating circular flume. In deposition experiments, the critical shear stress for deposition ($\tau_{cd} = 0.050$ N/m^2) and the amount of sediment that would stay in suspension permanently were established. For two consolidation periods, 41 and 138 hours, respectively, the critical shear stress for erosion of the surface sediment layer was estimated as 0.12 N/m^2. Finally, empirical relationships were developed to estimate the sediment deposition and erosion as a function of bed-shear stress and recommended for future modelling of fine sediment transport in the pond studied.

Caractéristiques du transport de sédiments fins provenant d'un bassin d'eaux pluviales en continu

par

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RÉSUMÉ À L'INTENTION DE LA DIRECTION

Cet article s'adresse aux chercheurs, aux concepteurs de l'environnement, aux planificateurs et aux gestionnaires des eaux qui s'intéressent à la planification, à la conception et au fonctionnement des bassins d'eaux pluviales servant à lutter contre la pollution des eaux pluviales. À ce titre, ce document s'inscrit dans les activités du secteur d'activités de la Nature du Ministère en ce qui regarde la compréhension des répercussions de l'activité humaine sur les écosystèmes et leur atténuation, ainsi que la protection et le rétablissement des écosystèmes d'intérêt prioritaire.

Parmi les meilleures pratiques de gestion des eaux pluviales en vigueur dans la région des Grands Lacs, l'installation de bassins d'eaux pluviales est une solution communément appliquée. Des centaines de ces installations ont été construites et il est établi qu'elles réduisent par décantation et de manière efficace la charge en matières en suspension de même que la charge correspondante de contaminants des eaux pluviales. Le dépôt des matières en suspension au fond de ces bassins est un mécanisme complexe et pas encore complètement élucidé. Afin de mieux comprendre la question du dépôt de particules dans les bassins d'eaux pluviales, nous avons étudié au laboratoire les caractéristiques du transport des sédiments provenant d'un bassin d'eaux pluviales en continu de Kingston en Ontario. L'analyse par essais du dépôt a conduit à la détermination de la tension de cisaillement critique pour le dépôt et à celle de la masse de matières restant en suspension dans l'eau. Les essais sur l'érosion ont conduit à une estimation de la tension de cisaillement critique pour l'érosion de la couche superficielle de sédiments. Ensuite, les résultats obtenus ont été appliqués au calcul de relations empiriques servant à l'estimation de l'érosion des sédiments et du dépôt de sédiments repris en suspension en fonction de la tension de cisaillement à s'exercer sur le fond. Ce type de relations peut être appliqué à la modélisation du transport des sédiments dans les bassins d'eaux pluviales.

Étapes suivantes : Nous prévoyons d'étudier davantage les sédiments des bassins d'eaux pluviales afin d'élucider les propriétés des sédiments de sources diverses et nous chercherons à généraliser la portée des résultats obtenus.

RÉSUMÉ

Nous avons étudié les caractéristiques du transport de sédiments fins qui se sont déposés dans un bassin d'eaux pluviales en continu, à l'aide d'un canal circulaire en rotation. Lors des essais portant sur le dépôt, nous avons déterminé la tension de cisaillement critique pour le dépôt ($\tau_{cd} = 0{,}050$ N/m^2) et la quantité de matières restant en suspension de manière permanente. Nous avons estimé à 0,12 N/m^2 la tension de cisaillement critique pour l'érosion de la couche superficielle de sédiments en fonction de deux périodes de consolidation, soit 41 et 138 heures. Enfin, nous avons déterminé des relations empiriques servant à l'estimation du dépôt et de l'érosion des sédiments de sédiments repris en suspension en fonction de la tension de cisaillement à s'exercer sur le fond, et nous avons recommandé de les appliquer à la modélisation du transport de sédiments fins dans le bassin à l'étude.

Transport Characteristics of Fine Sediments

from an On-Stream Stormwater Management Pond

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Running title: *Suspended Sediments in Stormwater Ponds*

ABSTRACT

Transport characteristics of fine sediment deposited in an on-stream stormwater management pond were studied in a rotating circular flume. In deposition experiments, the critical shear stress for deposition ($\tau_{cd} = 0.050$ N/m^2) and the amount of sediment that would stay in suspension permanently were established. For two consolidation periods, 41 and 138 hours, respectively, the critical shear stress for erosion of the surface sediment layer was estimated as 0.12 N/m^2. Finally, empirical relationships were developed to estimate the sediment deposition and erosion as a function of bed-shear stress and recommended for future modelling of fine sediment transport in the pond studied.

INTRODUCTION

Stormwater detention ponds are used extensively in urban stormwater management to provide such benefits as the protection of downstream areas from flooding by temporary storage of stormwater runoff and enhancement of stormwater quality mostly by removal of suspended solids and associated pollutants (Lawrence, Marsalek, Ellis & Urbonas, 1996). The efficiency of ponds in trapping sediment and suspended solids depends on a number of factors, including the flow velocity distribution patterns in the pond and the properties and transport characteristics of sediments carried by stormwater. While the flow patterns in ponds can be predicted with various success by the available computational fluid dynamic models, such as FIDAP (Pettersson, 1997), PHOENICS (Shaw, Watt, Marsalek, Anderson & Crowder, 1997), or FLUENT (Pettersson, 1999; Persson, 2000), transport characteristics of fine sediment carried in suspension (also referred to as suspended solids) are poorly understood. However, this type of sediment is particularly of interest in assessing the pond performance, because it represents the majority of particulates in stormwater and carries the bulk of stormwater contaminants. Such concerns were confirmed by chemical and toxicological analyses of suspended particulate obtained by in-situ centrifuging of stormwater pond water and reported by Marsalek, Watt, Anderson & Jaskot (1997) and Dutka, Marsalek, Jurkovic, McInnis & Kwan (1994). With respect to sediment chemistry, trace metal concentrations in suspended particulate always exceeded those in bottom sediment, and indicated a marginal-significant pollution according to the Ontario Ministry of Environment classification of sediment quality (1992). Dutka et al. (1994) noted that in sediment

toxicity testing, suspended particulate at the outflow from four stormwater ponds was found toxic.

