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# SIZE DISTRIBUTION AND SETTLING VELOCITY OF COHESIVE SEDIMENTS DURING SETTLING

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NWRI CONTRIBUTION 91-61

RRB 91-29

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Y.L. Lau & B.G. Krishnappan

Rivers Research Branch
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario

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## MANAGEMENT PERSPECTIVE

Fine-grained sediments play an important role in the transport of certain classes of hydrophobic contaminants in river systems. The contaminant concentration in particulate form can be several orders of magnitude higher than that in the dissolved phase. The concentration also varies with the size of the particle; the finer the particle, the higher the concentration. Therefore, an understanding of the dynamics of the settling of various sizes of sediments is essential to the understanding of pathways and fate of contaminants. This report provides new information on the settling of fine sediments. It is found that deposition occurs in all size classes and that the size distribution of a suspension becomes finer as settling proceeds. It is also found that the settling velocity does not remain constant throughout the settling process. This new information improves our ability to model the transport of sediment and contaminants.

## PERSPECTIVE DE LA DIRECTION

Des sédiments de faible granulométrie jouent un rôle important dans le transport de certaines classes de contaminants hydrophobes dans les réseaux hydrographiques. La concentration de contaminants sous forme de particules peut être de plusieurs ordres de grandeur plus élevée que celle des contaminants en solution. La concentration varie également avec la taille des particules; plus le diamètre de la particule est petit, plus la concentration est élevée. Il est donc essentiel de comprendre la dynamique de la décantation des sédiments de différentes tailles pour connaître les voies d'acheminement et le devenir des contaminants. Le présent rapport fournit de nouvelles données sur la décantation des sédiments de faible granulométrie. Les particules de toutes les classes de granulométrie sédimentent et la distribution granulométrique d'une solution s'établit des particules les plus grosses au plus petites. On a également constaté que la vitesse de sédimentation n'est pas constante tout au long du processus. Cette nouvelle donnée nous permet d'établir un meilleur modèle du transport des sédiments et des contaminants.

## ABSTRACT

Experiments on settling of cohesive sediments were carried out in turbulent flows in an annular flume using kaolinite clay as well as a natural river sediment. Results indicate that the finer fractions were able to deposit because they were settling as flocs. Data on concentration and size distribution of dispersed samples were used to calculate the effective settling velocities for the different size fractions.

## RÉSUMÉ

Des expériences sur la sédimentation des sédiments cohérents ont été réalisées dans des écoulements turbulents dans un bassin circulaire en se servant de kaolinite, minéral argileux, aussi bien que de sédiments d'un cours d'eau. Les résultats montrent que les fractions de plus faible granulométrie pouvaient se déposer parce qu'elles le faisaient sous forme de flocs. Les données sur la concentration et la distribution granulométrique d'échantillons de dispersion ont été utilisées afin de calculer les vitesses de sédimentation réelles des différentes fractions granulométriques.

## INTRODUCTION

Erosion and deposition of fine cohesive sediments are two of the key processes governing the movement and fate of sediment-bound contaminants in the aquatic environment. While the transport processes for non-cohesive sediments are fairly well known, the same cannot be said for cohesive sediments. Due to physicochemical forces as well as biological factors, fine sediments form flocs and aggregates which settle at rates completely different from those of their constituent primary particles. Material which would never be able to deposit if they were cohesionless can flocculate and settle out and in the process remove the associated contaminants from the water column. Knowledge of the manner in which cohesive sediments settle and deposit is therefore very important for modelling the fate and pathway of contaminants, especially since the degree of affinity of contaminants with sediments can vary with size.

Kranck (1980) measured the size distribution during the settling of a suspension of kaolinite in a 15 cm diameter cylinder and found that the shape of the distribution curves stayed constant while the concentration in all sizes decreased. This lead to the conclusion that each floc contained within it a duplicate of the single grain size distribution of the whole suspension, which also meant that the material deposited consisted of the same size particles as those left in suspension.

Mehta and Lott (1987) proposed a model for settling in which each size class has its own critical shear stress. If the bed shear stress is below this critical value, all the initially suspended material of that size will eventually deposit. For a bed shear stress above the critical value, there will be no deposition at all. For any given flow, sediment in those classes in which the critical shear stress is less than the bed shear stress will not deposit. According to this model, the deposited material will have a size distribution quite different from the material left in suspension.

There is relatively little information on the change in size distribution during settling in turbulent flows. Patheniades and Kennedy (1966) analyzed one sample from an annular flume experiment after the settling suspension had reached equilibrium and found that the median diameter had decreased to 0.2 µm from the initial value of 0.9 µm. Mehta et al. (1982) measured the size distribution of material which was deposited in a 100 metre long flume in which a kaolinite-water slurry was discharged continuously into the upstream end. It was found that the median diameter increased with distance along the flume from about 4 µm to 10 µm, with most of the clayey fraction passing out of the flume.

In this paper, measurements of changes in concentration and size distribution during the settling of several types of suspensions are reported. The settling experiments were carried out in turbulent flows in an annular flume. These data can provide some useful insight into the process of settling of cohesive sediments.

## EQUIPMENT AND PROCEDURE

The experiments were carried out in an annular flume which has an outside diameter of two metres and a channel 20 cm in width. A top ring which fitted inside the channel could be lowered so that it just touched the water surface. Flows were generated by rotating the ring at various speeds.

Two different sediments were tested. The first was a kaolinite clay with a mean diameter of about 6.8 microns. The second was a sediment obtained from the Nith river in Southern Ontario, containing a combination of kaolinite and mortmorillonite and having a mean diameter of about 12 microns. The kaolinite clay was tested using distilled water as well as a 2% salt solution as the fluid medium, while the river sediment was tested using water drawn from the river. Flow depths were kept relatively constant at about 8 cm.

Before beginning an experiment, the water sediment mixture was thoroughly mixed first by a mechanical mixer and then by running the top ring at a high speed. The ring was then slowed to the desired speed to begin the experiment. Samples were withdrawn from the flume periodically until the concentration reached and remained at a constant equilibrium value. The samples were taken at mid-depth as tests had shown that the concentration was virtually uniform over the depth. Following the completion of one experimental run, the sediments were completed resuspended and the experiment was repeated using another speed for the top ring.

The concentration of each sample was determined by filtration, drying and weighing. The grain size distribution of the dispersed samples, i.e., the primary particle distribution, was determined using the Malvern Particle Size Analyzer (model 2600 c) which operates on the light diffraction principle (Fraunhoffer diffraction). Complete details of the instrument can be found in Weiner (1984). Prior to introducing the samples into the sample cell of the instrument they were treated with a dispersing agent and were shaken on a shaker to break up any flocs which might have formed. A magnetic stirrer in the sample cell kept the particles in suspension during the measurement.

The output of the Malvern Particle Size Analyzer consists of percentage of particles by volume in different size fractions and a cumulative size distribution curve from which median diameter and other statistics of the size distribution were calculated.

Bed shear stress measurements were made using a 2 mm diameter Preston tube. The shear stress increases steadily from the inner wall to the outer wall and the value at mid-width is a reasonable representation of the average bed shear stress.

## RESULTS AND DISCUSSION

The pattern of the decrease in concentration during settling is similar to that found by Mehta and Partheniades (1975) and Lick (1982). As deposition takes place, the suspended sediment concentration first decreases and then becomes constant at some value which has been termed the equilibrium concentration. The ratio between the equilibrium concentration and the initial concentration depends on the bed shear stress generated by the flow. This ratio decreases when the bed shear stress is reduced as more sediment is able to deposit.

The data show that the median diameter, $D_{50}$, of the material left in suspension (in dispersed state) also behaves in the same manner as the concentration, i.e., it decreases with time before levelling off at a constant value. As shown in Figs. 1 to 3, the curves of $D_{50}$ versus time are very similar to the concentration versus time curves. The median diameter becomes constant at about the same time the concentration becomes constant. This behaviour can be found for every test run. Size distribution curves for a typical test run are shown in Fig. 4. From the above results one can infer that the material which has deposited does not have the same size distribution as the initially suspended material.

After reaching equilibrium, the suspension has a median diameter, $D_{eq}$, which is finer thatn the $D_{50}$ of the original suspension. The values of $D_{eq}$ for the various runs are listed in Table 1. It can be seen that $D_{eq}$ decreases as the bed shear stress decreases. With a lower shear stress, there are less disruption of the flocs and more flocs are able to deposit.

