NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL de RECHERCHE sur les EAUX

COHESIVE SEDIMENT TRANSPORT

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NWRI CONTRIBUTION NO. 95-59

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MANAGEMENT PERSPECTIVE:

This review paper examines the state-of-the-art of the cohesive sediment transport research. It gives an overview of the cohesive sediment literature with an emphasis on emerging issues and knowledge gaps. It also describes the cohesive sediment research programme of the National Water Research Institute at Burlington, Ontario, Canada and concludes that a multidisciplinary approach is needed to make further progress in this field.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Ce document de synthèse fait le point sur les recherches dans le domaine du transport des sédiments cohésifs. On y présente un aperçu de la littérature traitant des sédiments cohésifs en insistant sur les problèmes nouveaux et les données qui manquent dans ce domaine. On y décrit également le programme de recherche sur les sédiments cohésifs de l'Institut national de recherche sur les eaux, à Burlington (Ontario), au Canada et on conclut qu'il faut une approche multidisciplinaire pour faire des progrès dans ce domaine.

ABSTRACT:

In recent years, there has been a renewed interest in cohesive sediment transport research in the environmental field. Cohesive sediments in the size classes of silt and clay are known to adsorb and transport many contaminants that are toxic and persistent. For a proper design of environmental monitoring and management of toxic contaminants bound to sediments, a better understanding of cohesive sediment transport processes is a prerequisite.

Since the pioneering work of Partheniades and Kennedy (1966), several investigators (such as Krone, Mehta and Lick, to name a few) have made significant contributions to our understanding of cohesive sediment behaviour in turbulent flows. In this paper, an overview of the cohesive sediment transport literature is given with an emphasis on emerging issues and knowledge gaps. In addition, the cohesive sediment research programme of the National Water Research Institute in Burlington, Ontario, Canada is described by highlighting the research facilities and showing a case study that dealt with the influence of pulp mill effluent on the transport characteristics of fine sediments of the Athabasca River near Hinton, Alberta, Canada. The study showed that the suspended sediment in the river was transported in the flocculated form even though the river is a part of a fresh water system and the effluent from the pulp mill affected the flocculation mechanism and consequently the deposition rate. The study also points to a need for a multidisciplinary approach to deal with the flocculation process of the sediments of the fresh water systems in the presence of pulp mill effluents.

RÉSUMÉ

Au cours des dernières années, on a observé un renouveau d'intérêt pour la recherche sur le transport des sédiments cohésifs dans le domaine de l'environnement. On sait que les sédiments cohésifs de la catégorie de tailles du silt et de l'argile adsorbent et transportent de nombreux contaminants toxiques et rémanents. Pour bien concevoir les travaux de surveillance de l'environnement et de gestion des contaminants toxiques fixés aux sédiments, il faut avant tout une meilleure compréhension des processus de transport des sédiments cohésifs.

Depuis les travaux de pionniers comme Partheniades et Kennedy (1966), plusieurs autres chercheurs (tels que Krone, Mehta et Lick, pour ne nommer que ceux-là) ont apporté une contribution importante à notre compréhension du comportement des sédiments cohésifs dans les courants turbulents. Dans le présent article, on présente un aperçu de la littérature sur le transport des sédiments cohésifs en insistant sur les problèmes nouveaux et les données qui manquent dans ce domaine. En outre, on y décrit le programme de recherche sur les sédiments cohésifs de l'Institut national de recherche sur les eaux de Burlington (Ontario), au Canada, ainsi que les installations de recherche et en signalant une étude de cas portant sur l'influence des effluents des usines de pâtes sur les propriétés de transport des sédiments fins de la rivière Athabasca, près de Hinton (Alberta), au Canada. L'étude a montré que les sédiments en suspension dans la rivière sont transportés sous forme de flocs, même si la rivière fait partie d'un réseau hydrographique d'eau douce et que les effluents des usines de pâtes ont un effet sur le mécanisme de floculation et donc sur la vitesse de dépôt de ces sédiments. L'étude signale aussi la nécessité d'adopter une approche multidisciplinaire dans les recherches sur le processus de floculation des sédiments des réseaux hydrographiques d'eau douce en présence d'effluents d'usines de pâtes.

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INTRODUCTION

Transport processes of fine-grained, cohesive sediments are markedly different from those of the coarse grained, cohesionless sediment. For example, fine-grained sediment particles in the size classes of silt and clay have a tendency to interact among themselves and form agglomeration of particles called flocs whereas the coarse grained particles in the size classes of sand and gravel behave as individual particles. While the size and the specific weight of the individually transported cohesionless sediment particles are well defined and invariant with the flow field, the same properties of the cohesive sediment floc are a function of the flow field (see, Van Leussen (1988); Krishnappan and Engel (1994); Lau and Krishnappan (1994a)). These parameters have to be determined before the prediction of the cohesive sediment transport can be attempted. In other words, the size and density of the cohesive sediment floc themselves become dependent variables, thereby increasing the complexity in the treatment of cohesive sediment transport. In addition, the agglomeration or the flocculation of the cohesive sediment depends on a number of factors such as particle mineralogy, electro-chemical nature of the flowing medium, biological factors such as bacteria and other organic material and the hydrodynamic properties of the flow field. For a complete understanding of this process, a multidisciplinary approach requiring expertise from different disciplines is needed.

The motivation for past research on cohesive sediment transport was provided by the need for better estimates of soil erosion, shoaling of channels and harbors, and dredging requirements for navigational purposes and as a result, the past research was mainly concerned with cohesive sediment in the estuaries and coastal areas. Recently, there is an additional motivation prompted by the need for a better understanding of transport of pollutants that are attached to cohesive sediment. A majority of highly toxic and persistent chemicals entering a river system from agricultural, industrial and municipal sources have high affinity for fine particles and are transported mostly in association with the cohesive sediment. Therefore, many existing ecosystem models dealing with contaminant transport, fate and bioaccumulation in aquatic environment invariably include a cohesive sediment transport component and require a better understanding of the cohesive sediment transport processes. In this paper, an overview of the cohesive sediment transport literature is given with an emphasis on emerging issues and knowledge gaps. In addition, a brief description of the current research on cohesive sediment at the National Water Research Institute in Burlington, Ontario, Canada is included at the end of the paper.

REVIEW OF LITERATURE

Transport processes and parameters that describe the behaviour of cohesive sediment in a flow field are identified in this review by examining a sediment mass balance equation. A form of the equation that was adopted by Teisson (1994) is used here. In this form, the equation and the boundary conditions are as follows:

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}_i \frac{\partial \bar{c}}{\partial x_i} + \frac{\partial (w - w_s)\bar{c}}{\partial z} = -\frac{\partial \overline{(u'_i c')}}{\partial x_i} + S(x,y,z) \qquad x_i = x,y,z \;\; and \;\; u_i = u,v,w \qquad (1)$$

where $\bar{c}$ is mean concentration of sediment in suspension

$\overline{u_i}$ and u_i are mean and instantaneous flow velocities

u_i' and c' are fluctuating velocity components and fluctuating sediment concentration

w_s is the settling velocity of the sediment particle

S(x,y,z) is the sediment source or sink within the solution domain other than the boundaries.