Fine suspended solids are subject to flocculent settling in stormwater ponds (Krishnappan, Marsalek Watt & Anderson, 1999), during which primary particles may aggregate (flocculate) to form flocs, and in turn, these flocs may break up in flow fields of various characteristics (Chocat, 1997). Besides flow conditions, the formation of flocs and the associated flocculent settling are strongly affected by particle concentrations and properties (including size and composition); water temperature, chemistry, and microbiology; and electrochemical forces (Droppo, Leppard, Flannigan & Liss, 1997; Krishnappan et al., 1999; Lau, 1990). Thus, flocculation contributes to dynamic changes in the size and density distributions of suspended solids, which control the settling of suspended solids in the pond. However, the relationships between these distributions and the flow and ambient water characteristics are not generally known and this limits the feasibility of predicting the transport characteristics of fine sediment in stormwater detention ponds (Krishnappan et al., 1999). In the past, this gap in knowledge was partly overcome by testing stormwater settleability in settling columns (Metcalf & Eddy, 1991), but these tests do not represent well field conditions characterised by flow fields and the associated turbulence resulting from flow through the pond or wind shear stress (Shaw et al., 1997).

Besides settling, erosion of materials deposited in stormwater ponds is also of interest and affects the stormwater pond performance in removal of suspended solids. In typical

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pond performance studies, only the "net" solids transport is considered and averaged over a number of successive events, or the entire season (Van Buren, 1994). In view of the fine nature of pond sediments (Marsalek et al., 1997), the risk of pond sediment erosion cannot be dismissed just on the basis of low average flow velocities, particularly in view of non-uniform flow fields in ponds (Shaw et al., 1997; Petterson, 1999; Persson, 2000). However, the risk of erosion is somewhat mitigated by sediment cohesion, as demonstrated for cohesive laboratory mixed deposits by De Sutter, Rushforth, Tait, Huygens, Verhoeven & Saul (2000) and tile drain sediment by Stone & Krishnappan (1998).

To advance the understanding of transport characteristics of fine stormwater sediments, erosion and deposition properties of sediments from a stormwater detention pond in Kingston, Ontario, Canada, were studied in the laboratory. Results of the laboratory experiments and their implications for modelling the transport of fine suspended solids in stormwater ponds are presented in the following sections.

METHODS

Stormwater sediment transport characteristics were assessed by collecting sediment samples from a stormwater pond and testing them in a laboratory flume, which was filled with native pond water. Details of sample collection, laboratory equipment and experimental procedures follow.

Sediment sample collection and preparation

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Samples of bottom fine sediments were collected from an on-stream stormwater detention pond in Kingston, Ontario, Canada (further referred to as the Kingston Pond). The pond consists of two cells; a wet cell with an approximate surface area of 0.5 ha and a permanent depth of 1.2 m, and a dry cell of a similar surface area. The pond was constructed in 1982 to minimise the impacts of runoff from a newly built shopping plaza (with an impervious area of 12.6 ha) on Little Cataraqui Creek, which flows through the pond and ultimately drains into Lake Ontario. Upstream from the pond, the creek drains an urbanising catchment with a drainage area of 4.5 km^2. Continuing development of the catchment has increased creek streamflow and therefore reduced the pond effectiveness in flow control (Van Buren, 1994). Furthermore, the pond storage volume has been reduced by ongoing sedimentation. By 1996, about 0.25 m of sediment had accumulated on the pond bottom, originating mostly from the urbanising catchment rather than the shopping plaza. Except for the sand delta at the pond inlet, bottom sediments were rather homogenous, comprised 45% silt and 55% clay, and were characterised by volumetric water content as high as 78% (Marsalek et al., 1997).

Bottom sediment samples were collected at a number of sampling stations within the wet cell of the pond using an Ekman dredge (grab sampler) and combined to form a composite sample (100 l) that was studied in the laboratory flume. In addition to the sediment samples, about 500 l of pond water was collected in 100 l plastic containers and also transported to the laboratory. The use of pond water in the flume as suspending medium preserved the chemical and biological characteristics of the sediment-water mixture in the laboratory experiments. Both the sediment and pond water samples were

stored in a cold room at 4 °C prior to testing in the flume. The storage time was made as short as possible to minimise any changes that might occur in the sediment properties during the time between the sample collection and testing in the flume. Testing in the flume was carried out under room temperature.

Laboratory flume

The deposition and erosion characteristics of the fine sediment from the Kingston Pond were studied in the rotating circular flume (RCF) at the National Water Research Institute at Burlington, Ontario, Canada. Fig. 1 shows a sectional view of the flume assembly. The RCF consists of a circular flume, which is 5.0 m in mean diameter, 0.30 m wide and 0.30 m deep, and rests on a rotating platform, which is 7.0 m in diameter. An annular cover plate (ring) fits inside the flume with a radial clearance of ~1.5 mm on either side. The full description of the flume can be found in Krishnappan (1993). The characteristics of flows generated in this flume were studied both experimentally (Krishnappan, 1993) and theoretically (Petersen & Krishnappan, 1994). These studies had showed that the flow field generated in the flume was two-dimensional with almost constant bed-shear stress across the width of the flume. The turbulence characteristics of this flow were quantified using the computational fluid dynamic flow model PHOENICS (Krishnappan, Engel & Stephens, 1994).

The RCF is equipped with a laser particle size analyser (manufactured by Malvern Instruments Ltd.) which is used to measure the size distribution of suspended sediment particles in the flume while the flume is in operation. The operating principle of the

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instrument is based on the Fraunhoffer Diffraction Theory (Weiner, 1984). The instrument is mounted in a cradle attached beneath the flume and is operated in a continuous flow-through mode. Fig. 2 shows schematically the arrangement of the instrument under the flume. The flow-through cell of the instrument is connected to a sampling intake tube, which passes through the flume bottom at a right angle. The end of the sampling tube inside the flume is bent 90° in the horizontal direction, aligned with the flow, and positioned to face flow over the flume centre, at the mid-depth of flow. The sediment suspension is drawn continuously from the flume through the sample cell by gravity. After passing through the sample cell and the laser beam, the sediment suspension drains into a reservoir from where it is pumped back into the flume.

The flume is also fitted with a second sampling intake located on the side wall of the flume (henceforth referred to as "the wall mounted sampling intake") at a different flume longitudinal section. This wall intake serves to withdraw whole water samples for measuring suspended sediment concentrations. The sampling intake tube extends perpendicularly from the flume wall and is also bent 90° (in the horizontal plane) to face the flow, and its orifice is positioned at mid depth, over the flume centre. The sediment concentrations were determined by a gravimetric method, in which samples are filtered, and the filter residue is dried and weighed (Environment Canada, 1988).

