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Deposition of Fine-Grained Sediment Under Wave Action

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DEPOSITION OF FINE-GRAINED SEDIMENT UNDER WAVE ACTION

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Abstract. Sources of contaminants in the Great Lakes include sediment laden waters from harbours and rivers. The dispersion and settling of the contaminants in the lakes is linked to the depositional and erosional characteristics of the sediment under the influence of wave action. Fine-grained sediment and water from Port Stanley harbour on Lake Erie were exposed to waves in a laboratory flume. Depositional characteristics of the sediment were studied as a function of bottom stress and time (and hence bacterial activity). The flocculation of the sediment was studied by measuring the *in situ* size distribution of the sediment using a particle sizing instrument that operated on the principle of laser diffraction. Both smaller shear and increased elapsed time result in production of larger flocs and more rapid deposition. Implications for transport are discussed.

Resumé. On compte parmi les sources de contamination des Grands Lacs l'eau chargée de sédiments qui provient des cours d'eau et des ports. La dispersion et le dépôt des contaminants dans ces lacs dépendent des conditions d'érosion et de dépôt des sédiments qui sont elles-mêmes déterminées en partie par l'action des vagues. On a soumis de l'eau et des sédiments fins provenant du havre de Port Stanley, Ontario, à l'action des vagues dans un canal construit en laboratoire. Le dépôt des sédiments a été étudié en fonction du stress effectif sur le fond et du temps (et, par voie de conséquence, de l'activité bactérienne). On a mesuré la floculation des sédiments en mesurant la distribution granulométrique *in situ* des sédiments au moyen d'un appareil à cette fin qui fonctionne selon le principe de la diffraction laser. Le cisaillement réduit et la durée accrue conduisent à la production de flocs de plus grande taille et à un dépôt plus rapide. Les effets sur le transport sont étudiés.

MANAGEMENT PERSPECTIVE

Sediment laden waters from harbours are one of the major sources of contaminants in the Great Lakes. The fine grained sediment that carries the contaminants flocculates and deposits under the influence of wave and current action. Preliminary studies in a laboratory flume using samples from Port Stanley, a harbour on Lake Erie, have provided initial information of the response to wave action. Increased wave action reduces floc formation, implying greater capacity for transport of sediment-associated contaminants. On the other hand increased residence time greatly increases bacterial growth and resultant floc formation which under the right circumstances may allow deposition of contaminated sediments within the harbour.

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INTRODUCTION

Fine-grained sediment in rivers and lakes that are transported by currents and waves are potential carriers of persistent and cumulative toxic chemicals. These chemicals include metals, pesticides, PCBs and PAHs (Chapman et al., 1982). Modelling the transport and fate of these chemicals requires a thorough understanding of the transport processes of the fine sediments in these systems. Fine sediments, when subjected to a flow field, are known to interact among themselves and form agglomerations of particles called flocs and are transported in a flocculated form rather than as individual particles (Droppo and Ongley, 1992, Krishnappan et al., 1992). Therefore, a correct description of the flocs and their transport are required.

Earlier studies of sediment flocculation have focused on estuaries and oceans where the main mechanism is the electro-chemical process (Van Leussen, 1988). In this mechanism, when two particles are brought into proximity by Brownian motion, fluid shear, and differential settling, they experience electro-chemical forces of attraction and repulsion. The relative importance of these forces determines whether particles form flocs or not.

In more recent studies of flocculation, bacteria and other micro-organisms were found to play a role in floc formation (Van Leussen, 1988, Rao et al., 1991). The micro-organisms secrete polymers (Leppard, 1993), which provide bonding among particles.

The waters of many of the Great Lakes harbours have a high sediment concentration. This is particularly so for those harbours that have been constructed at the mouth of a tributary which has a large sediment load. The sediment has the potential for carrying toxic chemicals either from upstream point and non-point sources or from sources within the harbour itself. Such a harbour is situated at Port Stanley, Lake Erie where the high sediment concentration is immediately evident upon visual inspection. The Kettle Creek, which discharges through the harbour, receives loadings from sewage treatment plants and from the agricultural drainage area. The waters from this harbour discharge directly into Lake Erie. An understanding of the response of the sediments to the waves and currents is essential for assessing the impact to the lake of the pollutants from the harbour.