The boundary conditions are:

$$(w - w_s)\overline{c} + \overline{w'c'} = 0 \qquad \text{(At the free surface)} \qquad (2)$$

$$-w_s\overline{c} + \overline{w'c'} = q_d + q_e \qquad \text{(At the bed)} \qquad (3)$$

where q_d and q_e are fluxes due to deposition and erosion respectively.

The turbulent flux of sediment is usually determined using the eddy diffusivity concept:

$$\overline{u'c'} = -\Gamma_{si}\frac{\partial \overline{c}}{\partial x_i} \qquad (4)$$

where Γ is the diffusion coefficient. If we assume that the velocity components are provided by a hydrodynamic model, then to close Eqn (1), we need to know the settling velocity, w_s, the expressions for erosion and deposition fluxes, q_e and q_d at the bed, and the sediment diffusion coefficient, Γ_s. The above equations are equally valid for cohesionless sediment. The difference between a cohesive and a cohesionless sediment transport model lies in the specification of the parameters, w_s, q_e and q_d.

SETTLING VELOCITY:
The settling velocity of cohesive sediment cannot yet be predicted theoretically because the particle size and the effective densities of the settling units change as a function of concentration and time as result of the flocculation process. Therefore, a better understanding of the flocculation process is needed before the settling velocity of the cohesive sediment can be quantified. A large number of studies have been reported in the literature on flocculation of estuarine sediment. A review of these studies is given by W. Van Leussen (1988). A brief account of the flocculation process and its impact on settling velocity is given below.

Flocculation Process:
Flocculation of particles is treated in terms of two mechanisms: One is the collision mechanism which brings the particles close to each other or makes them collide and the second is the cohesion mechanism which makes the nearby or collided particles to bond and form flocs. Under the collision mechanism, three prominent processes were identified. These are: 1) Brownian motion due to thermal energy of the fluid, 2) Velocity gradients (laminar and turbulent shear) causing particles to collide because of the relative motion of fluid at different levels and 3) Differential settling that results in particle collisions when fast settling larger particles overtake and collide with slower settling smaller particles. Collision frequency functions, which are measures of probability of collisions among particles, were established for these processes and were used in models of flocculation in settling basins (see, Valioulis and List (1984a, 1984b, 1984c); Pearson et al (1984); Krishnappan (1990, 1991)). Hunt (1980) compared these functions to show the relative importance and concluded that for particles less than 1.0 μm, the Brownian motion is important and for particles larger than 10 μm, the shear flow and differential settling are dominant. The shear flow plays a dual role in the flocculation process. While an increase in the velocity gradient increases particle collisions and promotes flocculation, it can also limit the size of the flocs because the

shearing action of the velocity gradient could exceed the shear strength of the floc and could break it into smaller units.

Cohesive mechanisms are responsible for bonding particles together once they are brought in contact by the collision mechanism. The most widely studied cohesive mechanism is the one governed by the electro-chemical processes. The surface forces involved under this mechanism are discussed in detail by Lambe as cited in Owen (1970). Briefly, the particles experience two opposing surface forces. The attractive force is due to the electrical fields formed by dipoles of individual particles and is commonly known as the Van der Waal's force and it depends on the distance between the two particles (inversely to the seventh power). The repulsive force is due to the clouds of positive cations surrounding the negatively charged sediment particles and it depends on the ion concentration and ion valency (inversely to the first power of both). The resultant force can either be attractive or repulsive depending upon the relative magnitude of these two forces. In suspensions with low ion concentration, the ion cloud is large and the repulsive forces keep the particles too far apart for the Van der Waal's force to be effective. When the ion concentration is increased, for example, by the addition of sodium chloride, the size of the ion cloud reduces and the particles can come closer. The reduced distance may be sufficient for the attractive force to overcome the repulsive force so that the particles could join and form a floc. This is the main flocculation mechanism that is responsible for generation of "turbidity maximums" often observed in estuaries when the salt water from the ocean intrudes into the fresh water in the river. Coating of particles with metallic and /or organic material in natural waters can affect the surface charge characteristics of suspended particles and influence the electro-chemical flocculation. Addition of pollutants to the river water can also have similar influence.

In more recent studies of sediment flocculation, bacteria and other micro-organisms were found to play a role in floc formation (see Van Luessen (1988) Rao et al (1991)). The micro-organisms secrete polymers (Leppard (1993), that provide the bonding among particles. The mechanism of flocculation by polymers is explained using the classical inter-particle bridging model described in Ruehrwein and Ward (1952) and La Mer and Healy (1963). According to this model, a polymer molecule attaches itself to the surface of a particle at one or more adsorption sites and the remainder of the molecule extends into the solution. The extended part of the molecule then attaches to vacant sites on a neighboring particle and form a bridge connecting two particles. The process can continue and more particles can be bridged to form a floc. Optimum flocculation occurs when a certain fraction of available adsorption sites of a particle is bridged. If too few sites are occupied, then the bond will be week. If more sites are covered, then the free sites available for formation of bridges with the next colliding particle become limited and the flocculation is hindered. Therefore, the optimum amount of polymers required is directly proportional to the particle concentration. It has been pointed out by Busch and Stumm (1968) that the quantity of polymers required for optimum flocculation is extremely small- about one mg/L. The flocculation of kaolinite by excreted polymers from bacteria was studied under laboratory conditions by Pavoni et al (1972) in standard jars at different pH values. They used the relative turbidity as a measure of aggregation and found that both pH and the polymer dose affected the rate of aggregation. At a pH value of 7.0, the polymer dose had a strong influence on aggregate formation at lower dose range. The aggregation increased with polymer dose for the dose range up to 50 mg/l and it decreased for higher dose values, which may have been due an imbalance in the optimal particle-polymer ratio. This study gives credence to the inter-particle bridging model described above. Flocculation by bacteria-secreted-polymers may be prevalent mechanism that is responsible for sediment flocculation in fresh waters.