Experimental Procedures

Both the deposition and erosion characteristics of the pond sediment were examined in the flume experiments. In deposition tests, the pond water was placed in the flume and a

known amount of the sediment was added to the water to establish a fully-mixed sediment concentration of about 200 mg/l. Full mixing was ensured by first mixing the flume contents mechanically, and then by rotating the flume and the lid at relatively high speeds (2.5 rpm for the lid and 2.0 rpm for the flume, which corresponds to a bed shear stress of 0.6 N/m^2) that were found to be sufficient to maintain all the sediment in suspension. Such a high-speed operation was maintained for a period of about twenty minutes. The speeds were then lowered to their respective test values required to maintain a particular bed shear stress in the flume. Water/sediment samples for concentration measurements were withdrawn from the flume through the wall mounted sampling intake at five-minute intervals during the first hour of the test and every ten minutes thereafter until the test completion. Each time a sample was withdrawn through the wall mounted sampling port, the volume removed was replaced by adding an equivalent amount of sediment/water mixture back into the flume, in order to keep the water surface in contact with the lid all the time. A test was considered to be completed after the suspended sediment concentration remained quasi-constant for about an hour. Overall test time was generally in the order of five hours. The size distribution of the sediment in suspension was measured at regular intervals with the Malvern Particle Size Analyser and recorded on a computer hard drive for later analysis. In this way, the formation of sediment flocs and changes in their size distribution with respect to time could be monitored. Tests were repeated for a range of flume and lid speeds.

Two erosion tests were carried out, in which the sediment-water mixture was left undisturbed in the flume for a period of time to allow the sediment to settle and

consolidate on the flume bed. Two different consolidation times were used, 41 and 138 hours. To begin an erosion test, the flume and the lid were started from rest and their speeds were increased in steps. Each step was maintained for a period of between 40 to 90 minutes. During each step, sediment samples were collected through the wall mounted sampling port and used to measure the concentration of the eroded sediment in the water column as a function of time. Whenever there was sufficient sediment suspended in the water column, the Malvern Particle Size Analyser was activated and the size distribution of the eroded sediment was measured. This procedure was repeated until a bed shear stress of 0.46 N/m^2 was reached.

RESULTS AND DISCUSSION

Altogether, seven tests were performed with the Kingston Pond sediment. A summary of the experimental conditions is given in Table 1.

Deposition Tests

Deposition tests were carried out for five different bed-shear stress magnitudes and the concentration versus time relationships for these tests are shown in Fig. 3. Even though the concentration data were obtained from single point (mid depth) measurements in the flume, they can be treated as depth averaged values because of the near uniform concentration profiles that would result when fine sediments settle in a turbulent flow field. This has been demonstrated theoretically by Dhamotharan, Gulliver & Stefan (1981) and experimentally by Fukuda & Lick (1980). The data in Fig. 3 indicate that after the initial 20-minute mixing period the sediment concentration decreases gradually

and tends to reach a steady state value. The steady state concentration is a function of the bed-shear stress. For example, for the lowest bed-shear stress tested (0.056 N/m^2), the steady state concentration was approximately 24 mg/l (12% of the initial concentration), whereas for the highest shear stress (0.324 N/m^2), the steady state concentration was about 140 mg/l (70% of the initial concentration). From such data, we can calculate the amount of sediment that would deposit under a particular bed shear stress in terms of the amount of sediment that was suspended initially (i.e., as a fraction of the initially suspended sediment, assuming an adequate detention time). The shear stress at which all of the initially suspended sediment will deposit (fraction deposited = 1) is defined as the critical shear stress for deposition and it was determined by extrapolating a fitted power law relationship between the fraction deposited and the bed shear stress. A value of 0.05 N/m^2 was obtained for the critical shear stress for deposition of the Kingston Pond sediment. The fitted power law relationship and the experimental data are shown in Fig. 4.

Fig. 5 shows the size distribution data measured during three of the five deposition tests. Since the measurements were carried out at a single point (mid depth at the centre of the flume) the data in Fig. 5 depict the size characteristics of flocs that exist at that point. The size distribution of the flocs is expected to vary over the depth because of the likelihood of floc breakage in the high shear region near the bed (Partheniades, 1986). However, for the purpose of the experiments discussed herein, which was to demonstrate that the Kingston Pond sediment would flocculate under a shear flow, single point measurements should suffice. In Fig. 5 the median sizes of the measured distributions

are plotted as a function of time. For the low bed-shear stress test (0.056 N/m^2), the median size of sediment decreases gradually suggesting that larger particles are settling out and leaving the finer ones in suspension, in a manner analogous to the settling of non-cohesive sediment without flocculation (discrete particle settling). However, with increasing bed-shear stress, the median size of the particles in suspension increased, as can be seen from the curve representing the bed-shear stress of 0.121 N/m^2. For this test, the median particle size increased from an initial value of about 30 µm to a final steady-state size of about 55 µm, indicating that the sediment is flocculating under this shear. As the bed-shear stress was further increased the floc sizes decreased as shown by the curve corresponding to the bed-shear stress of 0.213 N/m^2. At this shear stress, floc breakage has occurred, as the maximum size of the floc formed was only about 45 µm.

The size distribution data presented in Fig. 5 show the importance of turbulence in the formation and preservation of flocs; it plays a dual role. When the bed-shear stress is low, for example as in test no.1, the turbulence level is low and hence the particle interactions (collisions) are not frequent and intense enough to cause the sediment to flocculate and, therefore, sediment particles settle as individual particles. When the bed-shear stress is increased (test no.2), the turbulence level is increased and contributes to an increased intensity of particle collisions, which promotes the flocculation of sediment particles (Metcalf & Eddy, 1991). But with further increase in turbulence, as in test no.4, the increased intensity of particle collisions has an opposite effect and the flocs break up as they are unable to withstand the intensity of collisions and turbulence forces. Therefore, there is an optimum level of turbulence, which produces the largest flocs. The

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small number of runs performed (three) did not allow to determine this optimal turbulence level for the Kingston Pond sediment. However, a cursory interpolation of bed-shear stress and floc diameter data from Fig. 3 indicates that this optimal level would correspond to bed-shear stress in the range from 0.14 to 0.16 N/m^2.

Erosion Tests

The experimental conditions for erosion tests are given in Table 1. Two different consolidation times, namely, 41 hours and 138 hours, were tested. Results from these two tests are shown in Figures 6 and 7, respectively, in the form of the shear stress steps and the corresponding concentration profiles. In addition, for the test with 138 hour consolidation (test no. 7), the median size of the eroded sediment is also plotted as a function of time during a part of the experiment when there was enough sediment in suspension to carry out the particle size measurement with the Malvern Particle Size Analyser.