Experiments were carried out in a wave flume to explore the transport characteristics of the Port Stanley sediment including the flocculation process under different wave parameters.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Sample Collection and Preparation

A preliminary investigation of the Port Stanley harbour was conducted to find sites where there was recently deposited fine-grained sediment on the harbour bottom close to the wharf. Water and sediment samples were collected from the periphery of harbour. A

submersible pump was lowered to the bottom off the wharf edge, by means of a hand held rope, at six sites around the harbour and used to fill 200 *l* barrels. The pump was repeatedly lowered onto and raised off the bottom so that some bottom sediment would be disturbed and collected by the pump. Twenty-eight barrels were collected and returned to the laboratory, where they were stored at 4° C. After the sediment settled, the supernatant was drawn off, and the sediment slurry was wet sieved using a 75 µm mesh sieve to remove the sand and larger fractions. After the flume was filled to the appropriate level, a suitable amount of agitated sediment slurry was added to the water to obtain the initial sediment concentration.

The Flume and Instrumentation

The wave experiments were conducted in the Small Wave Flume in the Hydraulics Laboratory at National Water Research Institute (Figure 1). The flume is 13 m long by 0.3 m wide with 0.5 m high walls. Waves were generated with a servo controlled hinged paddle. The spending beach at the down-wave end of the flume had a slope of 1:10 with slats about 2.0 cm by 2.0 cm in cross section extending up its face. Eight 200 *l* barrels of the Port Stanley harbour water, topped up with four barrels of distilled water, were used for the experiments reported herein. Still water depth in the test section was maintained at a depth of 0.15 m. The water surface elevation was measured about 0.5 m upwave of the sampling station with three capacitance wires arranged to permit reflection measurements (Mansard and Funke, 1980), water velocity was measured 0.3 m downwave of the sampling station with a Sontek acoustic doppler current meter, normally with the sensing volume positioned 2.0 cm above the bottom of the flume.

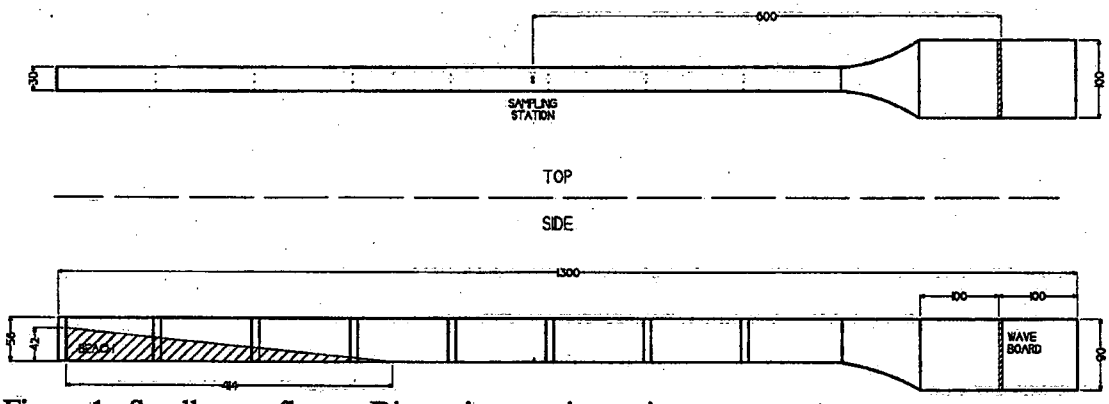


Figure 1. Small wave flume. Dimensions are in centimetres.

The sampling station to monitor the suspended concentration and the *in situ* suspended particle size was established at a distance of 6.0 m from the wave paddle. The station consisted of two pipes of nominal 4.0 mm inside diameter, 2.5 cm on either side of the centre line of the flume extending up from the bottom 5.0 cm. The pipe ends were flared

to form ports with minimal flow disturbance (In uni-directional flow the port is aligned into the flow and the sample withdrawn iso-kinetically - this is not possible in oscillating flow). Two horizontal plates, diameter 2.0 cm, were attached to the port for the particle size analyzer, one flush with the flared end of the tube the other 4.0 mm above the first. This modification was put in place to see if there was an effect on the measured particle size compared to the open flared port. There was no noticeable difference with or without the plates, so they were left in place.

The suspended sediment size was measured with a Malvern Particle Size Analyzer (MPSA), which operates on a light diffraction principle (see Weiner, 1984). Continuous *in situ* measurements of the floc sizes were made by mounting the MPSA immediately below the flume so that the flow-through sensor was located directly below the port. The sediment suspension was drawn continuously from the flume by gravity through the 4.0 mm tube, the sensor, then into a reservoir and pumped back into the flume downwave of the port. The length of the tube was minimized to avoid floc disturbance, and the withdrawal rate was just large enough to avoid deposition of sediment in the tubes. The second port was used to withdraw samples of the sediment laden water for concentration measurements.