Impact of flocculation on Settling velocity:

The effect of flocculation on the settling velocity of suspended sediment has been studied extensively in the laboratory by a number of investigators (see Whitehouse et al (1960); Migniot (1968, 1977); Owen (1970); Kranck (1980,1986a,1986b); Fukuda and Lick (1980)). These studies show that the flocculated sediment particles can have settling velocities up to four orders of magnitude larger than the unflocculated material. Results of Kranck's experiments, shown in Fig. 1., depict a considerable difference in the settling behaviour of unflocculated and flocculated sediments. Curves 1,2 and 3 are concentration vs time curves for a clay suspension dispersed in calgon solution settling in still water, whereas curves 4, 5 and 6

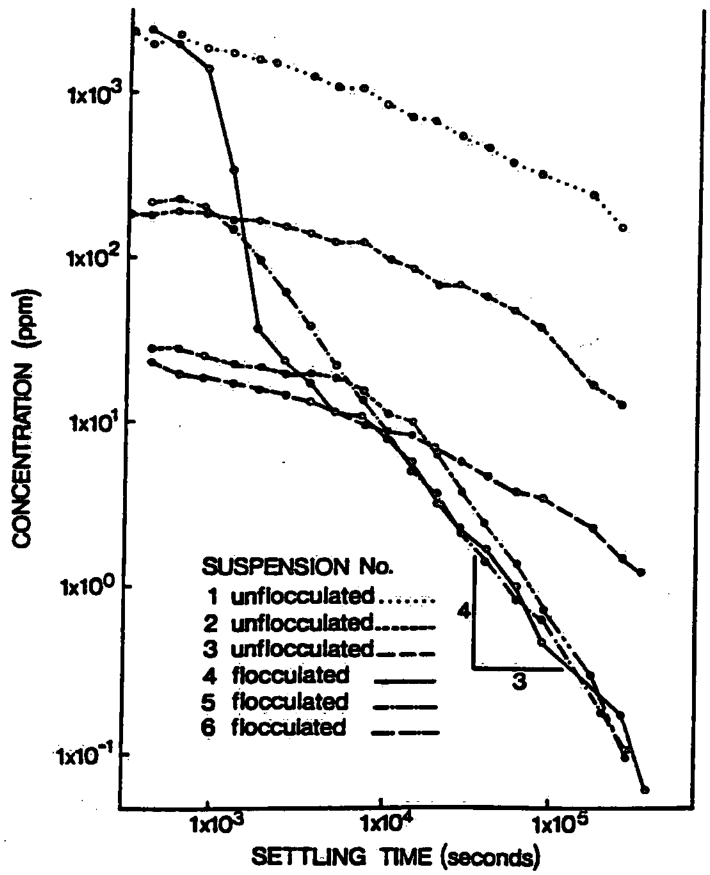

Fig. 1. Effect of flocculation on settling - Data from Kranck(1980)

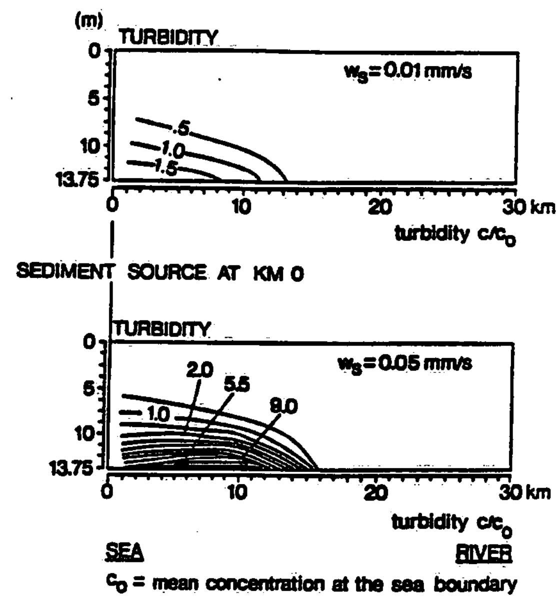

Fig. 2. Sensitivity of settling velocity
Predictions of Markofsky et al (1986)

are for the same material in a 3% NACL solution. These curves clearly show the onset of flocculation and the associated increase in settling velocities.

The importance of a realistic estimate of settling velocity of suspended sediment has been demonstrated by Markofsky et al (1986) in their calculation of suspended sediment distribution using a two dimensional, laterally averaged model. The results of Markofsky are reproduced in Fig. 2 and it shows the turbidity distributions computed using two different fall velocities. The top distribution is computed using a settling velocity of 0.01 mm/s whereas the bottom distribution is computed using a fall velocity of 0.05 mm/s. A mere five fold increase in settling velocity has resulted in a substantially different turbidity distributions as can be seen in Fig.2.

In majority of existing models of cohesive sediment transport, flocculation process is considered only indirectly by assuming the settling velocity to be a power function of sediment concentration as:

$$w_s = k\bar{c}^n \qquad (5)$$

where k and n are empirically determined constants. The above expression is based on the fact that increased concentration of particles will increase the settling velocity by the increased inter-particle collisions. This is valid only for low concentrations. As the concentration increases, the settling of sediment becomes hindered due to the development of a continuous network of flocs and the settling occurs as a result of interstitial fluid escaping upwards. At these concentrations, the settling velocity is found to show an inverse relationship with sediment concentration.

An explicit treatment of flocculation process was proposed by Krishnappan (1991), who used a coagulation equation to represent the flocculation process. This equation expresses the rate of change of sediment particles per unit volume in a particular size class, say i , as:

$$\frac{\partial N(i,j)}{\partial t} = -N(i,t)\sum_{j=1}^{\infty} K(i,j)N(j,t) + \frac{1}{2}\sum_{j=1}^{\infty} K(i-j,j)N(i-j,t)N(j,t) \qquad (6)$$

where N(i,t), N(j,t) are number concentrations of size classes i and j respectively at time t and K(i,j) is the collision frequency function, which is a measure of the probability that a particle of size class i collides with a particle of size class j in unit time. The collision frequency function K accounts for the various collision mechanisms. Krishnappan (1991) applied this equation together with a dispersion advection equation for multiple size classes to a stretch of a river in Canada and showed that flocculated material deposited very quickly in comparison to the unflocculated material. However, in Krishnappan's formulation, the break-up of flocs by turbulence was not considered due to the lack of quantitative information on this process. More work is needed in this area to advance the modeling activities on the flocculation phenomenon and obtain better estimates of settling velocities.

EROSION AND DEPOSITION RATES:

Erosion and deposition rates of cohesive sediment were studied extensively under laboratory conditions using straight and rotating circular flumes. A brief review of these studies is given in this section.

Erosion Rate:

Unlike cohesionless sediment beds, the erosion characteristics of cohesive sediment depend on a number of physico-chemical properties of sediment and fluid in the water column and in the sediment bed. Hayter (1987) presented a list of prime factors that govern the erosion of cohesive beds in a tabular form as shown in Table 1. Because of the large number of parameters involved and of the complexity of the process, it is not possible at the present time, to derive analytical expressions for erosion rate. The approach taken to tackle this problem was to derive empirical relationships based on laboratory

Table 1.