A comparison of the concentration data from tests 6 and 7 shows that the concentration of the eroded sediment is initially higher in test no. 6. But, when the shear stress step of 0.21 N/m^2 ended (an elapsed time of about 350 minutes), the concentrations in both tests became close and they continued to remain close until the end of the tests. Such an observation suggests that the amount of sediment eroded from the bed layer that was resistant to the shear stress of 0.21 N/m^2 was about the same in both tests, implying that the bed layer was fully consolidated within the time period of 41 hours. The differences in the concentrations during the initial stages of stress application (i.e., within the elapsed

time of 350 minutes) was caused by the formation of a more erosion resistant top layer in test no. 7, during the intervening period between 41 and 138 hours, perhaps due to biological processes (Droppo et al., 1997). Because of this resistive layer, the critical shear stress for erosion has increased from 0.09 N/m^2 (third shear stress step) for test no.6 to 0.12 N/m^2 (fourth shear stress step) for test no. 7. The consolidation process was ruled out as the cause for the increase in the critical shear stress for erosion, because the layer between the top resistive layer and the consolidated bottom layer was relatively loose and eroded readily when subject to a relatively large erosion rate at the shear stress of 0.21 N/m^2 (shear stress step 6) in test no. 7. Assuming that the bed stabilisation due to consolidation and biological processes was completed within the 138 hours, test no. 7 was selected to determine the erosion characteristics of the Kingston Pond sediment.

The value of critical shear stress for erosion, 0.12 N/m^2 (determined from test no.7), is larger than the critical shear stress for deposition. This is a distinguishing characteristic of cohesive sediment; for coarse-grained cohesionless sediment, the two critical stresses are equal (Partheniades, 1986). Furthermore, the sediment concentration at each shear stress step showed a tendency to level off and reach a steady state concentration. This behaviour is also a typical characteristic of cohesive sediments and has been also observed by others (e.g., Lick, 1982; Partheniades, 1986; Parchure & Mehta, 1985). Partheniades (1986) and Parchure & Mehta (1985) argued that the attainment of steady state concentration during the erosion process was due to a reduction in the erosion rate of the sediment as a function of time and not because of a balance between the erosion rate and the deposition rate. In fact, they argue that the cohesive sediments do not

deposit while being eroded at a constant shear stress. In the case of cohesionless sediment, simultaneous erosion and deposition of the same sediment at a constant shear stress do occur (Yalin, 1972; Partheniades, 1986).

The amount of sediment eroded as a function of the bed shear stress was calculated from the experimental results of the erosion test no. 7. The amount eroded was expressed as a fraction of the sediment available for erosion, and the calculated values are plotted in Fig. 8 as a function of the bed shear stress. These values are later used to derive an empirical relationship that can be used for modelling the fine sediment transport through the Kingston Pond.

The size distribution data measured during the erosion test no. 7 are plotted in Fig. 7 as the median floc size variation in time. The size measurements began at the 310-minute mark during the shear stress step of 0.21 N/m^2 and continued until the end of the erosion test. The initial floc sizes measured were in the order of 90 microns, but these sizes decreased to about 40 microns at the end of the test, when the applied shear stress was 0.46 N/m^2. The initial size of 90 microns is larger than any of the sizes that were measured during the deposition tests. The maximum floc size that was measured during deposition was 55 microns and it was for a shear stress of 0.12 N/m^2. The presence of large flocs in the water column implies that the depositing flocs have interacted and formed a network of floc aggregates on the bed (Partheniades, 1986). The erosion process has broken up the network at the weakest contact bonds (failure plane) and re-

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suspended floc aggregates that are larger than the originally deposited flocs. With the increase in shear stress these large floc aggregates break up into smaller floc units.

A Proposed Modelling Approach

The results of the present experimental investigation have demonstrated that the sediments from the Kingston Pond behave in a manner similar to that of cohesive sediments and hence the modelling of sediment transport in the pond has to account for the cohesive sediment transport characteristics. Differences between the cohesionless and cohesive sediment transports arise from the fact that the critical shear stresses for erosion and deposition are equal for cohesionless sediments, and hence such sediments undergo simultaneous erosion and deposition when subjected to a constant bed-shear stress. On the other hand, for cohesive sediments, these two stresses are not equal and, therefore, the sediment flocs do not undergo deposition and erosion simultaneously. A deposited sediment floc remains on the bed until it is exposed to a shear stress that exceeds the critical shear stress for that sediment floc (Partheniades, Cross & Ayora, 1968; Lau & Krishnappan, 1994). A mathematical model reflecting this distinction was developed by Krishnappan (1997, 2000) for streamflows and its application to the Kingston Pond sediment is recommended on the basis of this study.

In the quasi-steady state model proposed by Krishnappan (1997), deposition and erosion functions were determined from the deposition and erosion experiments respectively, and these functions were used to quantify the vertical exchange of sediment at the sediment/water interface for different bed-shear stress conditions.

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The deposition function determined for the Kingston Pond sediment is shown in Fig. 4 and expresses the fraction of the deposited sediment as a function of the bed-shear stress. The bed-shear stress is normalised using the critical shear stress for deposition. This function satisfies the condition that when the bed-shear stress is less than the critical shear stress for deposition, then all of the initially suspended sediment is deposited, i.e. the fraction deposited equals one. When the bed-shear stress is greater than twelve times the critical shear stress for deposition then none of the initially suspended sediment deposits, i.e. the fraction deposited is equal to zero. When the bed-shear stress is within these two limits, then the fraction of sediment deposited is given by the power function depicted in Fig. 4. The mathematical form of the deposition function is given below:

$$f_d = 1.0 - 0.325(\tau_0 / \tau_{cd} - 1)^{0.469} \, for\{1 < \tau_0 / \tau_{cd} < 12\}$$
$$f_d = 1.0 \, for\{\tau_0 / \tau_{cd} < 1\}$$
$$f_d = 0 \, for\{\tau_0 / \tau_{cd} > 12\}$$

where f_d is the fraction deposited, τ_0 is the bed-shear stress and τ_{cd} is the critical shear stress for deposition ($\tau_d = 0.05$ N/m^2).

The erosion function evaluated from the experimental data is shown in Fig. 8. For normalised shear stress values up to 10 (covered by experimental observations), f_e is displayed as a full line; for shear stress values between 10 and 30, f_e was extrapolated as shown in Fig. 8 (a broken line), assuming gradual bed erosion. This assumption will require further research; should a sudden bed disintegration occur in this extrapolated

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region, it would be better described by a step-wise function. The erosion function reflects the fact that the critical shear stress for erosion is approximately 2.5 times the critical shear stress for deposition and the shear stress that is needed to erode 100% of the deposited sediment is 30 times (i.e., 12 multiplied by 2.5) the critical shear stress for deposition. Therefore, for the bed-shear stress lower than 2.5 times the critical shear stress for deposition, none of the deposited sediment will be eroded, i.e. the fraction of sediment eroded is equal to zero, and for shear stresses greater than 30 times the critical shear stress for deposition, all of the deposited sediment will be eroded, i.e. the fraction of the sediment eroded equals one. The mathematical form of the erosion function is as follows:

$$f_e = 0.239(\tau_0 / \tau_{cd} - 2.5)^{0.432} \, for\{2.5 < \tau_0 / \tau_{cd} < 30\}$$
$$f_e = 0 \, for\{\tau_0 / \tau_{cd} < 2.5\}$$
$$f_e = 1 \, for\{\tau_0 / \tau_{cd} > 30\}$$

where f_e is the erosion function.