Experiments

Regular waves with a period of one second were used for all of the tests reported here. Three different wave heights were used, approximately 5.0, 7.0 and 9.0 cm, respectively. These three wave heights produced 'bottom representative' or root-mean-square bottom shear stresses (Madsen et al., 1988) of approximately 0.07, 0.14 and 0.23 Pa. Before the beginning of each test, the flocs were broken up mechanically to reproduce as closely as possible the same initial particle size. Once the flocs were broken up as small as possible, the wave height was set to the value for that test, and an initial sediment concentration sample was taken and initial particle size distribution measurement made. Concentration and distribution measurements were made periodically for the duration of the test, typically lasting some 7 or 8 hours. The tests were divided into two series, A and B. Series A extended from Day 0 to Day 8, during which the test conditions were cycled through the three wave heights two times; series B was from Day 11 to Day 20, and again the test conditions were cycled through the three heights twice. Before the first test of series B, on Day 11, the concentration was topped up with sediment that had been stored at 4° C, because the initial concentration for each run had continuously dropped.

RESULTS

Over the course of the tests, two features were dominant. The first feature was that the initial particle size increased with time. The second was that the initial concentration decreased from day to day. The latter was attributed to the fact that all of the sediment was not resuspended at the beginning of each test, because some of the interior surfaces of

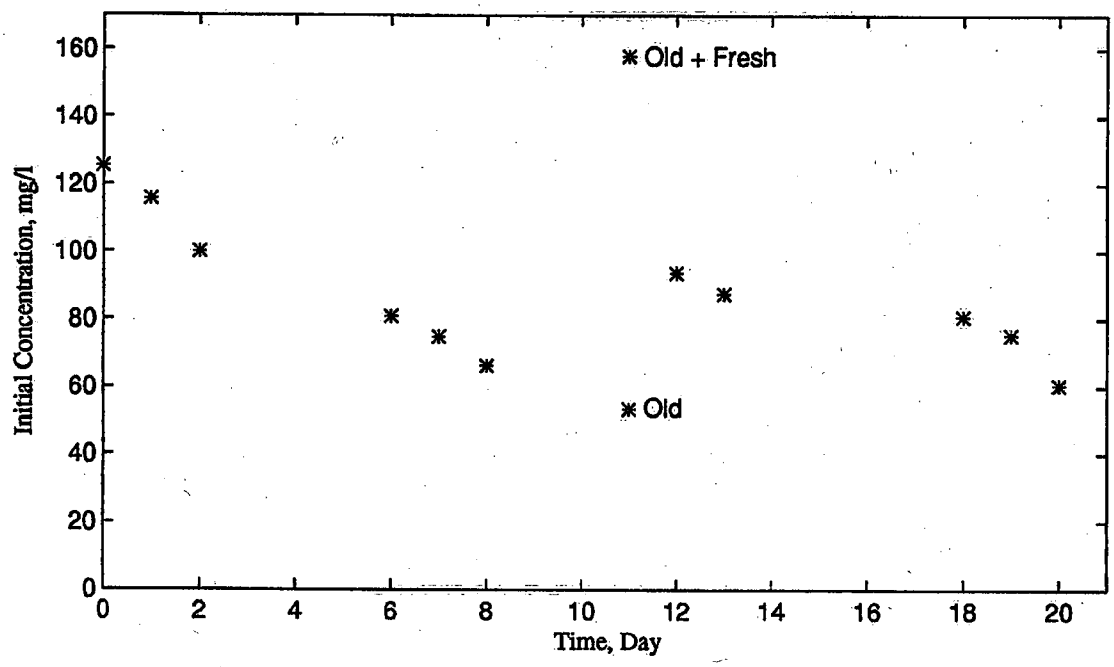
the flume (for example the wave dissipater behind the wave board) could not be wiped down at the start of each test to resuspend sediment. These points are summarized in Figure 2 and in Table 1.

Test Series	Day	Shear Stress, Pa	Initial Concentration, mg/l	Initial D_{50}, µm
A	0	0.14	125.4	4.4
	1	0.07	115.7	5.1
	2	0.23	100.0	5.2
	6	0.23	80.9	6.9
	7	0.14	74.9	6.9
	8	0.07	66.3	7.7
B	11		53.4	9.1
	11	0.23	158.0	5.4
	12	0.14	93.7	6.8
	13	0.07	87.5	7.6
	18	0.23	80.8	8.8
	19	0.14	75.3	9.4
	20	0.07	60.5	10.0

Table 1. Concentration and particle size at the beginning of each test. (Note for Day 11 the first row is for the original sediment and the second is after the addition of sediment.)

