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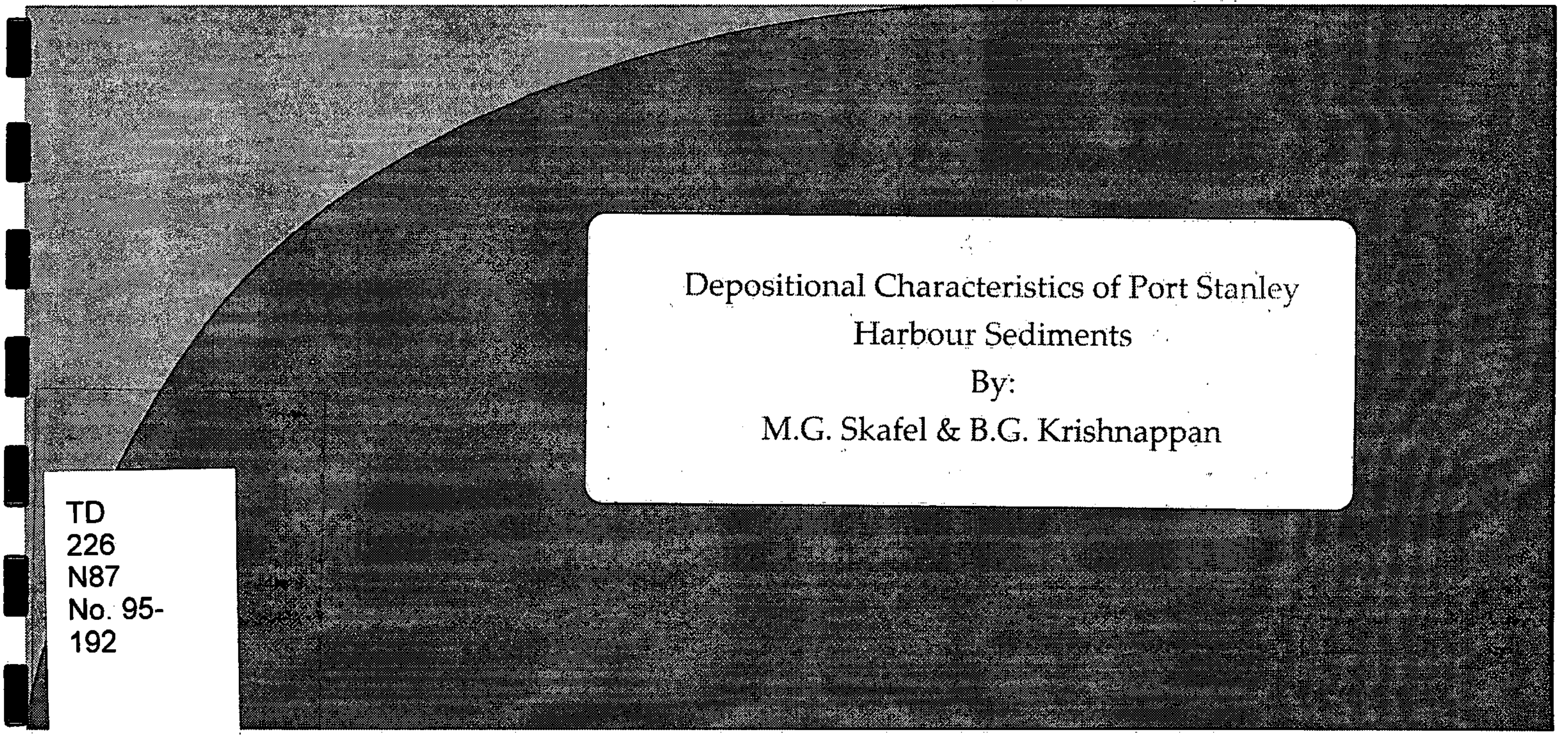

Depositional Characteristics of Port Stanley Harbour Sediments

By:

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DEPOSITIONAL CHARACTERISTICS OF PORT STANLEY HARBOUR SEDIMENTS

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ABSTRACT

Sources of contaminants in the Great Lakes include sediment laden waters from harbours and rivers. The settling and dispersion of the contaminants in the lakes are linked to the depositional and erosional characteristics of the sediment under the influence of wave and current action. Fine-grained sediment and water from Port Stanley harbour on Lake Erie were exposed to waves in a laboratory wave flume and currents in a laboratory rotating flume. Depositional characteristics of the sediment were studied as a function of bottom stress and time (and hence bacterial activity). Smaller shear stress and increased elapsed time resulted in production of larger flocs and more rapid deposition in both wave action and shear flow. Implications for transport are discussed.