The two power-law type relationships describing the deposition and erosion processes of Kingston Pond sediment are similar to those used to describe the transport of tile drain sediment from an agricultural watershed (Stone & Krishnappan, 1998). The coefficients defining the power law, the ratio between the critical shear stress for erosion and deposition, and the actual value of the critical shear stress for deposition, differ from sediment to sediment and hence have to be determined empirically for site specific sediments tested in circular flumes, such as the one used in the present study.

Using these two functions, sediment transport through the pond can be calculated by dividing the pond into a number of segments over which the spatial variation of bed shear stress can be considered to be small and calculating the sediment mass balance through these segments knowing the flow field calculated from a hydrodynamic flow model. An implementation of such a scheme will be attempted in future research.

SUMMARY AND CONCLUSIONS

Transport characteristics of sediment from an on-stream stormwater pond in Kingston, Ontario, Canada were studied in a Rotating Circular Flume of the National Water Research Institute at Burlington, Ontario, Canada. Both erosion and deposition processes were studied. The results of the experimental investigation show that the sediments from the pond exhibit cohesive behaviour and form particle aggregates (flocs) when subjected to a flow field. The experimental investigation also provides quantitative data on the fraction of the sediment that would deposit under a particular bed-shear stress and the fraction of the deposited sediment that would be eroded. These data were used to develop empirical relationships for estimating the amounts of eroded and deposited sediments. Such information is useful for mathematical modelling of the vertical exchange of sediment at the sediment-water interface and the calculation of sediment transport in the pond.

Acknowledgements

REFERENCES

Chocat, B. (Ed) (1997). *Encyclopédie de l'hydrologie urbain et de l'assainissement.* Lavoisier TEC & DOC, Paris.

De Sutter, R., Rushforth, P.J., Tait, S.J., Huygens, M., Verhoeven, R., & Saul, A.J. (2000). The erosion of cohesive mixed deposits: implications for sewer flow quality modelling. *Urban Water,* 2(4), 285-294.

Dhamotharan, S., Gulliver, J.S., & Stefan, H.G. (1981). Unsteady One-Dimensional Settling of Suspended Sediment. *Water Resources Research,* 17(4), 1125-1132.

Droppo, I.G., Leppard, G.G., Flannigan, D.T. & Liss, S.N. (1997). The freshwater floc: a functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. *Water, Air and Soil Pollution,* 99, 43-54.

Dutka, B.J., Marsalek, J., Jurkovic, A., McInnis, R. & Kwan, K.K. (1994). A seasonal ecotoxicological study of stormwater ponds. *Zeitschrift fuer angewandte Zoologie, 80* (3), 361-381.

Environment Canada (1988). *Laboratory procedures for sediment analysis.* Inland Waters Directorate, Ottawa, Canada.

Fukuda, M.K. & Lick, W. (1980). The entrainment of Cohesive Sediments in Freshwater. *Journal of Geophysical Research, 85*(C5), 2813-2824.

Krishnappan, B.G. (2000). Modelling cohesive sediment transport in rivers. *The Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer* (Proceedings of a symposium held at Waterloo, Canada, July 2000). IAHS Publication No. 263, 269-276.

Krishnappan, B.G. (1997). *A new model of the fine sediment transport for the Fraser River.* Report No. 97-51, National Water Research Institute, Burlington, Ontario.

Krishnappan, B.G. (1993). Rotating Circular Flume. *Journal of Hydraulic Engineering (ASCE), 119*(6), 758-767.

Krishnappan, B.G., Engel, P. & Stephens, R. (1994). *Shear velocity distribution in a rotating flume.* Report No. 94-102, National Water Research Institute, Burlington, Ontario.

Krishnappan, B.G., Marsalek, J., Watt, W.E., & Anderson, B.C. (1999). Seasonal size distributions of suspended solids in a stormwater management pond. *Water Science and Technology, 39*(2), 127-134.

Lau, Y.L. (1990). Temperature effect on settling velocity and deposition of cohesive sediments. *Journal of Hydraulic Research, 30*(5), 673-684.

Lau, Y.L. & Krishnappan, B.G. (1994). Does reentrainment occur during cohesive sediment settling? *Journal of Hydraulic Engineering, ASCE, 120*(2), 236-244.

Lawrence, A.I., Marsalek, J., Ellis, J.B., & Urbonas, B. (1996). Stormwater detention and BMPs. *Journal of Hydraulic Research, 34*(6), 799-813.

Lick, W. (1982). Entrainment, deposition and transport of fine-grained sediments in Lakes. *Hydrobiologia, 91,* 31-40.

Marsalek, J., Watt, W.E., Anderson, B.C. & Jaskot, C. (1997). Physical and chemical characteristics of sediments from a stormwater management pond. *Water Quality Research Journal of Canada, 32*(1), 89-100.

Metcalf & Eddy, Inc. (1991). *Wastewater engineering, treatment disposal and reuse.* McGraw Hill, Inc., New York.

Ministry of the Environment and Energy. (1992). *Guidelines for the protection and management of aquatic sediment quality in Ontario.* MOEE, Toronto.

Parchure, T.M. & Mehta, A.J. (1986). Erosion of soft cohesive sediment deposits. *Journal of Hydraulic Engineering (ASCE), 111*(10), 1308-1326.

Partheniades, E., Cross, R.H. & Ayora, A. (1968). Further results on the deposition of cohesive sediments. *Proceedings, 11th Conference on Coastal Engineering,* London, England, Vol. 2, 723-742.

Partheniades, E. (1986). A fundamental framework for cohesive sediment dynamics. In: Mehta, A.J. (Ed.), *Estuarine cohesive sediment dynamics.* Springer-Verlag, Berlin.

Persson, J. 2000. The hydraulic performance of ponds of various layouts. *Urban Water,* 2(3), 243-250.

Petersen, O. & Krishnappan, B.G. (1994). Measurement and analysis of flow characteristics in rotating circular flume. *Journal of Hydraulic Research (IAHR), 32*(4), 483-494.