The decrease of the median diameter with time means that more of the coarser fraction have settled out, leaving finer material in suspension. This may not seem very different from the settling of cohesionless material in which the grains are settling singly. However, it can be shown that the size distribution of the suspension is quite different from that resulting from single grain settling. Fig. 5 gives the size distribution histograms for a run using the Nith River sediment. Shown ar the initial distribution, when the concentration was 10424 ppm, and the distribution at t = 274 min. when the settling had reduced the concentration to 5274 ppm. It can be seen that the concentration of every size fraction had decreased, indicating that material from every size range had deposited. Also shown in the figure is the distribution obtained from a numerical model assuming single grain settling. The numerical model is a solution of the advective diffusion equation, with a constant horizontal velocity and a fall velocity given by Stokes Law. Using the initial size distribution and total concentration, the initial concentration of each size class is calculated. The model is then applied to each size class to obtain the change in concentration and subsequently, the change in size distribution with time. The computed size distribution when the total concentration has dropped to 5274 ppm is shown as a comparison. In this case, there is practically no deposition of the material smaller than 3 microns. The deposition of the finer fractions is also much smaller, while a much larger amount is deposited from the coarser fractions. Thus it is evident that floc settling was occuring in the experiments and this enabled the finer fractions to settle out much sooner than they would have otherwise, even though the coarser material was still depositing faster.

Table 1. Change of $D_{eq}$ with bed shear stress

| | Top ring speed (rpm) | Bed shear stress (dynes/cm$^2$) | $D_{eq}$ (micron) |
|---|---|---|---|
| Kaolinite-distilled water | 7.0 | 1.32 | 5.2 |
| | 8.0 | 1.72 | 5.5 |
| | 9.0 | 2.18 | 5.8 |
| | 10.0 | 2.69 | 5.9 |
| | 11.0 | 3.25 | 6.4 |
| Kalonite-2% salt solution | 7.4 | 1.47 | 5.0 |
| | 8.0 | 1.72 | 5.1 |
| | 11.0 | 3.25 | 6.2 |
| Nith River sediment | 7.0 | 1.32 | 9.4 |
| | 8.0 | 1.72 | 9.7 |
| | 9.0 | 2.18 | 10.2 |
| | 11.0 | 3.25 | 10.5 |

Using the data on total concentration and size distribution, it is possible to calculate the concentration of each particular size fraction in the suspension. With samples obtained throughout the period of settling, the change in concentration of each size fraction with time can be obtained. This data can be used to calculate the effective settling velocity of each size fraction.

The time rate of change of concentration in the suspension can be written as

$$\frac{dC_i h}{dt} = -W_i C_i \tag{1}$$

in which $C_i$ is the concentration of the ith size class, $W_i$ is the effective settling velocity for that size class, h is the water depth and t is the time. In most models of sediment transport, the settling velocity is considered to be constant for any size class (Mehta and Lott, 1987, Onishi, 1981). This may be true for cohesionless material but when sediments are settling as flocs the effective settling velocity may well be changing as settling progresses. However, for any discrete period of time, one can define an average settling velocity as

$$\bar{W}_i = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} W_i dt \tag{2}$$

By integrating Eq. 1, the average settling velocity over a given time period can be calculated from the concentration data as

$$\bar{W}_i = \frac{h}{t_2 - t_1} \ln\frac{C(t_1)}{C(t_2)} \tag{3}$$

Fig. 6 is a plot of the average settling velocity of some of the size classes against time for a run in which the shear stress was low enough for all the material to eventually deposit. It can be seen that there is a definite increase of $\bar{W}_i$ with size in the early stages. However, the settling velocity for the larger sizes decreases much more rapidly so that $\bar{W}_i$ becomes practically the same for all sizes as time goes on. The same trend is found for all the other runs as well. Some typical examples are shown in Figures 7 to 9. It can be seen that, except for the smallest size class, $\bar{W}_i$ does not remain constant during settling.

It is fairly well known that the overall settling rate of a sediment suspension is an increasing function of the total concentration, provided that the concentration is not so high that hindered settling takes place. In their model for cohesive sediment settling, Mehta and Lott (1987) extended this idea to the distribution of settling velocity for the various size classes. Their assumption is that the distribution of the settling velocity, $\phi(W_i)$, is the same as the distribution of initial concentration, $\phi(C_{0i})$. The critical shear stress for deposition for each size is also related to its settling velocity and hence to the distribution of initial concentration. Their model also assumes that the sediment comprising those classes for which the critical shear stress for deposition is larger than the actual bed shear stress will all deposit while those classes with critical shear less than the bed shear will not deposit at all. These assumptions can be examined using the presented data.

Figure 10a shows the concentration histograms for a kaolinite-distilled water test at the beginning and partway through the settling. Figure 10b shows the corresponding settling velocity histograms. There is little resemblence between the concentration and settling velocity distributions at either times. This is found to be true for all the test runs. Figures 11 and 12 show typical results from the kaolinite-salt solution and the Nith River sediment data. These results, plus the finding that deposition of all sizes occur during settling, certainly cast doubt on the assumptions used by Mehta and Lott.

## SUMMARY AND CONCLUSIONS

Size distribution measurements of the dispersed suspended sediment samples show that the change of the median size with time is similar to that of the total concentration, i.e., an initial decrease followed by steady state value at about the same time as the concentration reaches its equilibrium value. As the bed shear stress increases, the steady state value of the median size also increases.

An examination of the full distribution of suspended sediment reveals that settling of sediment occurs in all size fractions with effective settling velocities varying depending on the size: the finer fractions settling slower than the coarser fractions. Settling was occuring in all size classes. This shows that the finer fractions must have been settling as flocs because under the condition of single grain settling, the deposition of finer fractions has to be practically zero as predicted by a numerical model.

The fact that the size distribution changes as settling progresses, with $D_{50}$ decreasing, implies that flocs are not composed of particles from all size classes in the same proportion as the original suspension, as inferred by Kranck (1980) from experiments in settling columns. This result suggests that the coarser particles are associated with stronger flocs which can withstand the higher shear near the bed and are able to deposit, while the flocs containing more of the finer material get broken up near the bed and are resuspended. This is also consistent with the result that $D_{50}$ increases as the shear stress increases. When the shear stress is increased, some of the flocs which were strong enough to settle previously are now also broken up and resuspended. As these contain more larger particles, the distribution in the suspension becomes coarser.

The present data also do not support the sediment sorting model proposed by Mehta and Lott (1987). According to Mehta and Lott, certain size fractions which have lower values of critical shear stress for deposition do not deposit at all. However, present results show that deposition is evident for all size classes.

The effective settling velocity which is usually assumed to be constant for a given size of sediment is shown to decrease as settling progresses. This should be taken into account in future modelling efforts.

## ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of Jesse Heidt in the experimental work and data analysis.

NOTATIONS

| | |
|---|---|
| $C_i$ | concentration in the ith size class |
| $C_0$ | initial concentration |
| $D_{50}$ | median diameter |
| $D_{eq}$ | median diameter in the equilibrium suspension |
| $h$ | depth of flow |
| $t$ | time |
| $W_i$ | settling velocity of the ith size class |
| $\phi$ | a function |