INTRODUCTION

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 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 of the pollutants from the harbour to the lake.

Experiments were carried out in a wave flume and a circular, rotating flume to explore the depositional characteristics of the Port Stanley sediment under different wave and current conditions. In this paper, details of the experimental procedure and the results are discussed and the dominant mechanisms governing the Port Stanley sediment deposition are identified.

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 to arrest any biological activity. 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 coarser than sand 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.

Wave Flume and Instrumentation

The wave experiments were conducted in the Small Wave Flume in the Hydraulics Laboratory at National Water Research Institute (Skafel and Krishnappan, 1995). 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, with the sensing volume positioned 2.0 cm above the bottom of the flume.

The sampling station to monitor the suspended sediment concentration and the *in situ* suspended particle size was established at a distance of 6.0 m from the wave paddle. The sampling ports 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 the rotating flume the port was 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 using a Malvern Particle Size Analyzer (MPSA), which operates on the 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 downstream 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, by filtering, drying and weighing.

Rotating Flume and Instrumentation

The rotating flume is 5.0 m in mean diameter, consisting of an annulus 0.30 m in width, 0.30 m in depth and rests on a rotating platform. A counter rotating top cover ('ring') fits into the flume and makes contact with the surface of the sediment-water mixture in the flume. By rotating the platform and the ring in opposite directions, it is possible to generate nearly two-dimensional shear flows and to study the behaviour of the sediment under different flow conditions. See Krishnappan (1993) and Petersen and Krishnappan (1994). The flume was filled with about 4 barrels of harbour water, to a depth of 0.12 m. There are two ports at mid-depth and mid-width of the flume for withdrawing the sediment for particle size analyses and concentration measurements. The same procedures were used as for the wave flume.

Wave 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 as small as possible with the objective of reproducing as closely as possible the same initial particle size. To do this, the mixture was agitated until the particle size, as measured by the MPSA, had reached a minimum. In the later tests, more effort was required to reduce the floc size to a minimum value. 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. Note that Day 0 was the same day that the water and sediment was first put into the flume. 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.

Rotating Flume Experiments

The shear flow tests in the rotating flume were set up to reproduce the root-mean-square shear of the wave flume tests: three shear stresses were used, 0.056, 0.121, 0.213 Pa, comparable to 0.07, 0.14 and 0.23 Pa estimated in the wave flume. The procedure to break up the flocs at the beginning of each test was slightly different from the wave tests. In the wave tests, the water was agitated as vigorously as possible until the floc size had reach a minimum. In the shear flow tests the mixture was agitated in the same manner at the beginning of each test: the sediment was cleaned off the bottom with a brush; the mixture agitated in a prescribed manner with a blender; followed by lowering the ring onto the surface and rotating the flume and ring at maximum speeds for 20 minutes before reducing the speeds to those required for the desired shear. Initial concentration and size measurements were made. One series of tests using all three shears was conducted in each of three consecutive weeks. Day 1 was the day after the water and sediment was first added to the rotating flume. Concentration and distribution measurements were then made periodically for the duration of each test, typically lasting 6 hours.

RESULTS

Initial conditions

Wave Flume

Over the course of the tests, two features were dominant. The first dominant 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 1 and in Table 1.

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

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

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 53.4 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.

FIGURE 1

Rotating Flume

The initial particle size increased much more dramatically in the shear flow tests than in the wave tests, while the concentration increased slightly in the third week. These points are shown in Figure 2 and Table 2.

TABLE 2. Concentration and particle size at the beginning of each test in the rotating flume.