For the Test Series A the initial concentration decreased from 125.4 to 66.3 mg/*l*, and the initial particle size, characterized by the initial median particle size (D_{50}), increased from 4.4 to 7.7 µm (The primary particle size distribution, also determined using the MPSA, was characterized by D_{50} = 3.8 µm, so that the initial D_{50} of 4.4 µm represented very little floc formation). At the beginning of Test Series B, the concentration was increased from 60.5 to 158 mg/*l*, by adding 'fresh' sediment (i.e. sediment that had been stored continuously at 4°C). As a result, the initial particle size at the start of the first test of Test Series B was 5.4 µm, not 9.1 µm which was the size before the fresh sediment was added. However, throughout the duration of the second series, the initial D_{50} rose to 10 µm. The increase in initial particle size is attributed to the growth of bacteria over the duration of the test series, resulting in more and more availability of polymers to bond sediment particles. The same level of mechanical agitation at the start of each test was less able to break down the flocs to the same degree as time progressed. These two features form the milieu within which the other results must be viewed.

The evolution of the floc size during each test changed markedly from Day 0 of Series A to Day 20, Series B. The evolution was clearly dependent on the time of the test as well as the bottom stress. In Series A, with water and sediment fresh from storage, the floc size was virtually constant throughout the first and second tests. These tests were at the intermediate and low stress levels respectively.



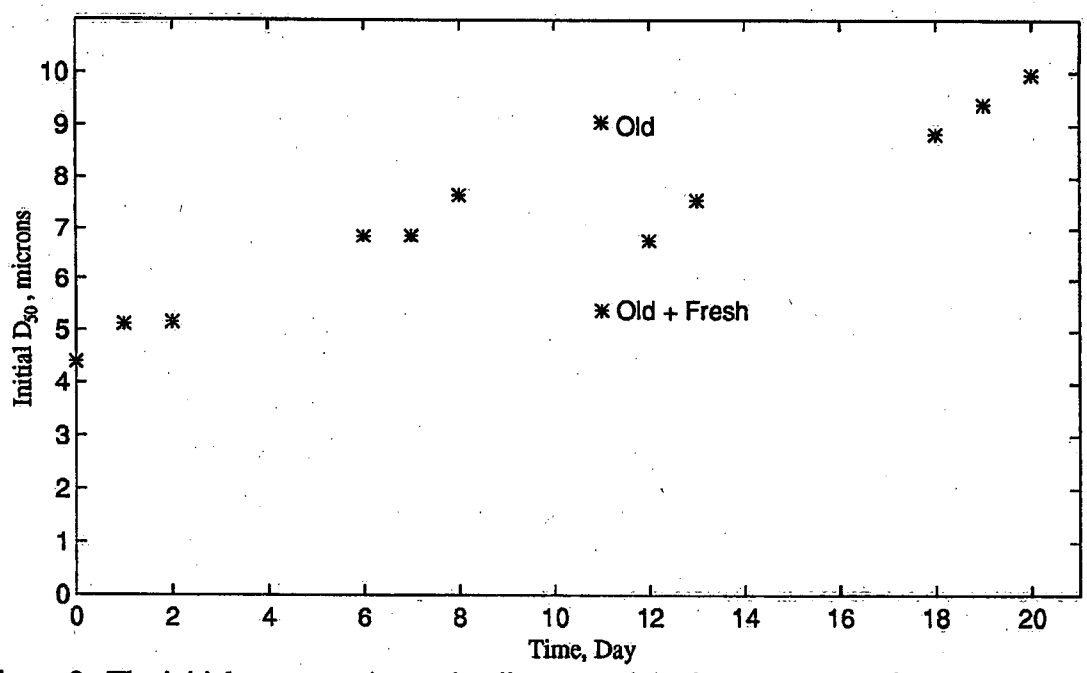


Figure 2. The initial concentration and sediment particle size versus time, for all tests.

On the third day, at the high stress level, the floc size grew from an initial D_{50} of 5.2 to 7-7.5 μm after about 150 minutes. These size evolution results are summarized in Figure 3. These three tests were repeated about one week later, with markedly different results. The order of stress level was changed slightly: high, intermediate followed by low. In all three cases the particle size increased from the initial value, reaching a maximum after about 150 to 200 minutes, followed by a modest decline (Figure 3). These two groups of tests about a week apart obviously form distinct sets. The wave conditions were repeated and the method to break up the flocs at the beginning of each test was the same for every test. The only parameter to change was the passage of time, allowing the growth of bacteria in the water.