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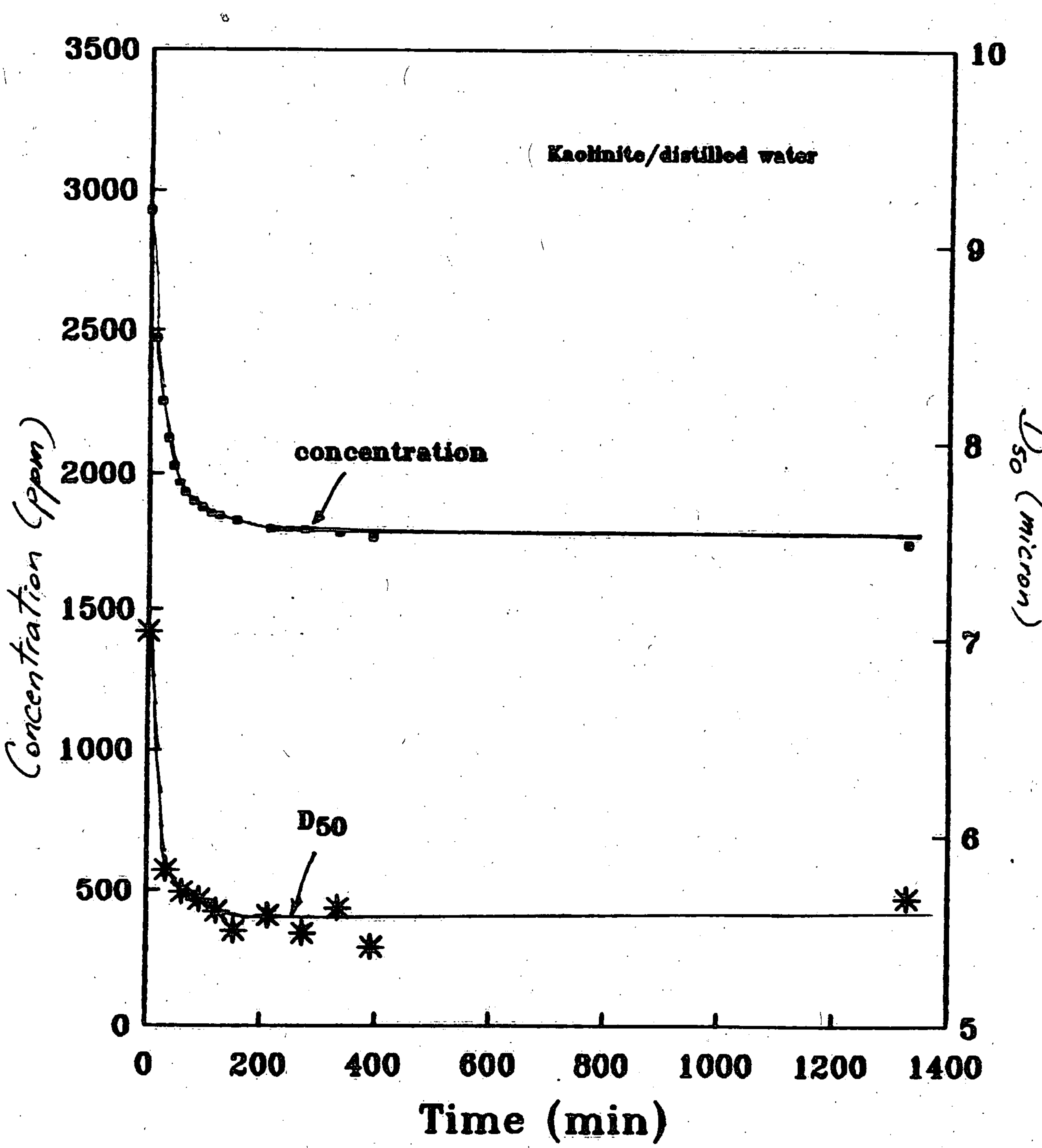


Fig. 1 Changes in concentration and median diameter with time. Ring speed = 8 rpm.

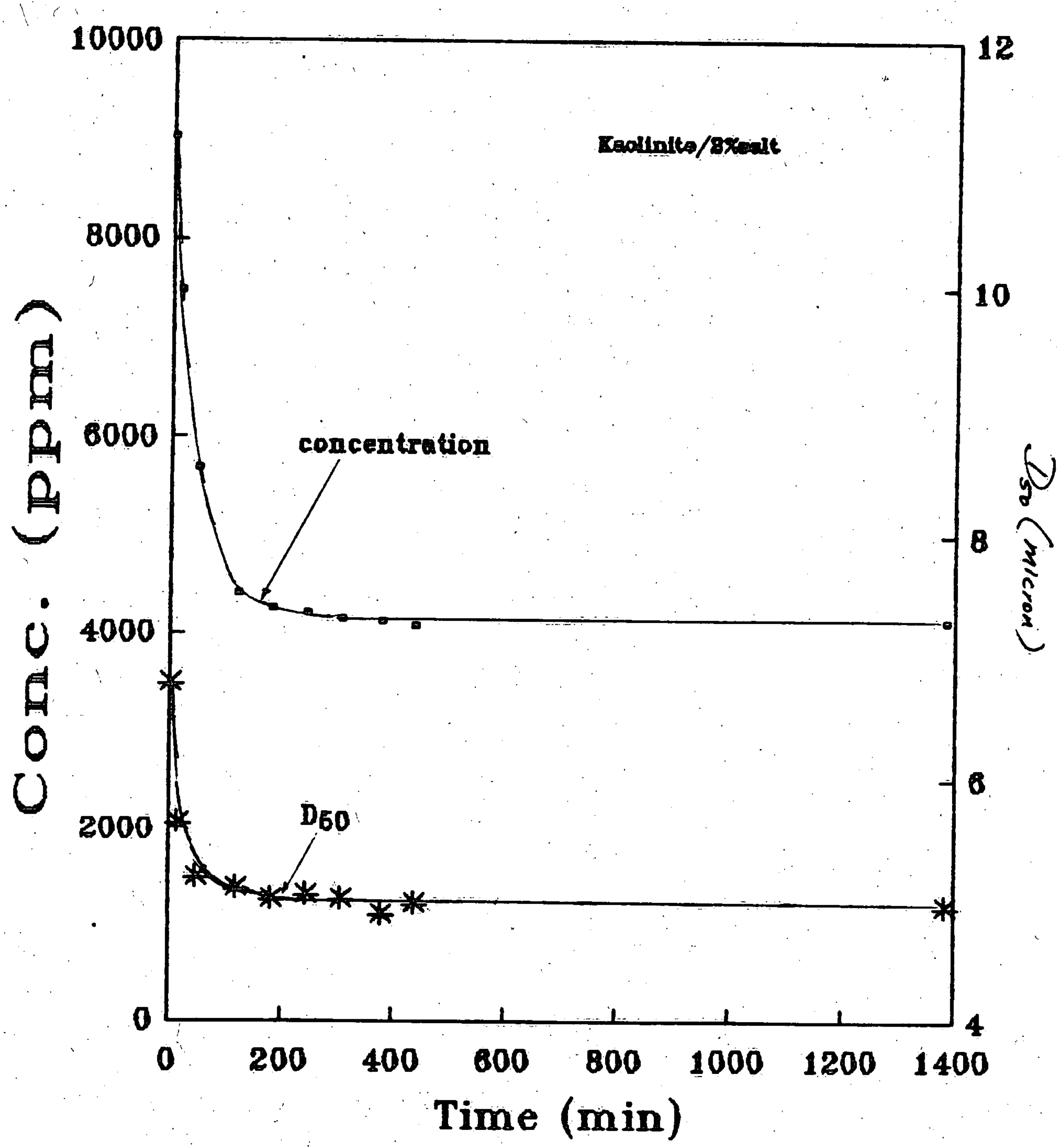


Fig. 2 Changes in concentration and median diameter with time. Ring speed = 7.4 rpm.