Day	Shear Stress, Pa	Initial Concentration, mg/L	Initial D_{50}, µm
1	0.213	186.26	8.76
2	0.121	191.86	11.84
3	0.056	182.54	13.66
7	0.213	189.60	28.80
8	0.121	189.71	37.97
10	0.056	185.73	56.36
15	0.213	202.16	69.68
16	0.121	200.47	65.07
17	0.056	192.20	61.87

The initial particle size increased from 8.8 to 61.9 µm from Day 1 to Day 17, with a maximum value obtained on Day 15. By way of contrast the concentration was relatively constant around 190 mg/L, with a slight tendency to higher values in the last week. The difference in methods used to break up the flocs is clearly evident. The same level of mechanical agitation at the start of each test in the rotating flume was less able to break down the flocs to the same degree as time progressed, whereas the procedure in the wave flume, wherein the particle size was monitored, was more successful in creating smaller flocs.

FIGURE 2

Concentration Evolution

Wave Flume

The time variation of concentration of sediment in suspension is shown in Figures 3a and 3b 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 3. These slopes, which are an approximate measure of the deposition rate exhibit a reasonable 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).

FIGURE 3

Table 3. Linear regression of concentration versus time in the wave flume.

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

Rotating Flume

The time variation of concentration of sediment in suspension is shown in Figures 4a, 4b, and 4c for shear stresses of 0.056, 0.121, and 0.213 Pa respectively. In the low shear case, there is a significant difference between the results for the first week and the next two weeks. In the first week, the concentration decreased slowly throughout to about 60 mg/L, without reaching a steady state, whereas in the next two weeks, the concentration decreased rapidly in the first hour and reached nearly constant values of about 8 and 4 mg/L respectively in six hours for the second and third weeks. With the intermediate shear, the overall concentration behaviour was similar in all three weeks, except for a more rapid loss of material in the initial hour, the values after six hours in the range of 80 to 110 mg/L; highest for the first week and lowest for the second week. The high shear case produced different results. Firstly, the concentration did not decrease substantially from the beginning to end of each test; secondly, the concentration after six hours was greater in each week: about 150, 160 and 175 mg /L respectively.

FIGURE 4

Particle Size Evolution

Wave Flume

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 of time of the test as well as the bottom stress.

In Series A (Figure 5a), with water and sediment fresh from storage, the floc size was virtually constant throughout each of the first and second test (Days 1 and 2), only increasing slightly in the second test. These tests were at the intermediate and low stress levels respectively. On Day 3, 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 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 (Days 6, 7, and 8 respectively). 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. 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.

FIGURE 5

In Series B, all tests are characterized by an increase in floc size from the initial value (Figure 5b.). The maximum D_{50} values for the first week (Days 11, 12 and 13) were intermediate in value between the first and second week of series A, probably due to the introduction of fresh sediment at the beginning of the series. By the second week (Days 18, 19 and 20) the maximum D_{50} values exceeded all previous values. In the first week, the size levelled 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.

Rotating Flume

The evolution of the floc size during each test is shown in Figures 6a, b, and c, for shear stresses of 0.056, 0.121, and 0.213 Pa respectively. For the low shear, in the first week the size dropped slightly from the initial value; in the next two weeks the size rose quickly then dropped rapidly to final equilibrium values. The rapid drops were coincident with the rapid drop in concentration. The particle size results for the two higher shears are markedly different from the low shear case. In the first week there was a slight increase in the size compared to a slight decrease. In the second week there was a rapid increase within the first hour to a constant value, about 70 µm for the medium shear and about 55 µm for the high shear. In the third week, both higher shears produced maximum (about 115 and 95 µm respectively) within the first hour, followed by a slight decrease to constant values of about 100 and 85 μm respectively for the medium and high shears.

FIGURE 6

The rapid drop in particle size at the lowest shear during the second two weeks, accompanied by loss of material, indicates that the shear was strong enough to promote the formation of flocs, but not so strong at the boundary to destroy them and prevent deposition. The opposite appears to be the case for the two higher shears. The larger shear promoted floc formation in the body of the fluid, but at each higher shear more material stayed in suspension, indicating that the bottom boundary shear was strong enough to destroy the flocs, with the result that there was less deposition. The floc size is largest at the medium shear. This indicates that at the highest shear the turbulence has increased to the extent that it is a limiting factor in the size development of the floc size.