Pettersson, T.J.R. (1997). FEM modelling of open stormwater detention ponds. *Nordic Hydrology, 28*(4/5), 339-350.

Pettersson, T.J.R. (1999). *Stormwater ponds for pollution reduction.* Ph.D. Thesis, Dissertation No. 14, ISBN 91-7197-846-1, Dept. of Sanitary Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Shaw, J.K.E., Watt, W.E., Marsalek, J., Anderson, B.C. & Crowder, A.A. (1997). Flow Pattern Characterization in an Urban Stormwater Detention Pond and Implications for Water Quality. *Water Quality Research Journal of Canada, 32*(1), 53-71.

Stone, M. & Krishnappan, B.G. (1998). Transport characteristics of tile drain sediment in clay loam soils. *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes* (Proceedings of a symposium held in Vienna, July 1998), IAHS Publication No. 249, 407-414.

Van Buren, M.A. (1994). *Constituent mass balance for an urban stormwater detention pond in Kingston Township.* M.Sc. thesis, Queen's University, Kingston, Ontario.

Weiner, B.B. (1984). Particle and droplet sizing using Fraunhofer Diffraction. In: Barth, H.G. (Ed.), *Modern Methods of Particle Size Analysis.* John Wiley and Sons, New York, N.Y. 135-172.

Yalin, M.S. (1972). *Mechanics of Sediment Transport.* Pergamon Press, Oxford.
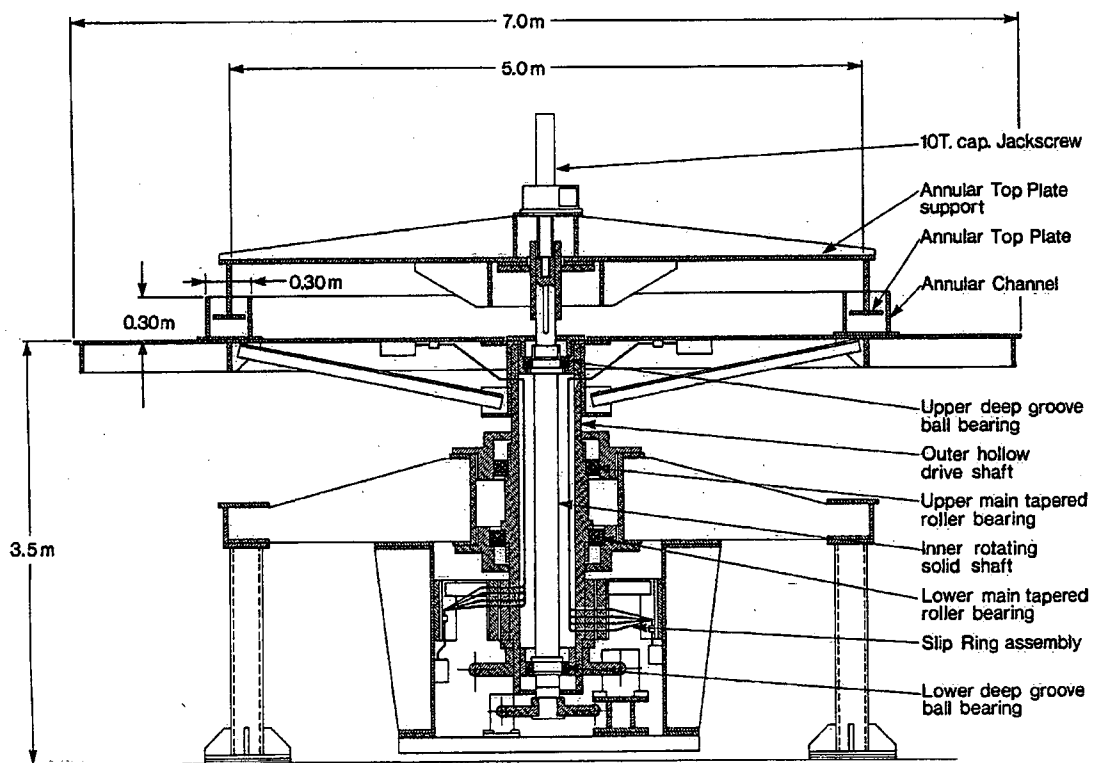
List of Figure Captions

Fig. 1. Sectional view of the rotating circular flume assembly

Fig. 2. Schematic view of the Malvern Particle Size Analyser arrangement beneath the flume

Fig. 3. Deposition characteristics of Kingston Stormwater Pond sediment

Fig. 4. Fraction of sediment deposited as a function of time

Fig. 5. Median size variation as a function of time for different bed-shear stresses

Fig. 6. Variation of shear stress and concentration as a function of time-erosion test with consolidation time of 41 hours.

Fig. 7 Variation of shear stress, concentration and median size as a function of time during an erosion test

Fig. 8 Erosion function

Table 1. Summary of experimental conditions

Test No.	Experiment type	Shear stress (N/m^2)	Initial conc. (mg/l)	Age of deposit (hours)
1	Deposition	0.056	200	n/a
2	Deposition	0.121	200	n/a
3	Deposition	0.169	200	n/a
4	Deposition	0.213	200	n/a
5	Deposition	0.324	200	n/a
6	Erosion	Varying	0	41
7	Erosion	Varying	0	138

n/a = not applicable

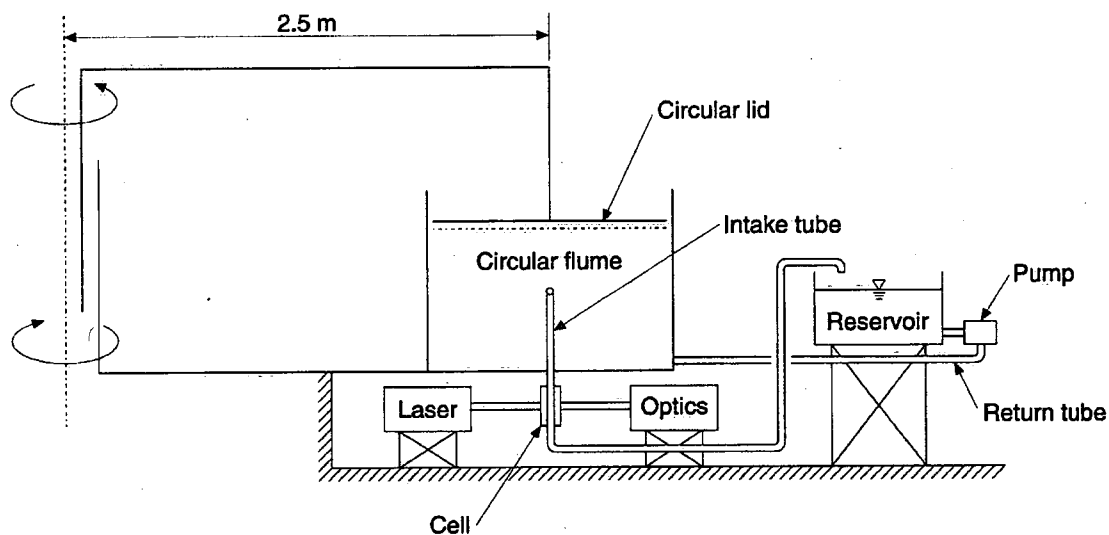Fig. 1. Sectional view of the rotating circular flume assembly