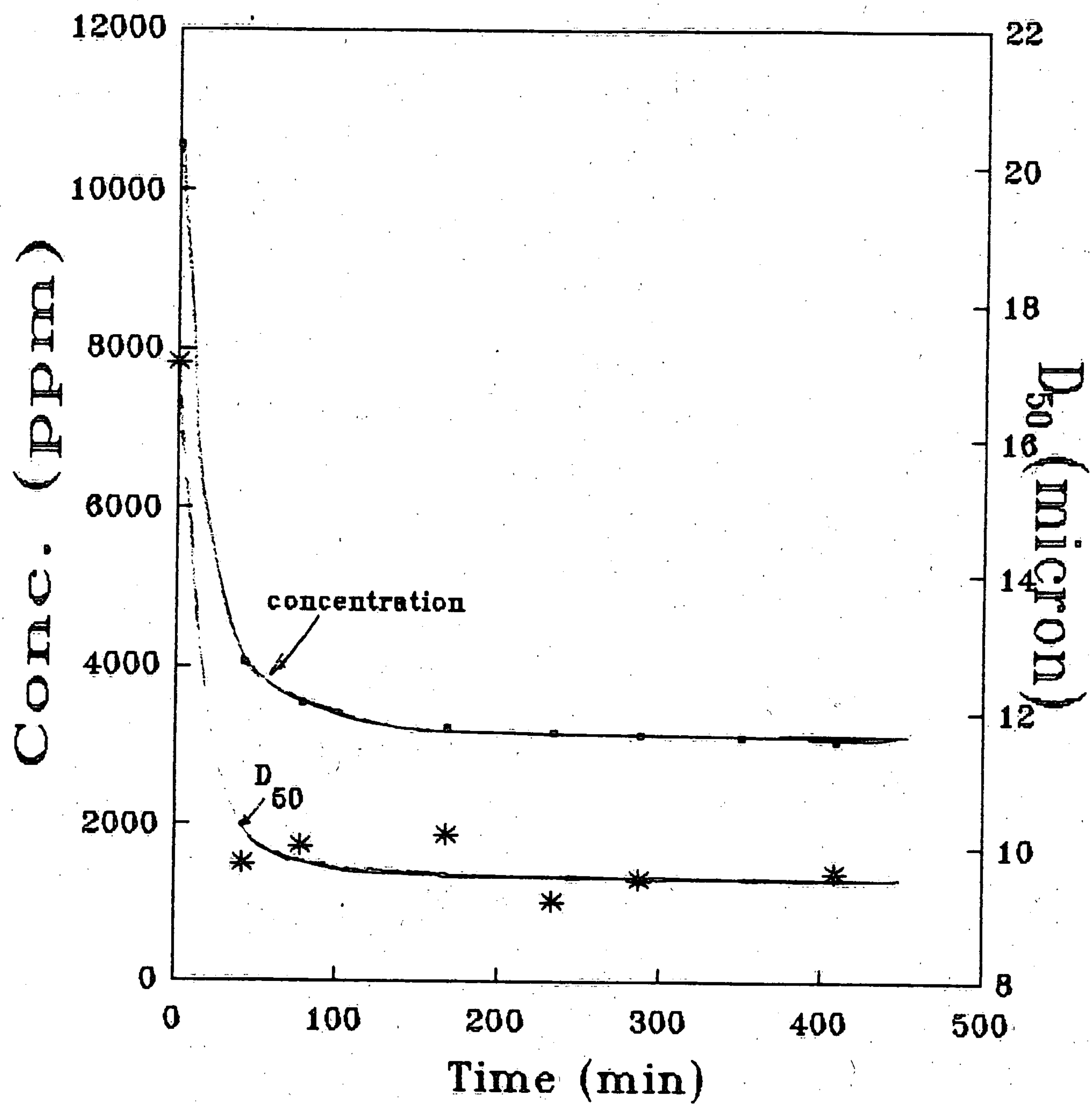


Fig. 3 Changes in concentration and median diameter with time. Ring speed = 8 rpm.

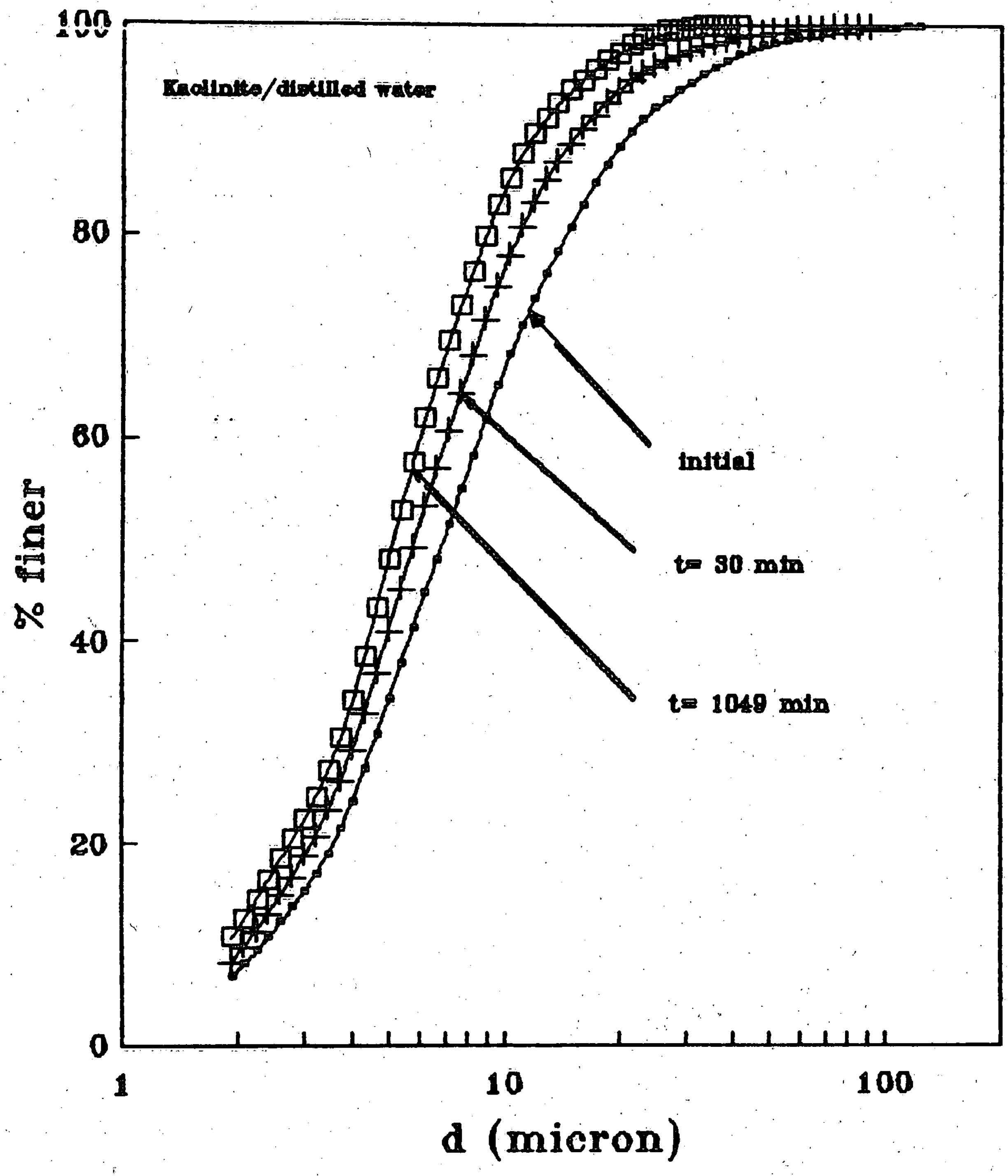


Fig. 4. Changes in size distribution during settling
Ring speed = 7rpm.