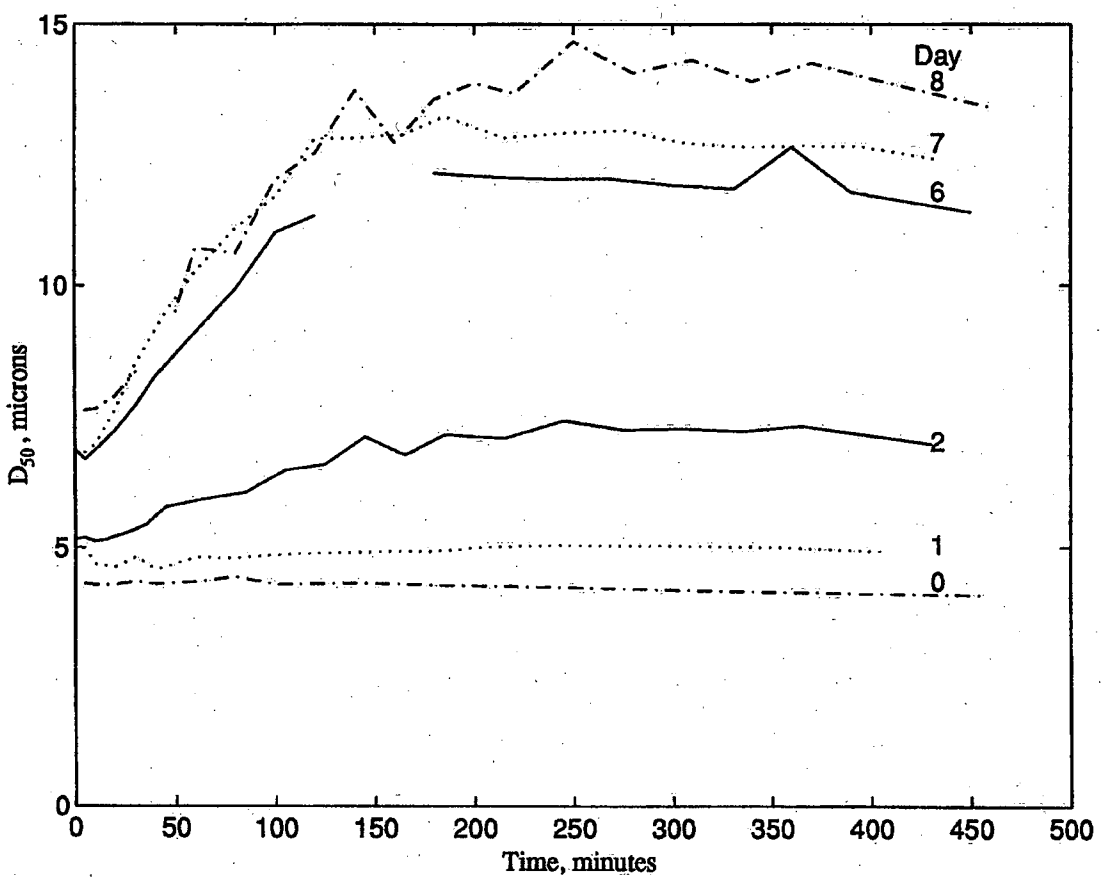


Figure 3. Sediment particle size versus time, for test series A. Low stress (–•–); medium (···); high (–).

In Series B, all tests are characterized by an increase in floc size from the initial value (Figure 4.). The maximum D_{50} values for the first week were intermediate in value between the first and second week of series A, probably due to the introduction of fresh