DISCUSSION AND CONCLUSIONS

The size distribution data from both the wave flume and the rotating flume experiments show that the Port Stanley sediment has a tendency to flocculate as it is subjected to the flow field and the extent of flocculation is a function of the bed shear stress induced by the flow fields and the length of time in which the sediment was tested in each flume. Dependency on the length of time that the sediment is in the flume may be explained on the basis of flocculation process mediated by bacteria. When the sediment was stored in the cold rooms at 4 degree C prior to testing, the bacteria and other micro organisms present in the sediment water mixture were inactive. Once the mixture was placed in the flumes and were subjected to flow fields under room temperatures (25 to 30 degree C), the bacteria and other micro organisms could become active and play a role in the flocculation process of the inorganic sediment particles. The role of bacteria on flocculation of sediment has been noted in the literature (see Van Leussen, 1988, Rao et al., 1991). The bacteria are known to secrete polymers (Leppard, 1993) that could "bridge" the inorganic sediment particles together to form flocs. As the duration in which the sediment was in the room temperature increased, there is a possibility for higher bacterial density and increased polymer concentration that could produce stronger flocs. This could explain the monotonic increase in initial D_{50} values of the sediment in both the flume tests (see Tables 1 and 2).

The influence of bed shear stress of a turbulent flow field on the flocculation mechanism has also been studied extensively in the literature (Krone, 1962, Partheniades and Kennedy, 1966, Mehta and Partheniades, 1975, Van Leussen, 1988, Krishnappan et al., 1994, Krishnappan, 1995). In a turbulent flow, the bed shear stress is a measure of turbulence level and, therefore, governs the collision frequency of the particles suspended in the flow. Its effect on sediment flocculation varies depending on its magnitude. At low shear stresses, the collision frequency is small and the rate of sediment flocculation is also small. But as the shear stress is increased, the collision frequency increases, which promotes flocculation and causes the size of the flocculated sediment to increase. But, with further increase in shear stress, the flocs start to break up as they are unable to withstand the higher shearing action of the flow. The size distribution data from the present study confirm that the bed shear stresses induced in the wave flume and the rotating flume had similar effect on the Port Stanley sediment. At low bed shear stresses, the sediment settled without appreciable flocculation and the size of the sediment decreased as a function of time (see Figures 5a and 6a). At medium and high shear stresses, the turbulence promoted flocculation and caused the floc sizes to increase as a function of time (Figures 5a, 6b and 6c).

The time variation of concentration as a function of time in both the flumes suggests that the influence of bacterial flocculation is pronounced only at low bed shear stresses when the sediment settling was without appreciable flocculation. But at medium and high bed shear stresses, this turbulence level plays a prominent role and the bacterial effects are not very pronounced.

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 7×10^6 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. Deposition would be enhanced within the harbour, and deposition outside the harbour in the nearshore would be more rapid and hence more local to the shoreline near the harbour.

The role of bacteria in the flocculation of the inorganic sediment needs further investigation.

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FIGURE CAPTIONS

Figure 1. The initial concentration and sediment particle size versus time for the wave flume.

Figure 2. Initial concentration and particle size for the rotating flume.

Figure 3 a) Concentration versus time for Test Series A, wave flume. Solid lines are data: dashed are regressions, see table 3.

b) Concentration versus time for Test Series B, wave flume. Solid lines are data: dashed are regressions, see table 3.

Figure 4. Concentration versus time for the rotating flume. Shear stress: a) 0.056 Pa; b) 0.121 Pa; c) 0.213 Pa.

Figure 5 a) Sediment particle size versus time, Test Series A, wave flume. Low stress (–••–); medium (•••); high (–).

b) Sediment particle size versus time, Test Series B, wave flume. Low stress (–••–); medium (•••); high (–).

Figure 6. Sediment particle size versus time, rotating flume. Shear stress: a) 0.056 Pa; b) 0.121 Pa; c) 0.213 Pa.

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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 laboratory studies using samples from Port Stanley, a harbour on Lake Erie, have provided initial information of the response to wave and current action. Increased wave action reduces floc formation, implying greater capacity for transport of sediment-associated contaminants outside the harbour, especially for storm events. On the other hand increased residence time greatly increases bacterial growth and, coupled with low shear flow in the harbour under low flow conditions, promotes floc formation allowing deposition of contaminated sediments within the harbour.