Principle Factors Controlling Erosion of
Saturated Cohesive Sediment Beds

HYDRODYNAMIC FACTORS (Erosive Force)

BED SHEAR STRESS
- Flow Characteristics
- Bed — Fluid Interface

BED AND FLUID PROPERTIES (Resistive Force)

SEDIMENT COMPOSITION
- Clay Mineral Type — Ion Exchange Capacity
- Clay Percentage by Weight
- Organic Matter

PORE FLUID COMPOSITION
- Mono-and Divalent Cations Concentrations { Conductivity (Na^+, Ca^{++}, Mg^{++})
- Relative Abundance of Mono- and Divalent Cations } SAR
- Temperature
- pH

ERODING FLUID COMPOSITION
- Salinity ($NaCl$, $CaCl_2$, $MgCl_2$)
- Temperature
- pH
- Cementing Agents (Iron Oxide, etc)

BED STRUCTURE
- Stress History { Placed Bed / Deposited Bed

experiments using straight and rotating circular flumes. Ariathurai and Arulandan (1978) obtained the following relationship for the erosion rate of a consolidated bed:

$$q_e = M\left\{\frac{\tau_b}{\tau_c} - 1\right\} \quad (7)$$

where τ_b is the bed shear stress and τ_c is the critical shear stress for erosion of the sediment bed. M is an erodibility constant and its magnitude has to be determined by conducting laboratory experiments in a flume for the sediment-water mixture under investigation. For flow deposited (stratified) beds, the experimental investigations of Partheniades (1962), Mehta and Partheniades (1975), Parchure (1980), and Dixit (1982) in straight and rotating circular flumes had resulted in the following expression for erosion rate:

$$q_e = q_{eo} \exp\left[\frac{\alpha(\tau_b - \tau_c(z))}{\tau_c(z)}\right] \quad (8)$$

where q_{eo} and α are empirical coefficients to be determined through experiments. Variation of the critical shear stress as a function of the bed depth $\tau_c(z)$ has to be determined also by experiments.

Deposition Rate:

The rate at which the deposition of sediment occurs was formulated by Krone (1962) and was given as a product of settling rate ($w_s \bar{c}$) and a measure of the probability that settled particles bond and stay at the bed (P_d). That is:

$$q_d = w_s \bar{c} P_d \quad (9)$$

Krone (1962) hypothesized that the probability P_d is a function of the bed shear stress and expressed it as:

$$P_d = \left\{1 - \frac{\tau_b}{\tau_{cd}}\right\} \quad (10)$$

where τ_{cd} is the critical shear stress for deposition defined as the bed shear stress above which no deposition would occur. Using this hypothesis, Krone developed an equation for sediment concentration in suspension during the deposition process as:

$$\frac{\bar{c}}{\bar{c}_0} = \exp\left\{\frac{-P_d w_s t}{h}\right\} \quad (11)$$

where $\bar{c}_0$ is the initial concentration. Krone suggested that the above expression was applicable only for low concentrations in the range 0 to 300 mg/l. For higher concentrations, he derived a different equation which assumed the following form:

$$\log \bar{c} = -\mathrm{K}\{\log(t)\} + const \quad (12)$$

where K is a function of P_d and h.

The deposition process of cohesive sediment was also studied by a number of other investigators under laboratory conditions using rotating circular flumes. Notable studies are those of Partheniades and Kennedy (1966), Partheniades et al (1968), Mehta and Partheniades (1975), Lick (1982) and Lee et al (1981). In these studies, fine sediment mixtures were kept in suspension by operating the flume at high shear stress and were allowed to settle at a lower shear stress. The concentration of the suspended sediment in the water column was monitored as a function of time. From these studies, they observed that the concentration of the suspended sediment reached a steady state value after an initial period of rapid deposition and that the value of the steady state concentration was a fixed percentage of the initial concentration when the bed shear stress was maintained constant. When the shear stress was increased, the ratio of the steady state concentration to the initial concentration increased.

In explaining above observations, two distinct schools of thought emerged regarding the erosion-deposition process of the cohesive sediment. The explanation put forth by Lick (1982) is based on the gradation of particle sizes of the suspended sediment. It suggests that all the larger particles settle out and all the fines remain in suspension. The intermediate size fraction participates in simultaneous erosion and deposition as in the case of cohesionless sediment transport. For a given bed shear stress, the deposition-erosion process results in an equilibrium concentration for the above size fraction. Since the fines and the intermediate size fraction are fixed percentages of the material that is initially suspended, the steady state concentration is a fixed percentage of the initial concentration. The explanation put forward by Partheniades et al (1968), and Mehta and Partheniades (1975) is based on flocculation mechanism of the cohesive sediment and suggests that simultaneous erosion and deposition do not occur. In their view, cohesive sediment settles as flocs and only those flocs that are strong enough to settle through the region of high shear near the bed can deposit and become a part of the bed. Other flocs get broken up as they approach the region of high shear and are returned to the flow. As there can only be a certain percentage of the material that can form stronger flocs in a given sediment mixture for a given bed shear stress, the concentration of the flocs that are remaining in suspension is a fixed percentage of the initial concentration.

<u>Resolution of the controversy on simultaneous erosion and deposition:</u>
The resolution of the controversy regarding the sediment settling process is important because it has implications for modelling contaminant transport. If we adopt Lick's hypothesis and model sediment transport allowing simultaneous erosion and deposition, the dispersion of the contaminated sediment will be high and the concentration of sediment associated contaminant will decrease at a much faster rate in the downstream direction in comparison to a model based on Partheniades' hypothesis. In the latter model, the sediment particles will undergo either erosion or deposition and are likely to preserve their chemical identity over a larger distance in the downstream direction. Recently, Lau and Krishnappan (1994) conducted specially designed experiments in a rotating circular flume to resolve this controversy and had concluded that reentrainment did not occur during cohesive sediment settling. On the other hand, Sanford and Halka (1993) showed that the models excluding simultaneous erosion and deposition fail to reproduce field data and a model with continuous deposition (i.e. without critical shear stress for deposition) produced the best fit. Therefore, the controversy still continues and more work is needed to address this issue.

OTHER ISSUES

There are number of other issues relating to cohesive sediment transport that are not dealt with in this review but are equally important for a better understanding of cohesive sediment behaviuor. For example, the issue of high concentration that can affect the flow field by affecting the rheology of the fluid and the consolidation of the deposited bed which has direct influence on the erodibility of the cohesive bed. Issues such as wave effects on cohesive beds in coastal regions give rise to complicated transport processes such as fluidization, turbidity currents and wave attenuation. These issues are reviewed in greater detail by Mehta (1989a, 1989b); Dyer (1989) and Teisson (1994).

COHESIVE SEDIMENT RESEARCH AT NWRI

The National Water Research Institute (NWRI) is an environmental research organization of the Government of Canada and is involved in research on many aspects of contaminant transport in aquatic ecosystem. Its cohesive sediment transport research, therefore, responds to the need to develop models of contaminant fate, transport and bioaccumulation and as such focuses on some of the transport processes that were reviewed above and also on processes relating to sediment, contaminant, and biota interactions. Since many of the transport parameters of cohesive sediment can only be obtained by direct measurements using site specific sediments, there is a need for a laboratory facility that can be used to measure the necessary parameters. To meet this need, a large rotating circular flume similar in operating principle to the one used by Partheniades and Kennedy (1966) was installed in the Hydraulics Laboratory of NWRI. In addition, a field instrument, capable of measuring the in-situ size distribution of suspended sediment in rivers was developed to ascertain the extent of flocculation in fresh water river systems. A brief description of these laboratory facilities and the investigation that was carried out to test the effect of a pulp mill effluent on the transport characteristics of sediments from a Canadian river is presented next.