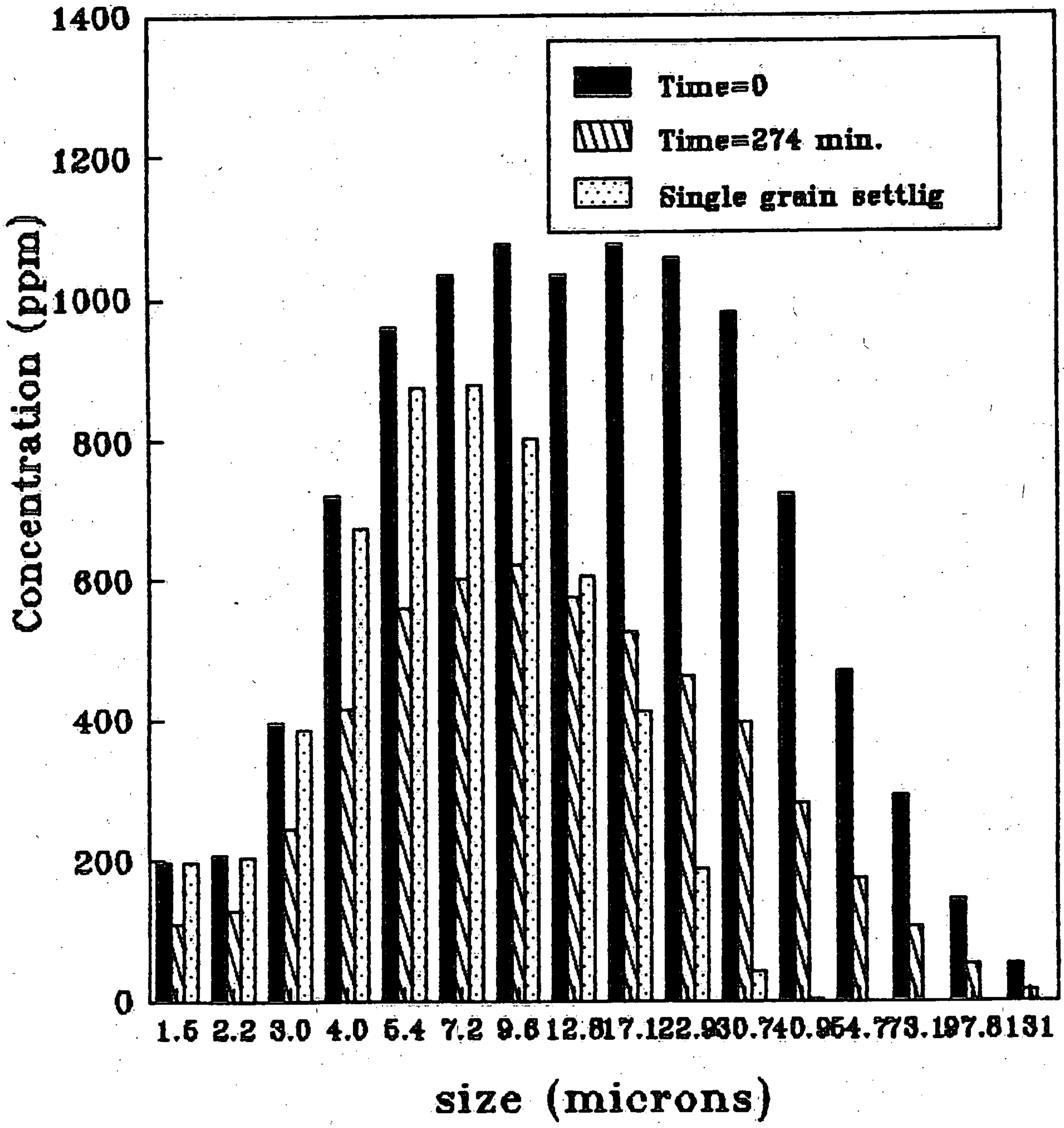


*Fig. 5. Measured concentration distributions and the computed distribution assuming single-grain settling. Nith river sediment, ring speed = 11 rpm.*

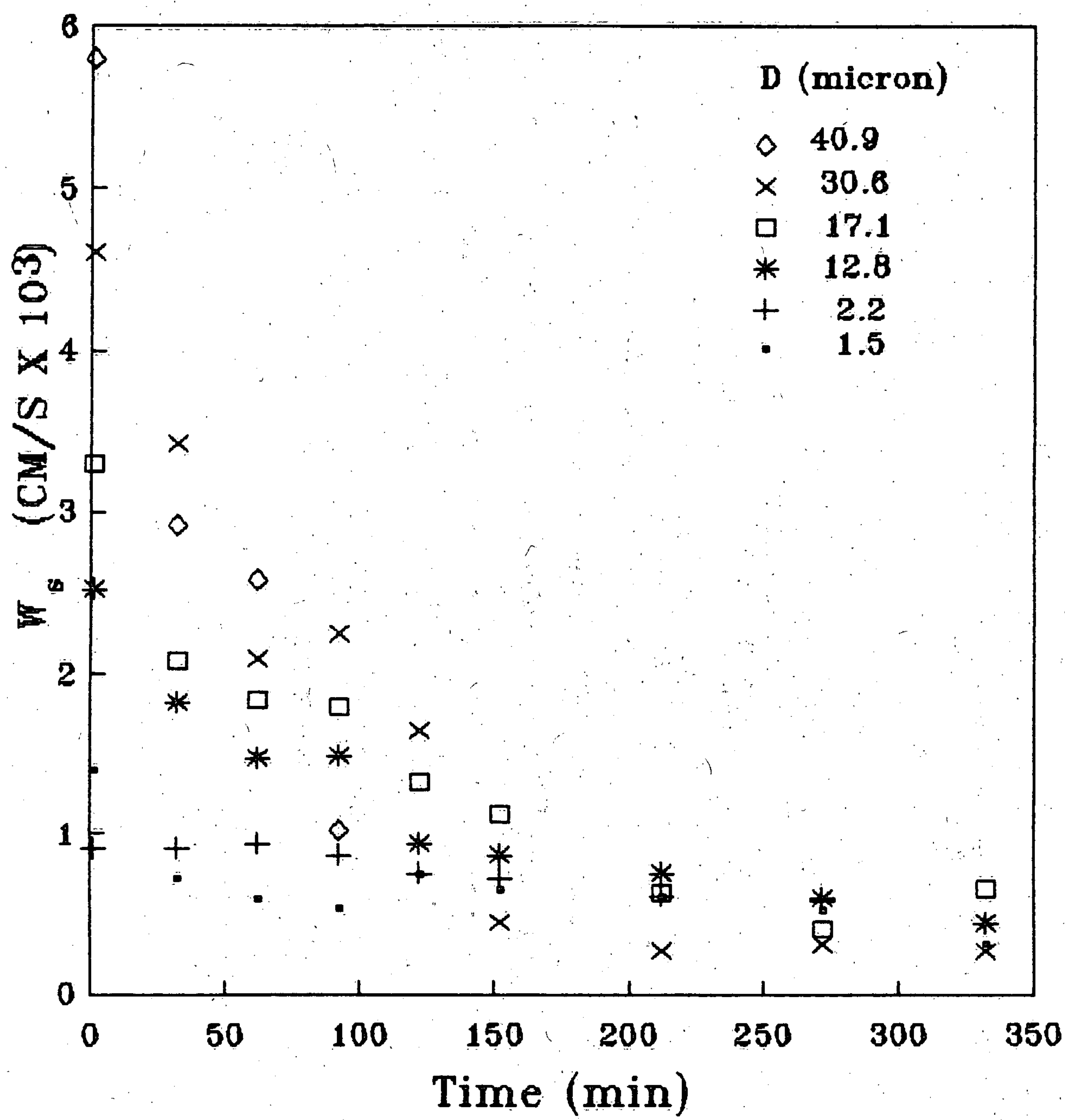


Fig. 6 Changes in settling velocity with time for different size classes. Kaolinite/distilled water, ring speed = 5.8 rpm.

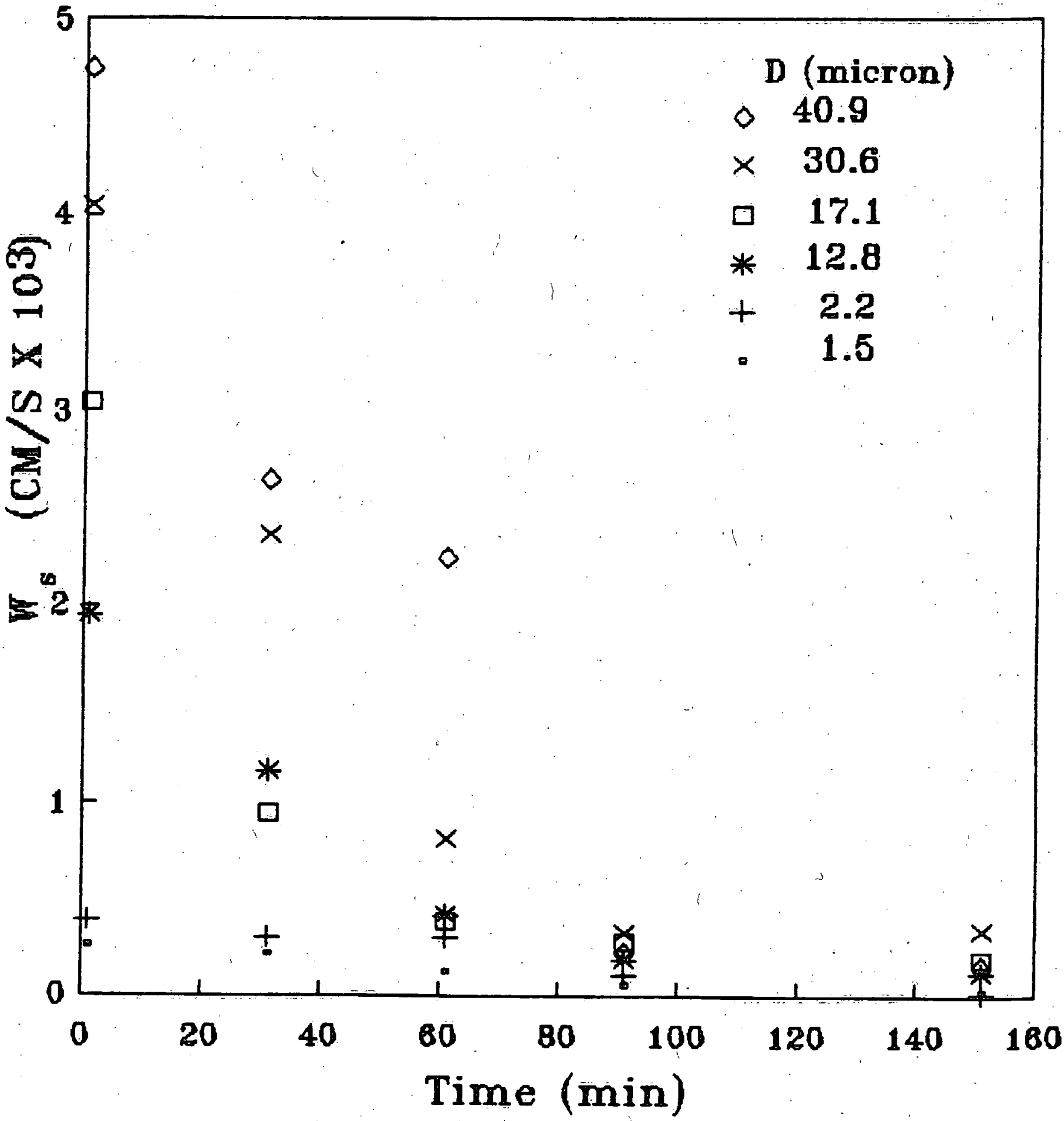


Fig. 7 Changes in settling velocity with time for different size classes. Kaolinite/distilled water, ring speed = 7rpm.