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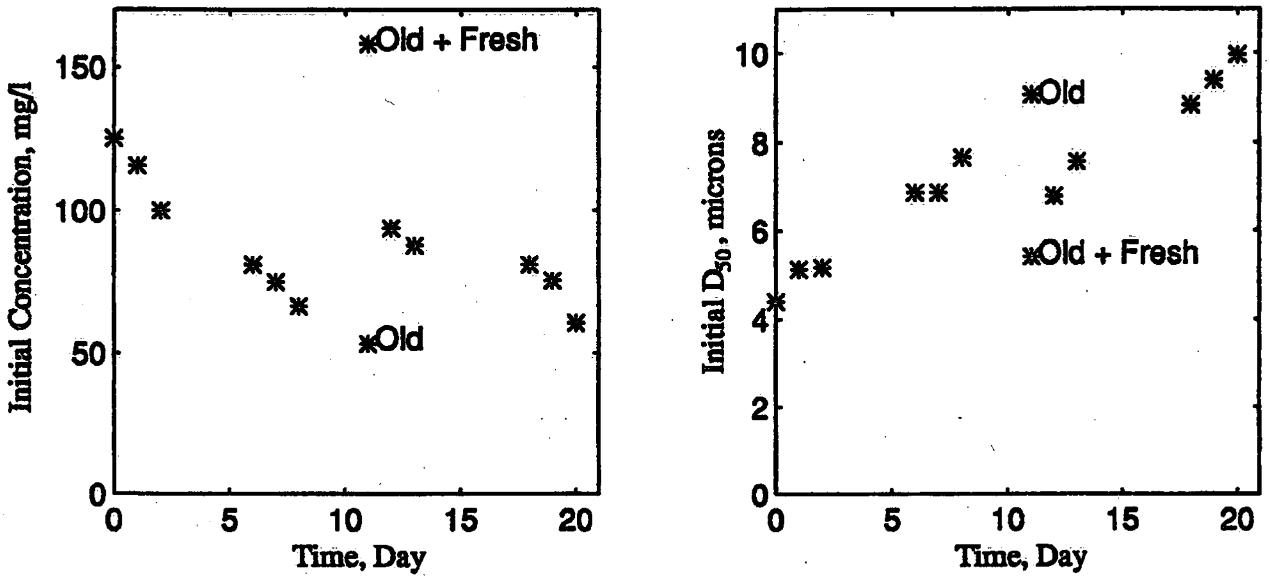

Figure 1

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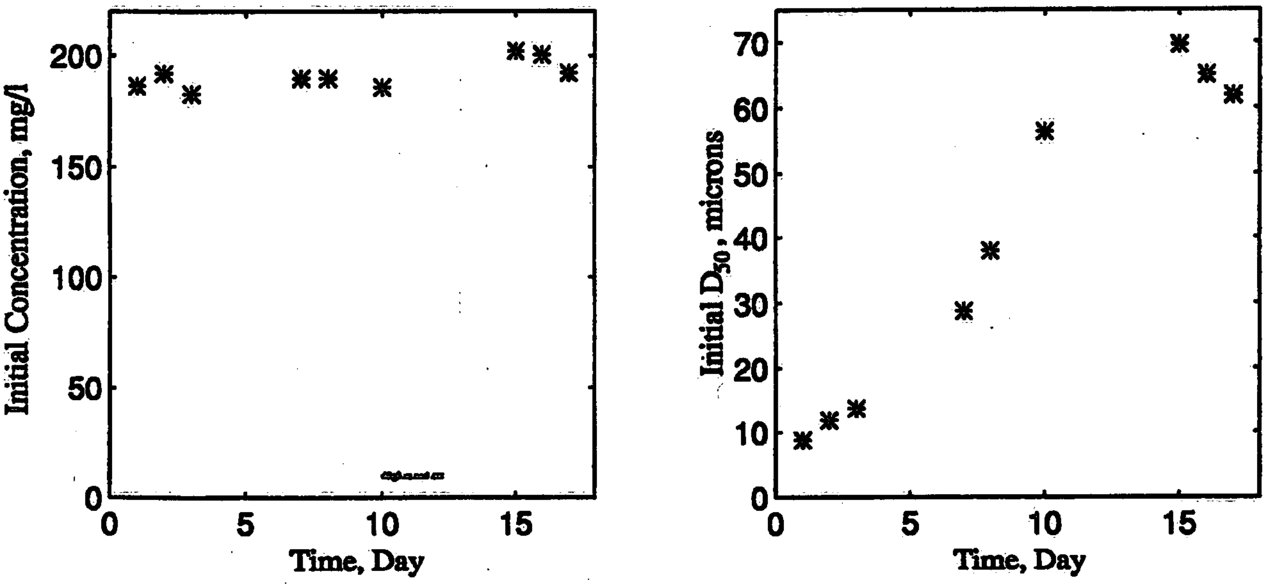