ROTATING CIRCULAR FLUME:

Partheniades and Kennedy (1966) were the first ones to use a rotating circular flume to measure cohesive sediment transport characteristics. Essentially, the flume consists of two components: a circular channel and an annular cover plate (ring) that fits inside the channel, and both components are rotated in opposite directions. The flume that was installed at NWRI is 5.0 m in mean diameter, 0.30 m in width and 0.30 m in depth, and rests on a rotating platform, which is 7.0 m in diameter. The ring fits inside the flume with close tolerance (1.5 mm on either side) The flow is generated by lowering the ring inside the flume until it makes contact with the water surface and by rotating the ring and the platform in opposite directions. The maximum speeds of rotation for ring and flume are three revolutions per minute each. A sectional view of the flume assembly is shown in Fig. 3. The flume is instrumented with a Laser Doppler Anemometer to measure the flow field including turbulence characteristics, a Preston tube to measure the bed shear stress, a Malvern Particle Size Analyzer to measure floc size distributions and an optical turbidity sensor to measure the suspended sediment concentration.

The characteristics of the flow field generated in the flume were studied in detail by Krishnappan (1993) and Petersen and Krishnappan (1994). These studies established that generation of a two dimensional flow field required simultaneous rotation of the flume and the ring in opposite directions and the two dimensionality of the flow field improved when the ring is rotated slightly faster than the flume. A numerical model based on the κ-ε model was developed to predict the flow field in this rotating flume and it is being used as an operating tool to predict the bed shear stress for given rotational speeds of the flume and the ring (see Krishnappan et al (1994)).

PARTICLE SIZING INSTRUMENT:

Sediment sizing techniques that require removal of sediment from the flow field are not adequate for sizing sediment flocs, as the act of sediment sampling disrupts the floc structure and affects the size distribution. This was demonstrated by Bale and Morris (1987) for estuarine sediment. To overcome this deficiency, a submersible laser particle size analyzer was developed at NWRI. The instrument was based on the principle of laser diffraction and consists of a 2mW laser, a receiving lens, a detector plate, an electronic interface and a microcomputer. The laser, the detector plate and the electronic circuitry are attached to an aluminum chassis mounted inside a watertight canister. The assembly details of the instrument are shown in Fig. 4. As can be seen from this figure, the laser beam emerges out through a glass window and passes through a laser path tube, which is attached to a dove prism that deflects the beam through 180 degrees. The deflected beam passes through the sensing volume and enters the canister through a second window. The receiving lens focuses the diffracted light onto a detector plate. From the measured distribution of the diffracted light, the size distribution of the particles in the sensing volume is calculated using the Fraunhofer Diffraction Theory (Wiener (1984)). Complete details of the instrument are given in Krishnappan et al (1992).