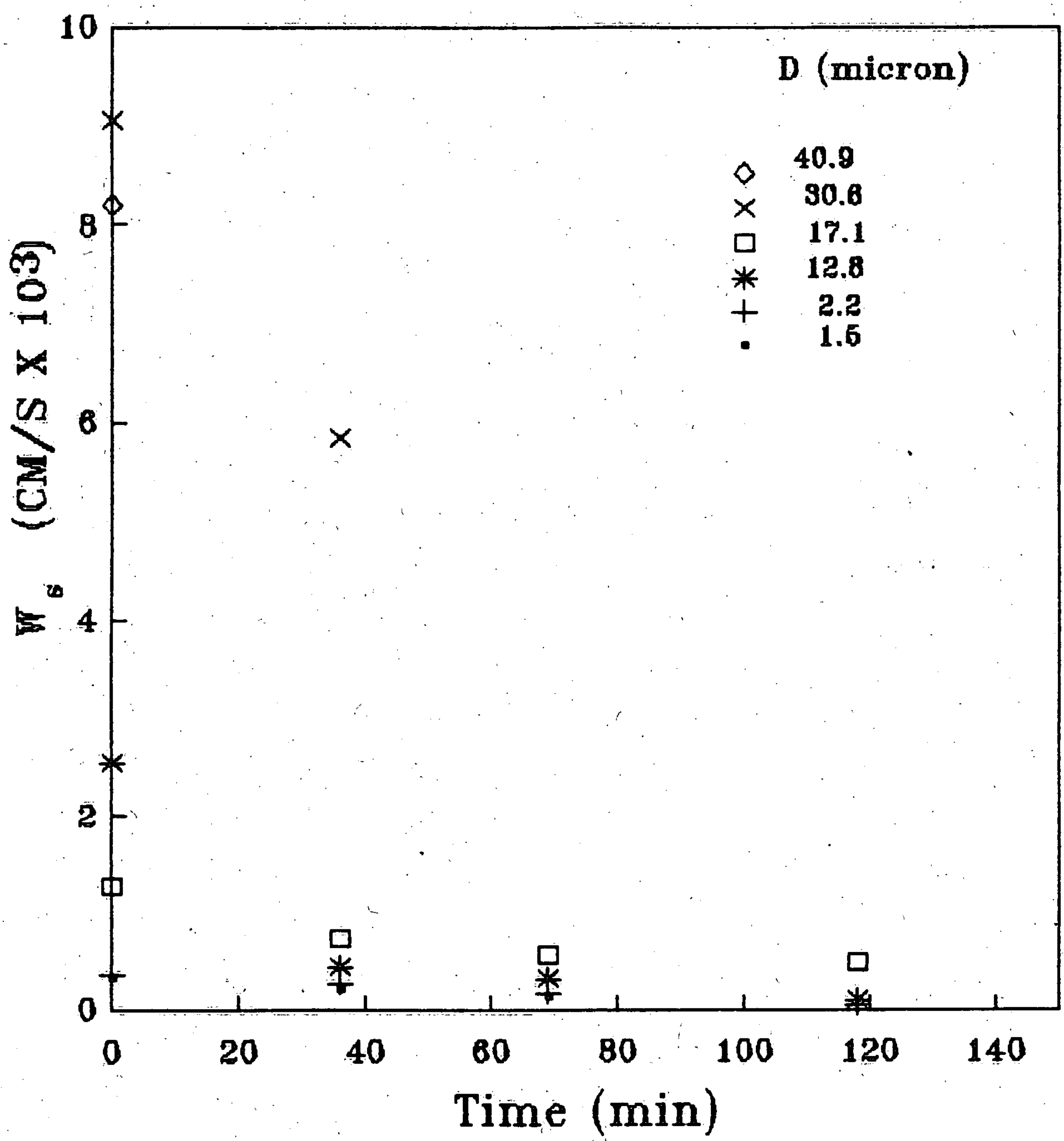


Fig 8 Changes in settling velocity with time for different size classes. Kaolinite/2% salt, ring speed = 8 rpm.

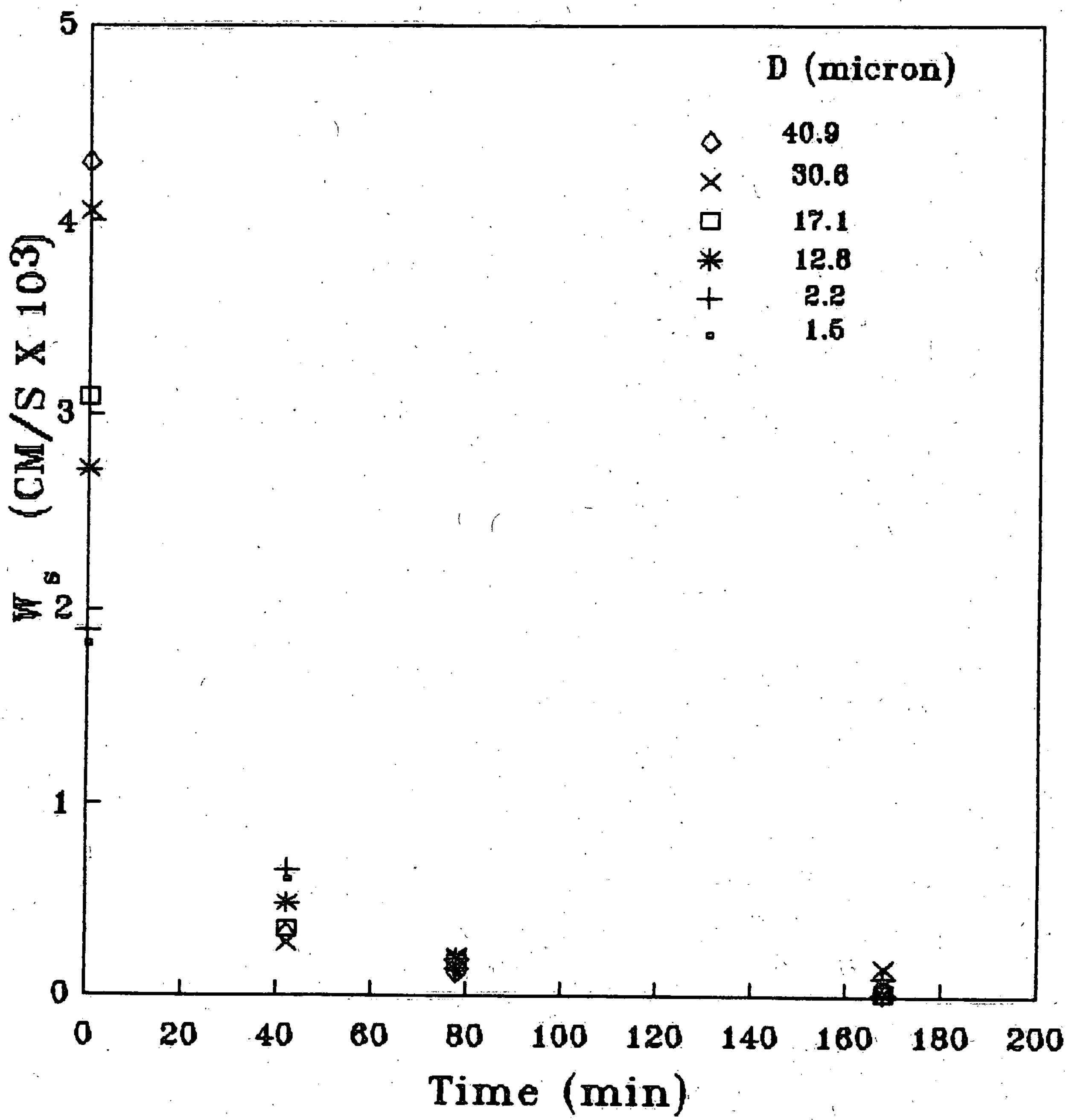


Fig 9. Changes in settling velocity with time for different size classes. Nith River sediment, ring speed = 7rpm.