Fig. 2 Schematic view of the Malvern Particle Size Analyzer arrangement beneath the flume
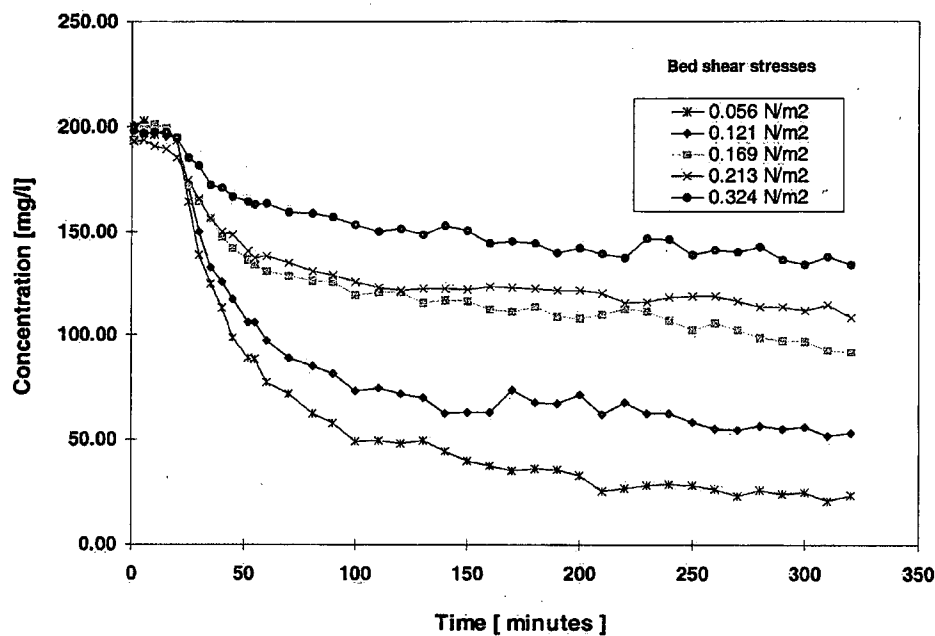
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Fig. 3. Deposition Characteristics of Kingston Stormwater Pond Sediment
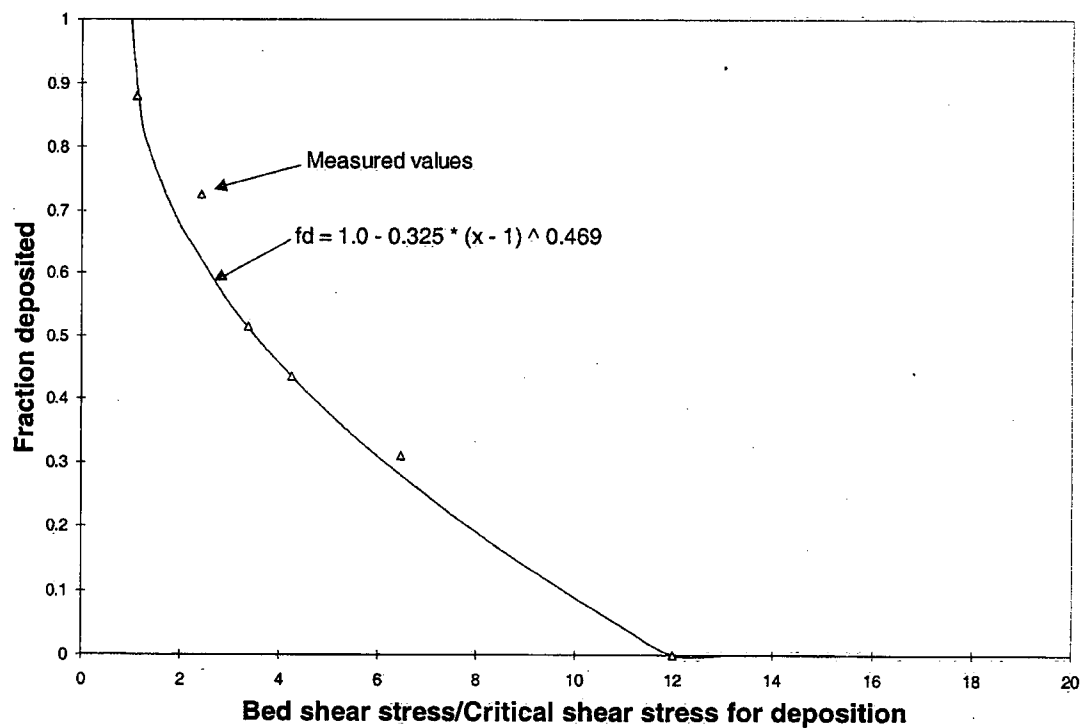

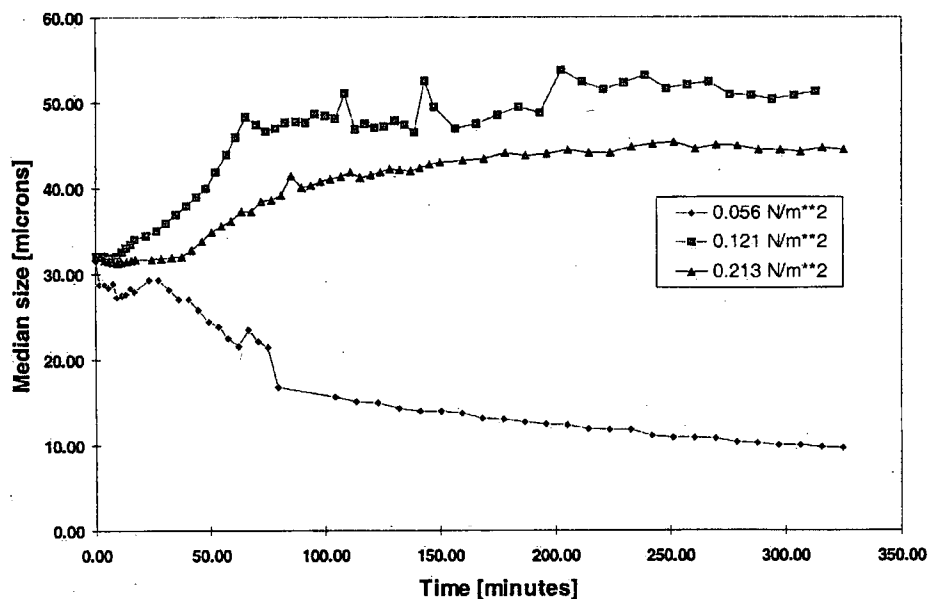Fig. 4. Fraction of the sediment deposited as a function of the bed shear stress.