Figure 2

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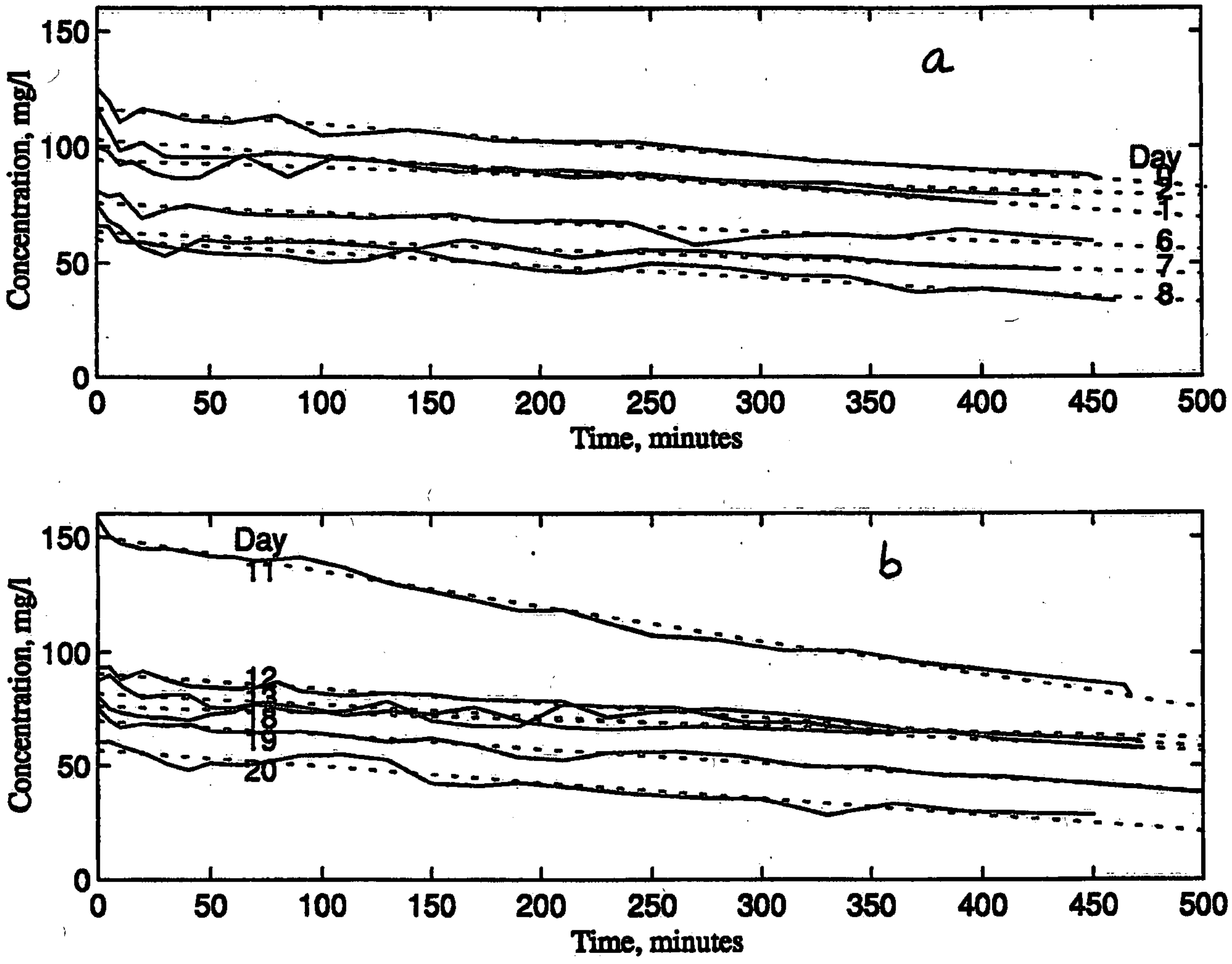