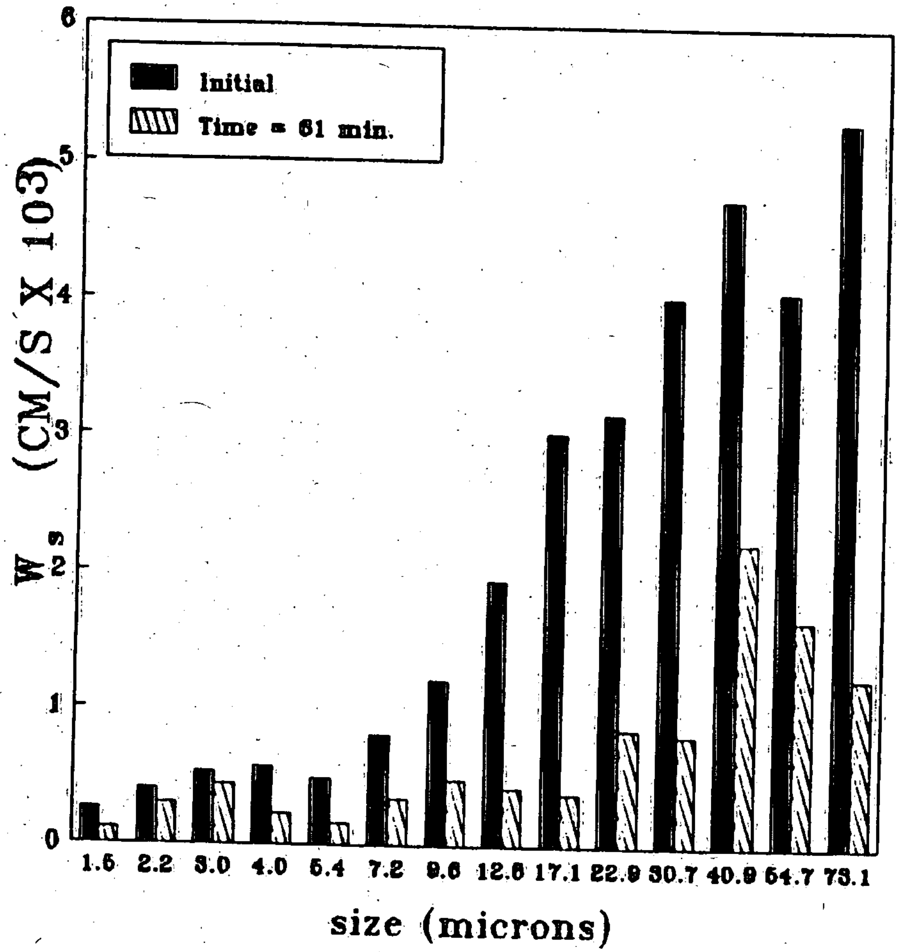


Fig. 10 a. Settling velocity distributions.
Kaolinite/distilled water, ring speed = 7rpm.

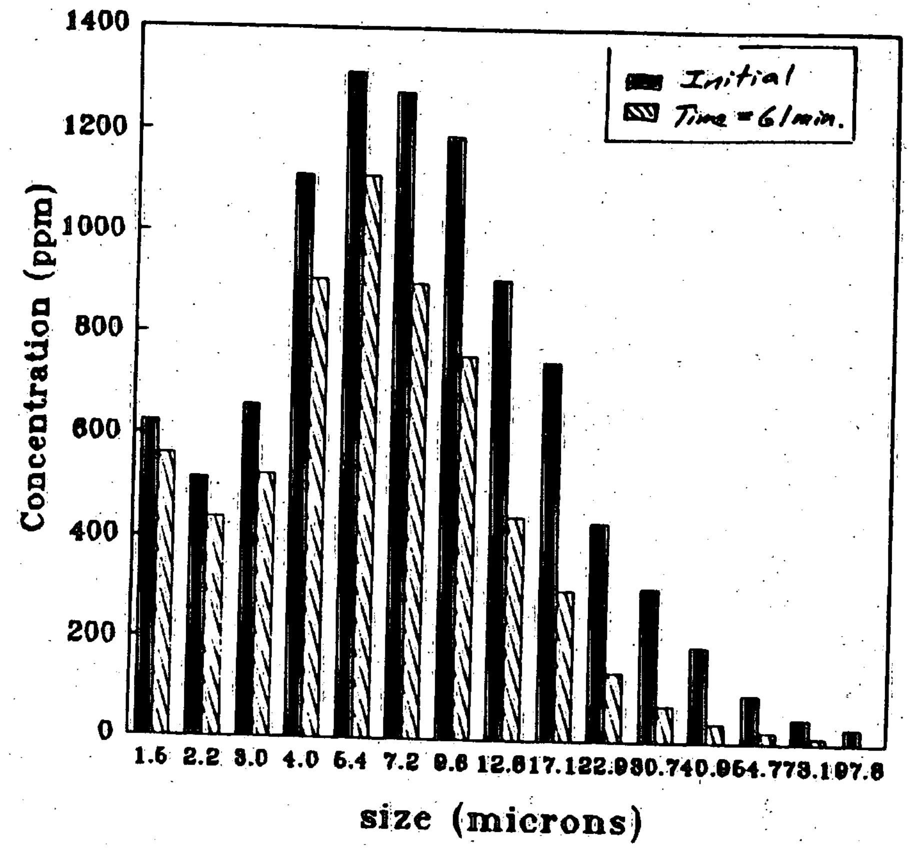


Fig. 10 b. Concentration distributions.
Kaolinite/distilled water, ring speed = 7rpm.

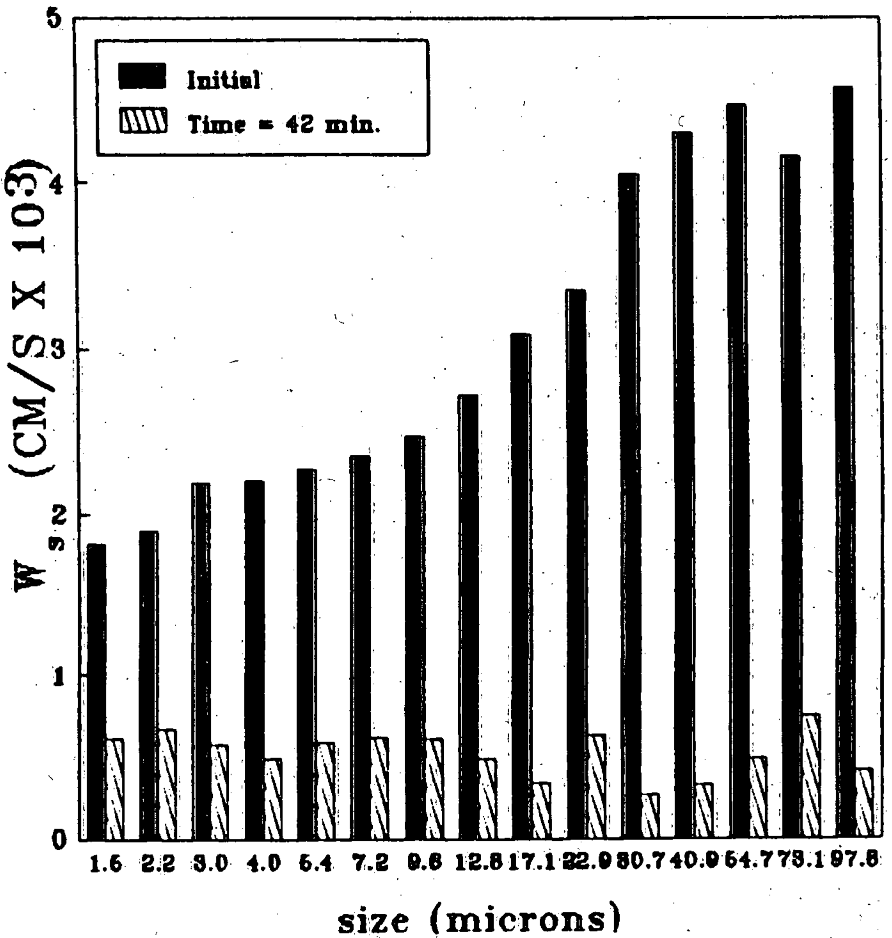


Fig. 11a. Settling velocity distributions. Nith River sediment, ring speed = 7rpm.