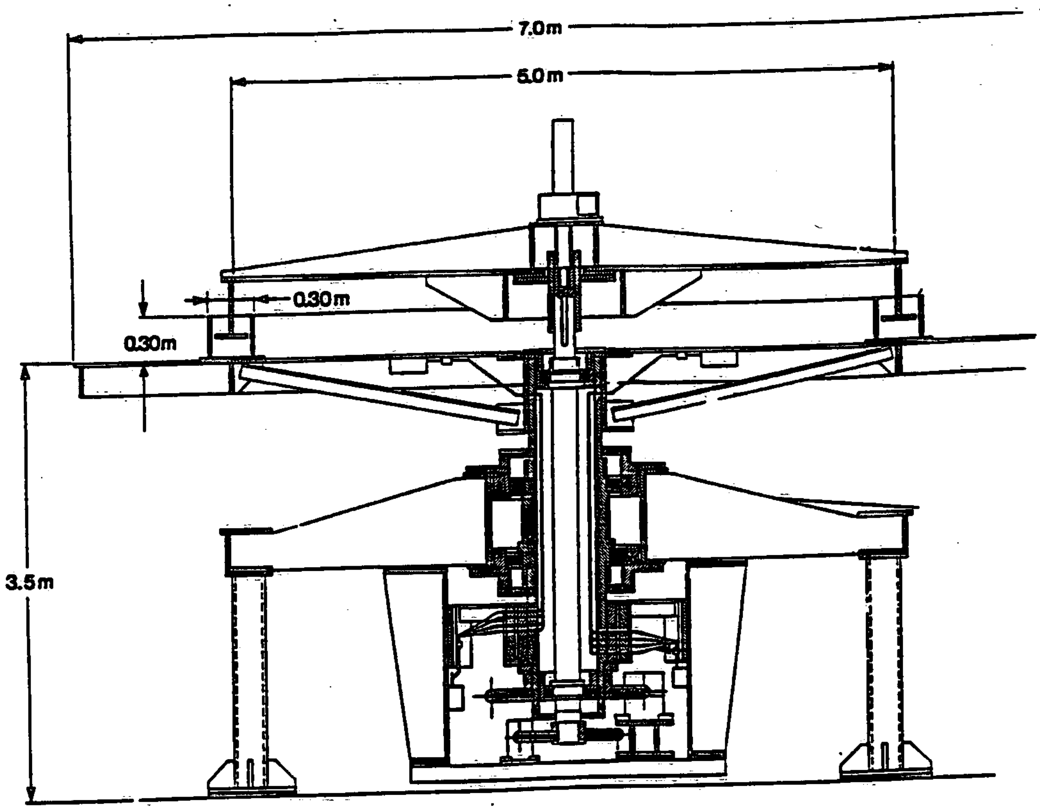

Fig. 3. Schematics of NWRI's Rotating Circular Flume

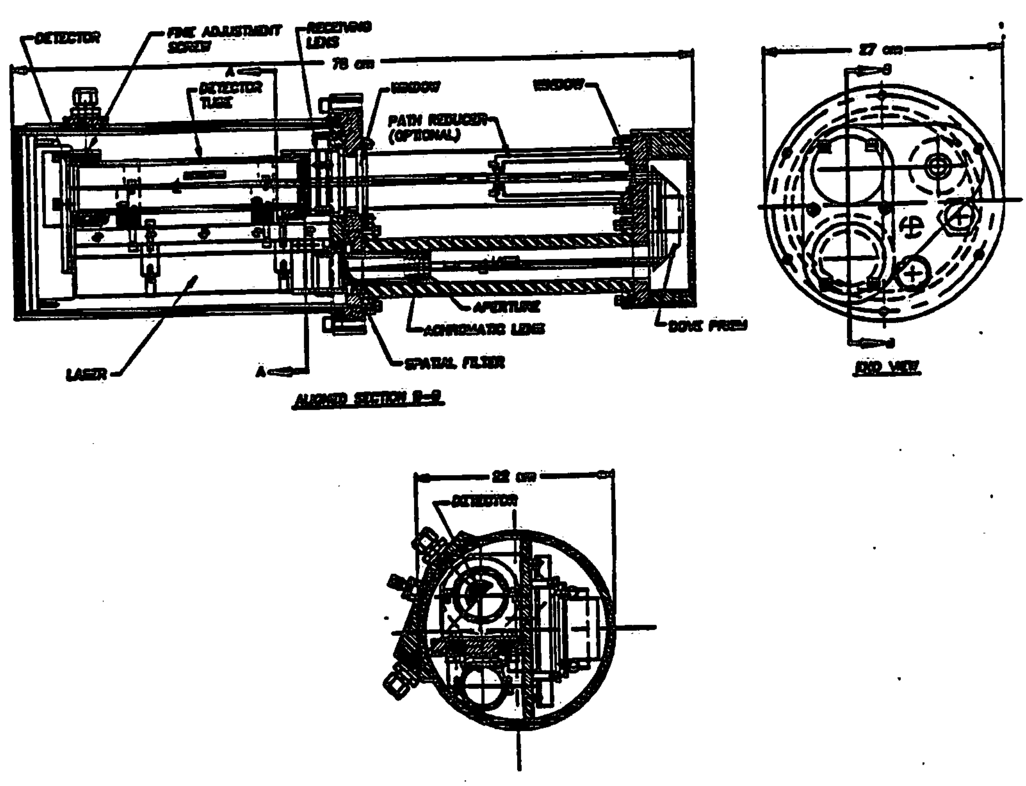

Fig. 4. Schematics of NWRI's Particle Sizing Instrument

A CASE STUDY: EFFECT OF PULP MILL EFFLUENT ON FINE SEDIMENT TRANSPORT: While the role of fine grained suspended sediments in the adsorption of toxic contaminants was studied extensively during the past decade (see, Allan (1986); Forstner and Wittman (1981); Frank (1981); Kuntz and Wary (1983)), there is practically nothing in the literature on the effect of contaminants on the transport characteristics of the sediment. Here a field and laboratory investigation that was carried out to study the effect of pulp mill effluent on suspended sediments of the Athabasca River near Hinton, Alberta, Canada is briefly described.

Field Study:

The field measurements consisted of two surveys: One, during the winter of 1993 when the flow was low and ice covered and the other, during the fall of the same year under open water conditions. In both surveys, the river reach covered was between the towns of Entrance and Windfall on the Athabasca River (see Fig. 5 for sampling locations) and the measurements consisted of flow, size distribution of suspended sediment and concentration of suspended sediment. Referring to Fig. 5, the transect at the town of Entrance is eight kilometers upstream from the pulp mill, which is located at the town of Hinton. The first transect downstream of the pulp mill is Obed and it is 20 kilometers from Hinton. The other transects are: Emersion bridge, Berland Bridge and Windfall bridge at 70, 105 and 175 kilometers respectively from Hinton. At each transect, the flow velocities, suspended sediment concentration and in-situ size distribution of suspended sediment were measured at a number of verticals. The size distribution of the suspended particles measured using the submersible size analyzer at the upstream transect, Entrance is shown in Fig. 6. In this figure, the distribution of the primary particles is also shown. The primary particle distribution was measured by collecting suspended sediment samples and measuring the size distribution after the sample was dispersed by sonication using an ultra sonic device. From this figure, it can be seen that the suspended sediment was transported in the flocculated form because, the in-situ distribution contains particles in the size classes 204 and 383 microns whereas the dispersed particle distribution did not show any particles in these size classes. The sonication has broken up the flocs and hence the primary particle distribution is considerably finer. It is interesting to see that sediments in the fresh water system are also transported in a flocculated form.

The suspended sediment concentrations (depth averaged) and the transport rates computed for the various transects are shown in Fig. 7 for the winter survey. From this figure, it can be seen that the suspended sediment concentration and the sediment transport rates were reduced drastically at transects downstream of the pulp mill outfall. About 75 percent of the incoming sediment had deposited within the first downstream transect. The river geometry and the flow characteristics did not change in any appreciable manner to cause such a sudden reduction of the sediment load. Therefore, the increased deposition rate immediately downstream of the outfall is attributed to the pulp mill effluent. It appears that the effluent has increased the flocculation of the ambient sediment and caused the sediment to deposit at a faster rate. To verify these field observations, laboratory experiments were performed in the rotating circular flume using sediment from the Athabasca River near Hinton and the effluent from the pulp mill.

Laboratory Study:

Sediment and river water samples were collected at the Entrance transect upstream of the pulp mill. A pumping system, similar to the one used in cleaning swimming pools, was used to vacuum the sediment deposited on the gravel bed and pump river water into 100 l plastic containers that could be sealed tightly for shipping. Eight such containers were filled and shipped to Burlington in trucks equipped with cold storage. In addition, an effluent sample of about 50 l was collected from the mill outfall. The sediment-water mixture was placed in the flume to give a prescribed flow depth of 12.0 cm and an initial fully mixed concentration of 200 mg/l. The sediment water mixture was then tested for depositional characteristics with and without the pulp mill effluent.

Before starting the test, the sediment-water suspension was thoroughly mixed in the flume with a mechanical mixer to break up existing flocs. The ring was then lowered until it contacted the water surface. The flume and the ring were rotated at desired speeds to establish a certain bed shear stress in the flume. Periodic measurement of suspended sediment concentration and the size distribution of suspended