Figure 3

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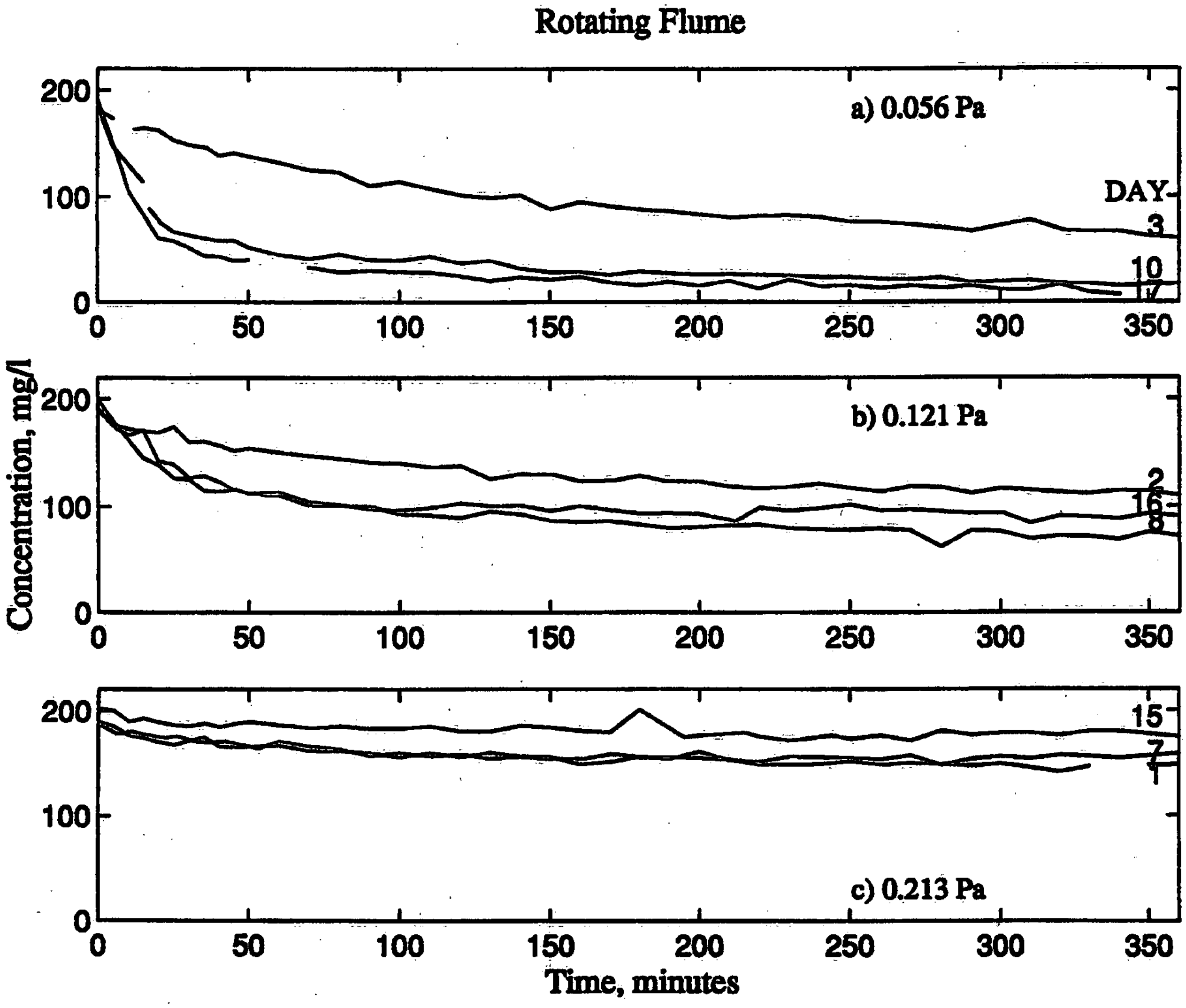