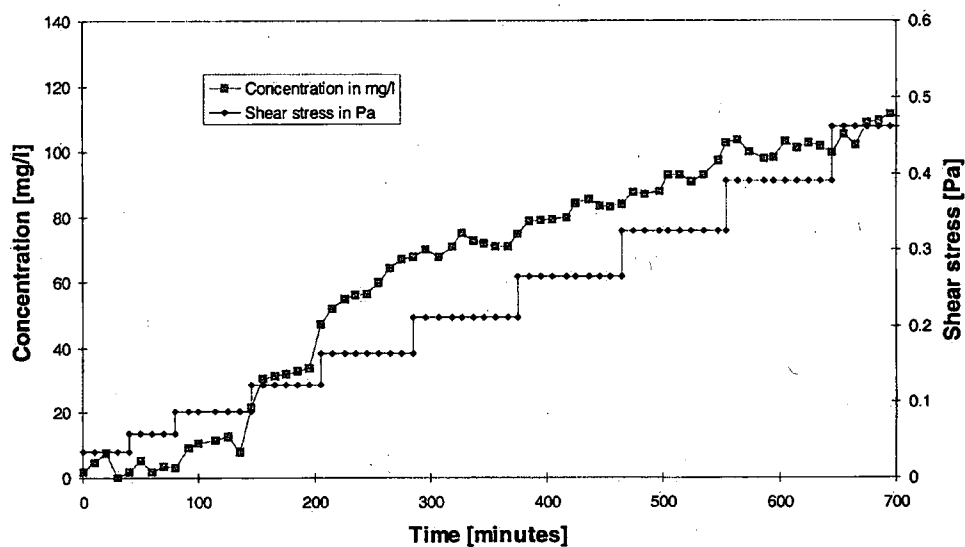Fig. 5. Median size variation as a function of time for different bed-shear stresses.

Fig. 6. Variation of shear stress and concentration as a function of time - erosion test with consolidation time of 41 hours
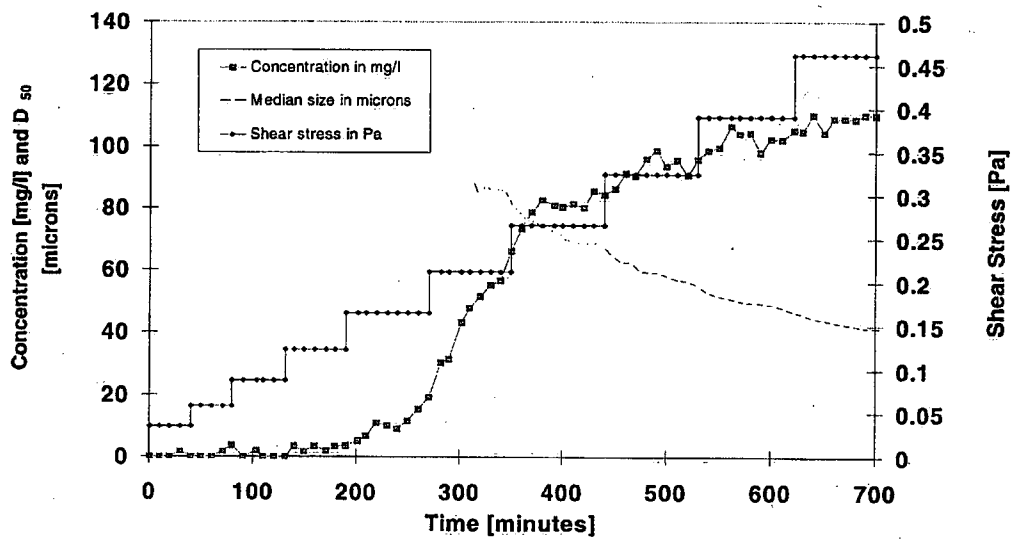
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Fig. 7. Variation of shear stress, concentration and median size as a function of time - erosion test with consolidation time of 138 hours.
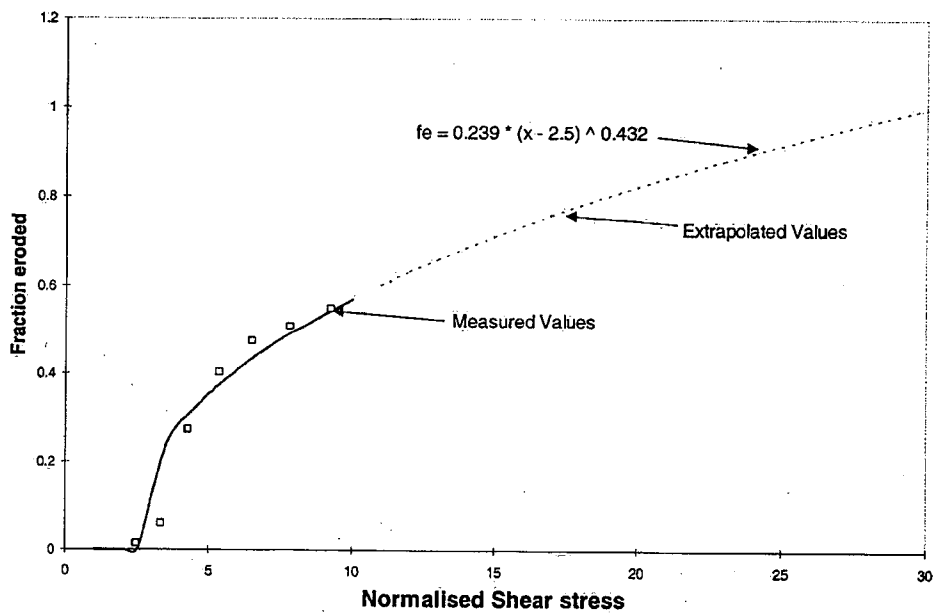

Fig. 8 Erosion Function

■✦■ Environment   Environnement   Canada🍁
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