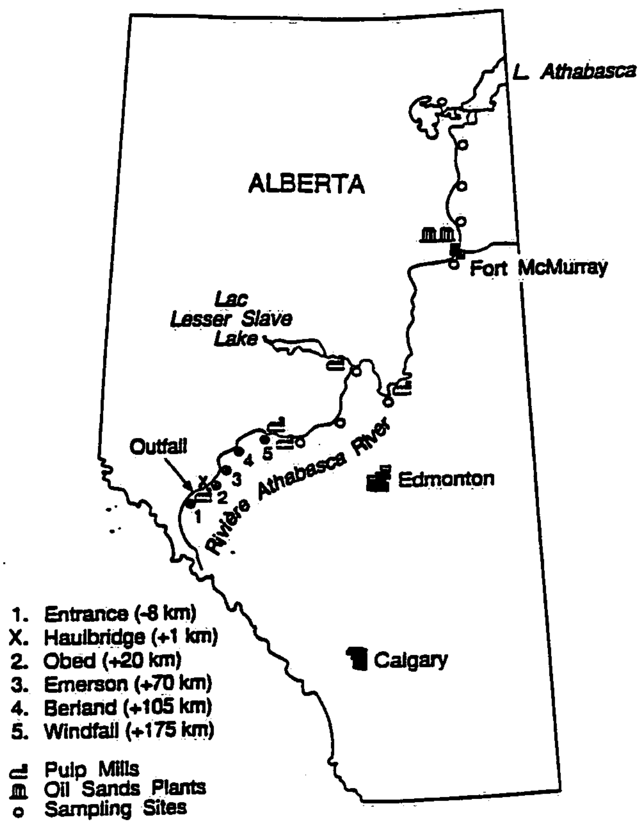

Fig. 5. Map showing sample sites

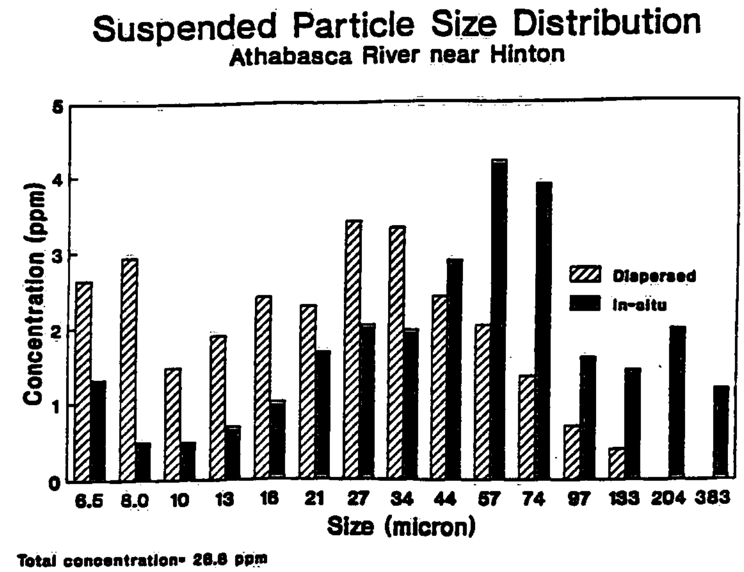

Fig. 6. Measured distributions of particle size

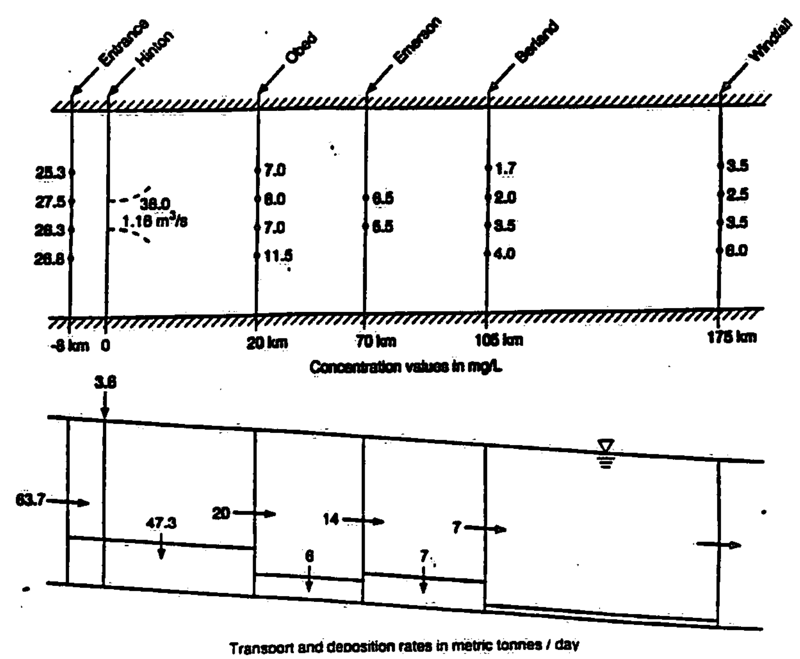

Fig. 7. Results of winter survey

sediment flocs were made. Measurements continued until the suspended sediment reached a steady state value. This took about 300 minutes from the start of the experiment. The experiment was then repeated with pulp mill effluent added to the flume. In addition, the effect of the bed shear stress and the initial concentration were also investigated as part of this study. The results of the study are described below:

The variation of the suspended sediment concentration as a function of time for all the bed shear stresses is shown in Fig. 8. From this figure, it can be seen that the concentration drops at a faster rate initially and reaches a steady state value after some time. The time to reach steady state value and the value of the steady state concentration are functions of the bed shear stress. Fig. 9 shows the concentration variation with time for two different initial concentrations when the bed shear stress was held constant at 0.324 N/m^2. This figure shows that the steady state concentration is a function of the initial concentration and confirms that the sediment behaves as a cohesive material. The flocculation of the sediment during deposition can be inferred from the size distribution data shown in Fig. 11. In this figure, the size distributions measured with the Malvern Particle Size Analyzer for different times during a deposition corresponding to a bed shear stress of 0.324 N/m^2 are shown. During the initial mixing period, the weaker flocs were broken up and the suspension contained sediment flocs with a median size of about 26 microns. As the deposition begins, the flocs are reformed and the median size of the flocs increases as function of time. The process continues up to a period of 70 minutes, at which time, the flocs attain a more or less steady state distribution with a median size of about 37 microns. Further studies are needed to understand the cohesion mechanism that is at work for this sediment.

The effect of the pulp mill effluent on the depositional characteristics of the sediment is shown in Fig. 10 and Fig. 12. In Fig. 10 the time variation of suspended sediment concentration is plotted against time for two runs with the same bed shear stress and initial concentration. In one of the tests, the pulp mill effluent was introduced at a concentration similar to that occurring in the river during low flow conditions. From this figure, it can be seen that the deposition rate for the test with the effluent is higher than that for the test without the effluent. This confirms the field observstion. In Fig. 12, the size distribution of the suspended sediment flocs is shown for the same two tests at a particular time during the deposition process. From this figure also it is evident that the sediment flocs that are formed in the presence of the effluent are larger. Investigation into the actual mechanism of flocculation of sediment in the presence of pulp mill effluent was not attempted in this study. This requires expertise from other disciplines such as Biology and Chemistry.

SUMMARY

Cohesive sediment transport processes such as flocculation, settling, deposition and erosion are reviewed in the light of a sediment mass balance equation and knowledge gaps and contradictions identified. Cohesive sediment transport research facilities of the National Water Research Institute at Burlington, Ontario, Canada are described along with a case study dealing with the influence of pulp mill effluents on the transport characteristics of fine sediments of the Athabasca River near Hinton, Alberta, Canada. The study showed that the suspended sediment in the river was transported in the flocculated form even though the river is a fresh water system and the effluent from a pulp mill located at Hinton, Alberta affected the flocculation mechanism and consequently the deposition rate of the sediment under low flows. The study points to a need for a multidisciplinary research to better understand the flocculation process of sediment in the presence of pulp mill effluents in fresh water systems.