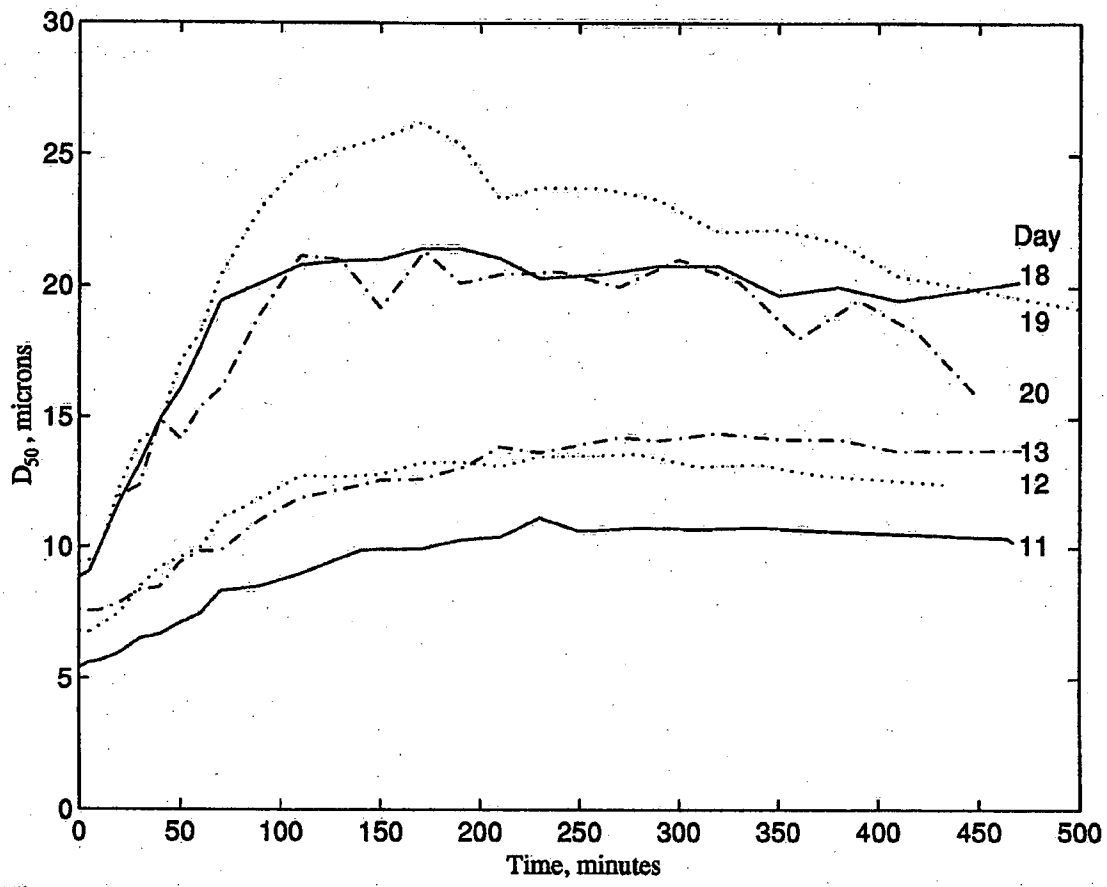


Figure 4. Sediment particle size versus time, for test series B. Low stress (–•–); medium (···); high (–).

sediment at the beginning of the series. By the second week the maximum D_{50} values exceeded all previous values. In the first week, the size leveled off after 200 to 300 minutes, and showed a slight drop off under the medium stress. In the second week, the maximum size was reached sooner, after 100 to 200 minutes, with noticeable drop off thereafter for all three stresses. The results from the two weeks form distinct sets as was the case in series A. The physical conditions were the same in the two sets, but again an additional week was available for bacteria growth.

The time variation of concentration of sediment in suspension is shown in Figures 5 and 6 for the two series of tests respectively. From these figures, it can be seen that the sediment concentration decreased throughout the course of the experiment for all the tests. The rate of decrease is fairly constant and hence the variation can be approximated by a straight line as shown in these figures. The slopes of these lines were obtained by performing a linear regression on the distributions and are summarized in Table 2. These slopes, which are an approximate measure of the deposition rate exhibit a reasonable