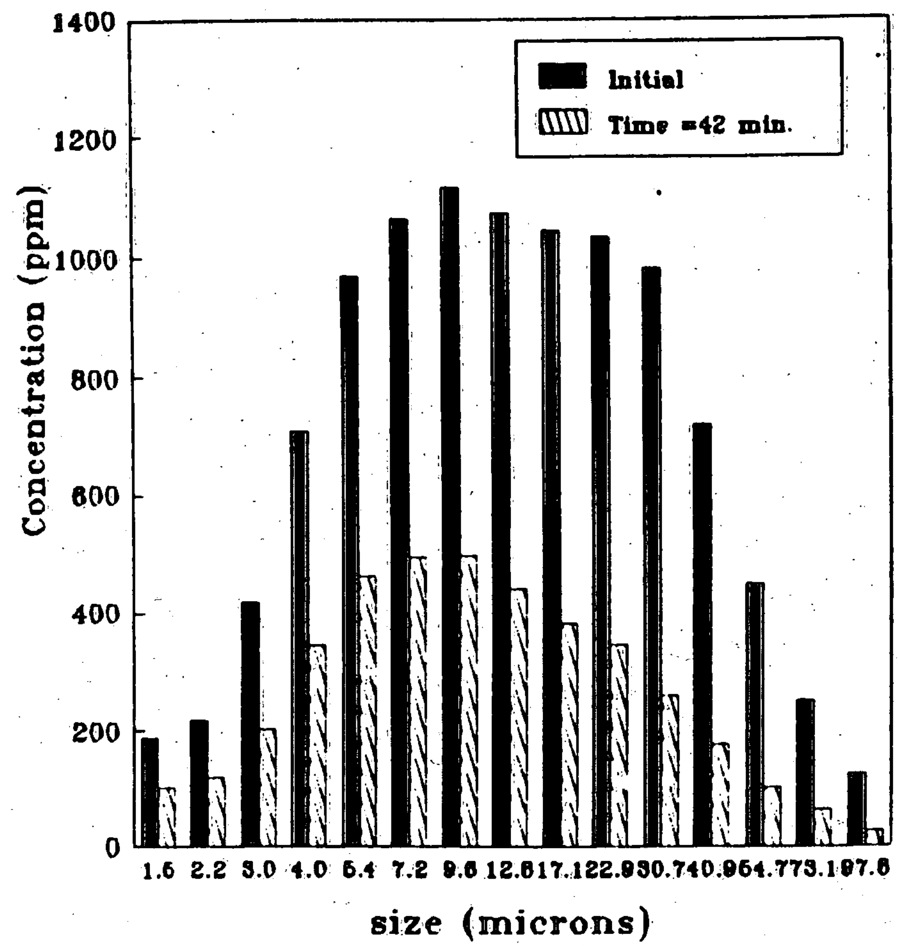


Fig. 11b. Concentration distributions. Nith River sediment, ring speed = 7rpm.

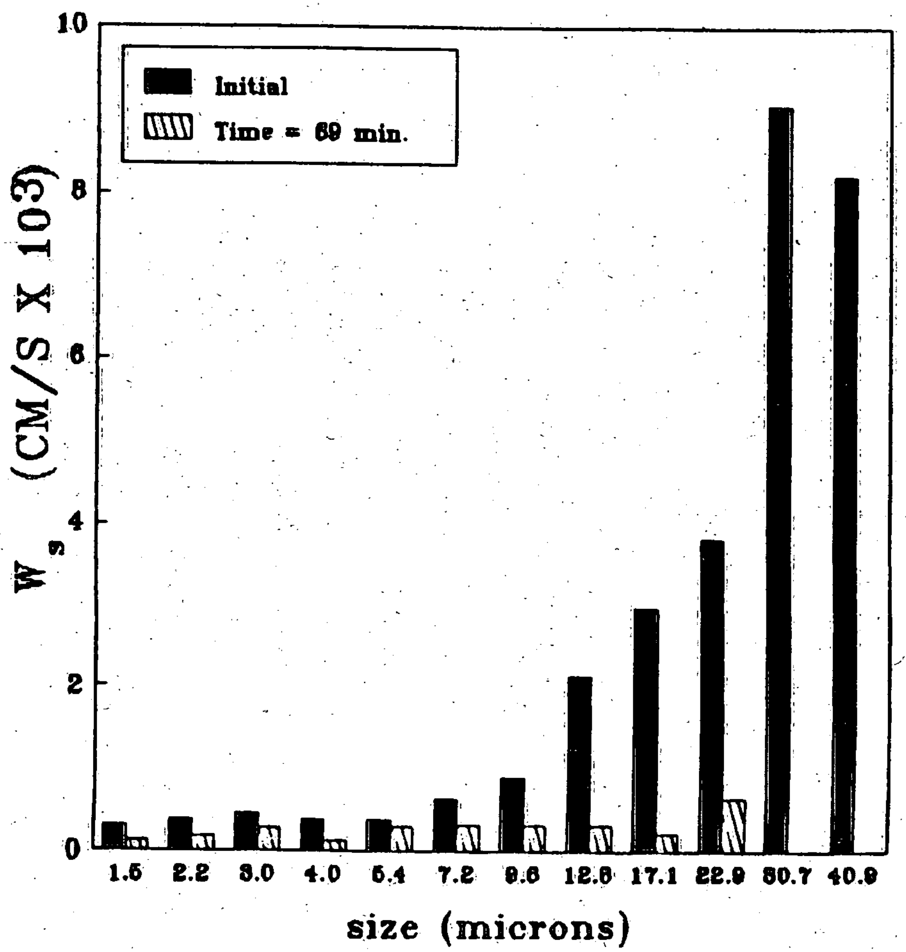


Fig. 12a. Settling velocity distributions. Kaolinite/2% salt, ring speed = 8rpm.

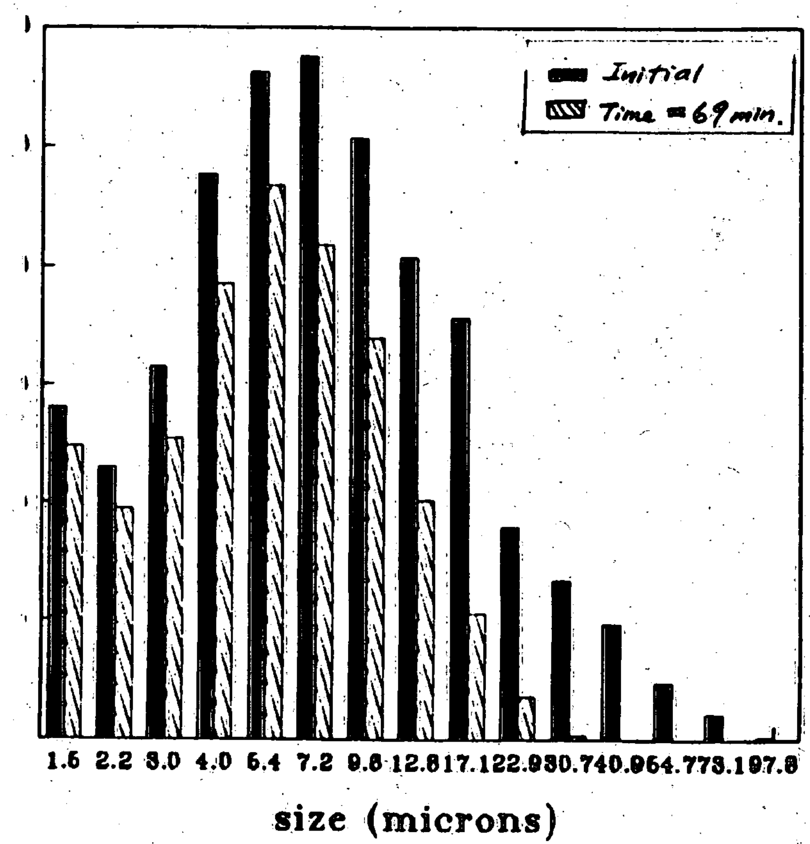


Fig. 12b. Concentration distributions. Kaolinite/2% salt, ring speed = 8rpm.

NATIONAL WATER RESEARCH INSTITUTE
P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

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INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX
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