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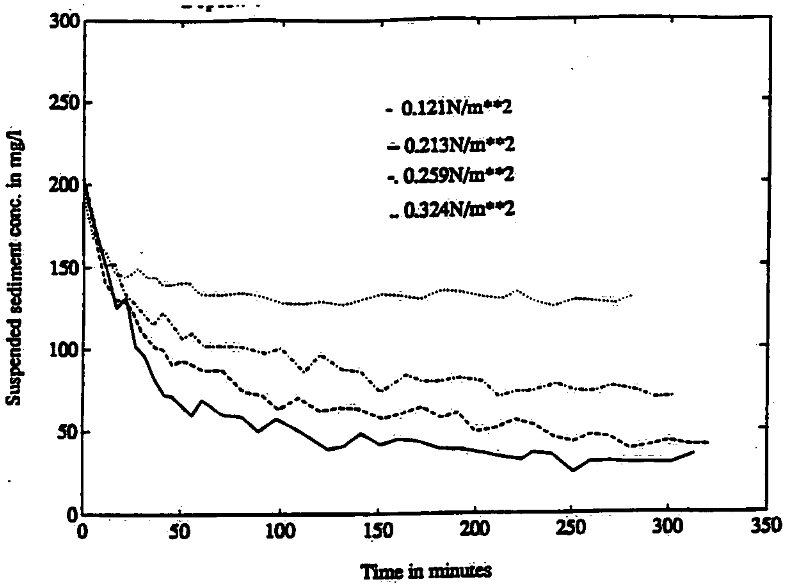

Fig. 8. Effect of bed shear stress on deposition

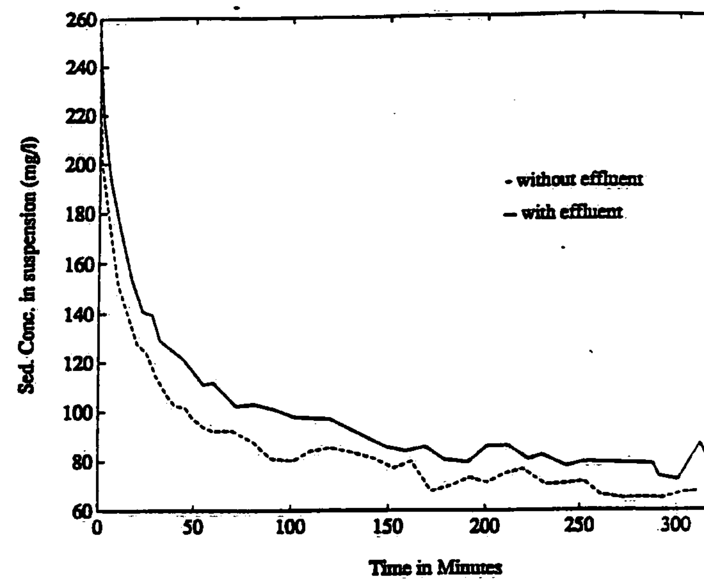

Fig. 10. Effect of effluent on deposition

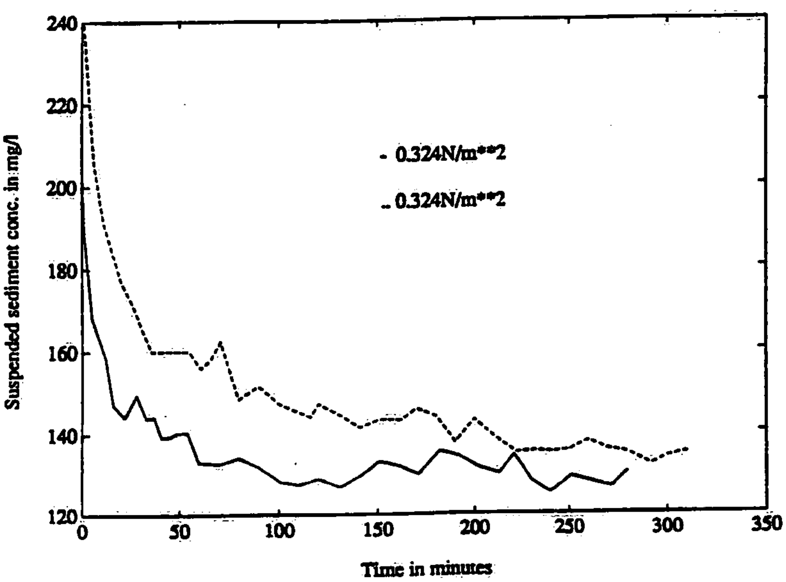

Fig. 9. Effect of initial concentration on deposition

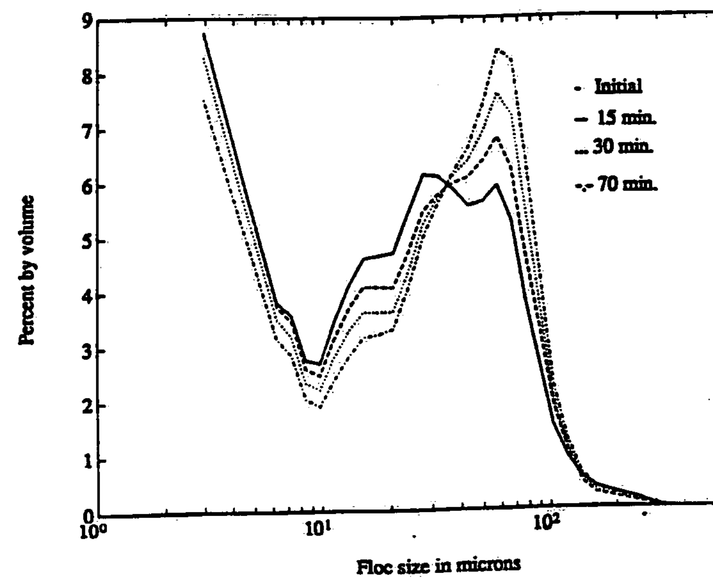

Fig. 11. Size distribution of flocs during deposition

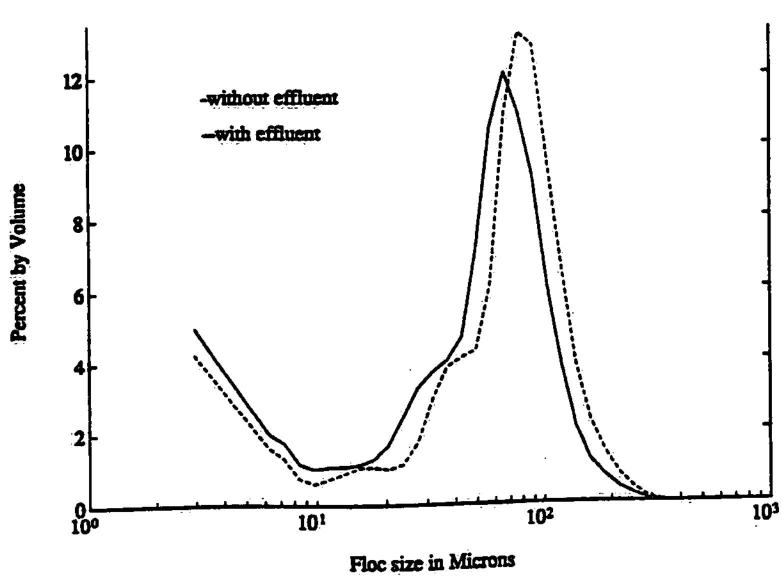

Fig. 12 Effect of effluent on floc size distribution

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