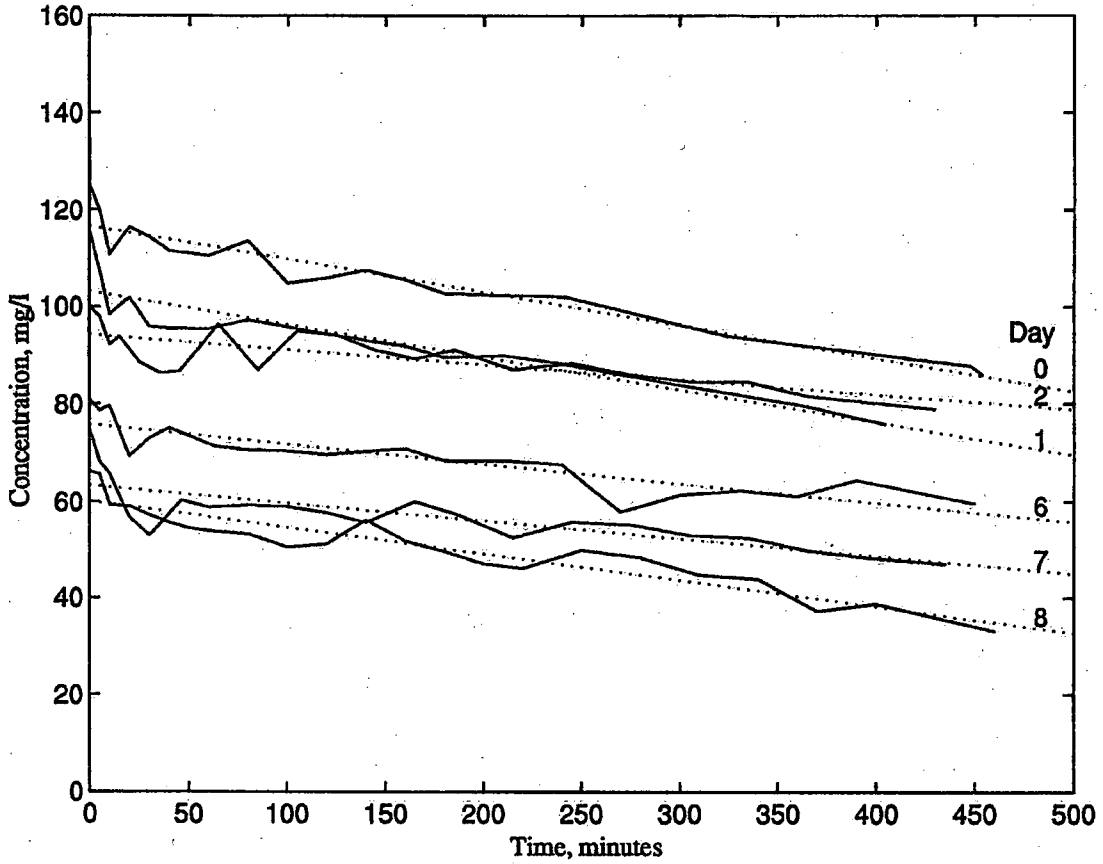


Figure 5. Concentration versus time for Test Series A. Solid lines are data; dashed are regressions (see Table B).

correlation with the average bed shear stress. That is, when the shear stress is high the deposition rate is small and the distribution is flatter. However, the distribution for the Day 11 test shows a much higher rate of deposition even though the shear stress is the highest. This could be due to the much higher initial concentration for this test. Higher initial concentrations are known to increase flocculation and the deposition rate (See Kranck, 1980).

Continuously decreasing concentration versus time curves observed in the present experiments were not observed in earlier works on cohesive sediments (see, for example, Mehta, 1988). However, the majority of these studies were conducted in circular flumes with either the top cover rotating or the top cover and the flume rotating. Results from these studies showed that, after an initial drop, the sediment concentration reached a steady state value. The difference could be due to the difference in the flow fields. A definitive statement, that the difference in the flow fields caused the different concentration response, cannot be made based on the present study because of the continuous drop of initial concentrations in the present experiments. The systematic