Figure 4

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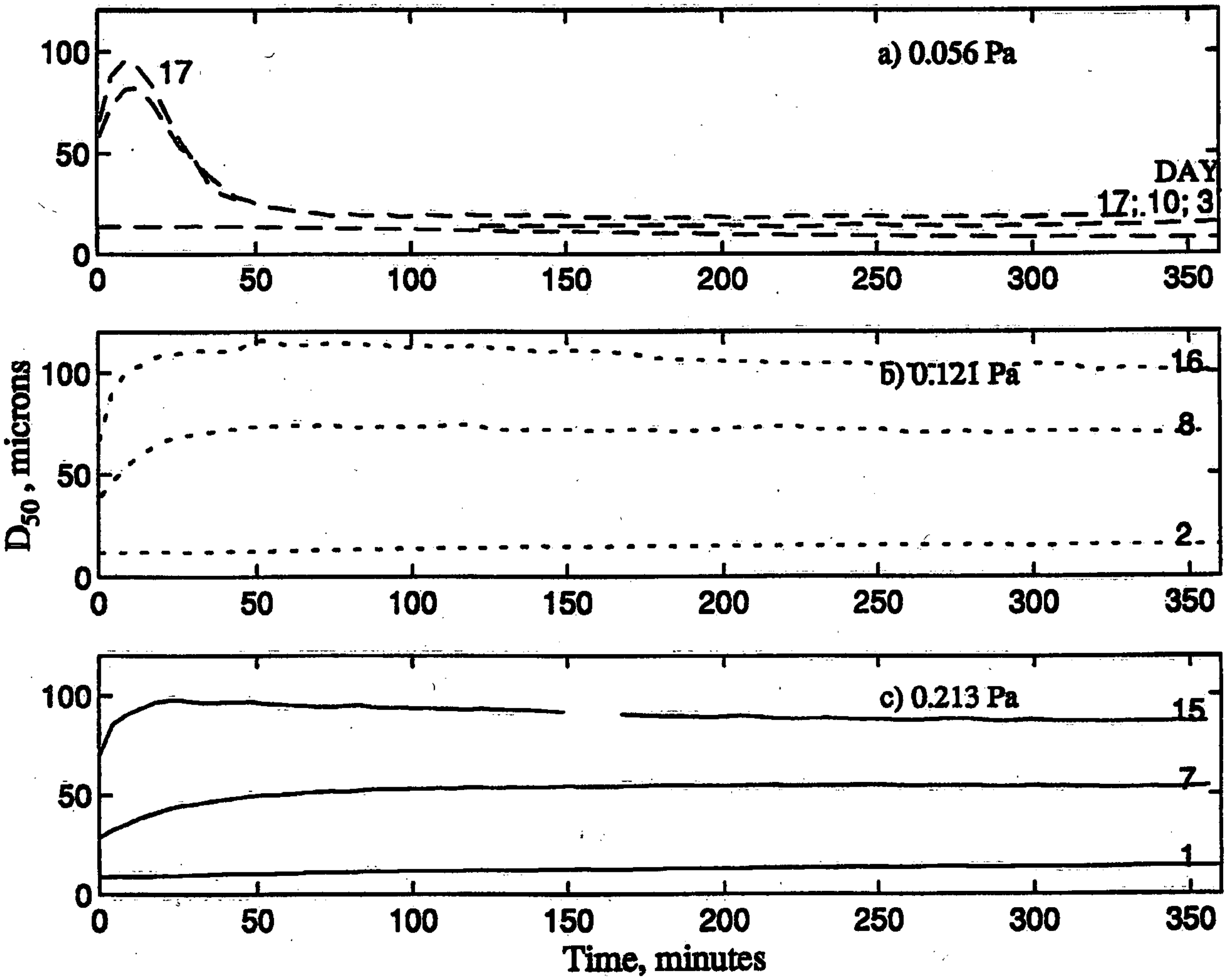

Figure 6

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