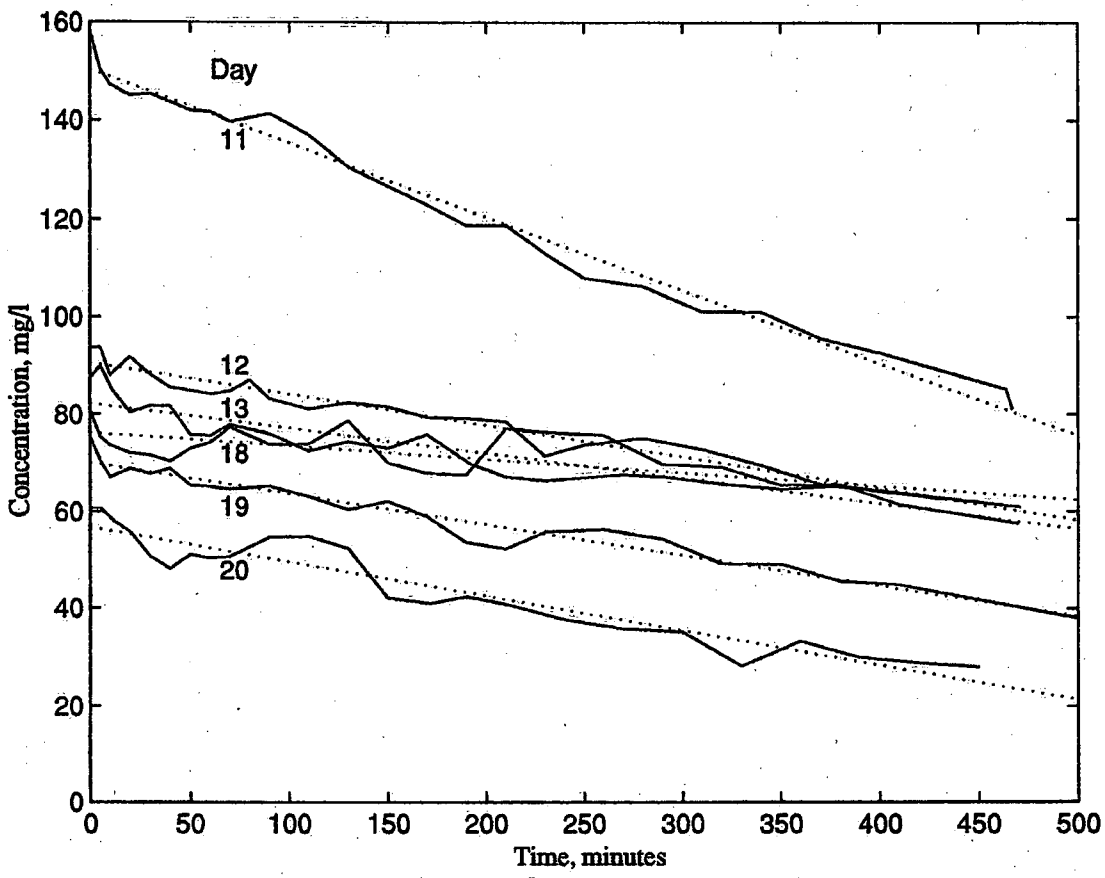


Figure 6. Concentration versus time for Test Series B. Solid lines are data; dashed are regressions (see Table 2).

Test Series	Day	Shear Stress, Pa	Slope, mg/l/min	Intercept, mg/l
A	0	0.14	-0.068	116.62
	1	0.07	-0.067	103.06
	2	0.23	-0.031	94.26
	6	0.23	-0.040	75.77
	7	0.14	-0.037	63.4
	8	0.07	-0.055	60.18
B	11	0.23	-0.150	150.35
	12	0.14	-0.065	90.69
	13	0.07	-0.052	82.27
	18	0.23	-0.028	76.18
	19	0.14	-0.063	69.95
	20	0.07	-0.071	56.77

Table 2. Linear regression of concentration versus time.

drop in initial concentration suggests loss of sediment out of the measurement zone and into, possibly, the head box behind the wave paddle, under the beach, into the wooden beach surface. Such a loss of sediment could also affect the concentration profiles during each test, yielding a constantly decreasing profile. More work is needed to resolve this issue.

DISCUSSION AND CONCLUSIONS

The strong dependence of the floc formation on the (implied) presence of polymers in the water has direct implications for the discharge of harbour waters into Lake Erie. Increased residence time at elevated or summer water temperatures will result in increased floc size and subsequently more rapid settling. On the other hand storm events would limit opportunity for floc formation. For example, consider a scenario when a storm event results in inflow of 80 m^3/s, or about $7x10^6$ m^3 in one day. At typical water levels, the harbour volume is about 230,000 m^3, so that an event of this magnitude would effectively discharge creek water directly into the lake. On the other hand, for typical summer flows of 0.5 to 1 m^3/s, the residence time is of the order of 3 to 6 days. In the first case the sediment leaving the harbour would likely behave somewhat like the test of Day 0: little floc formation and hence significant potential for longshore transport by waves in the surf zone, or other long range transport due to other coastal currents, depending on the wind and current regime at the time. In the second case, the longer residence time in the harbour would provide an opportunity for bacterial growth and hence floc formation. As these waters leave the harbour, it is to be expected, based on earlier rotating flume experiments, that deposition would be more rapid and hence more local to the shoreline near the harbour.

The experiments reported here showed the overriding importance of the growth of bacteria on the development of flocs in sediment-water samples from Port Stanley. Floc formation was greatly enhanced by increased presence of bacteria and resulting polymers which promote bonding between particles. At the present time it is not possible to establish a quantitative relationship. The experiments provided some evidence of increased deposition rates that would be expected to accompany the increased floc formation. Additional experiments in a rotating flume are planned to provide additional information on the deposition aspect.

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