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RIVER SEDIMENTS AND CONTAMINANT TRANSPORT -CHANGING NEEDS IN RESEARCH

by

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ABSTRACT

The importance of fine sediments in chemical transport and the basic knowledge requirements for developing mathematical models of fine sediment transport are reviewed. The flocculation process has been identified as the most important process requiring further research as it affects the fall velocity of the fine-grained sediments and the depositional and erosional characteristics of the sediment-water interface.

The review of literature on the erosion and deposition processes of fine sediment reveals that there exist two different schools of thought regarding the transport process near the sediment-water interface. The mechanism proposed by Partheniades suggests that the fine sediments undergo either deposition or erosion but not both at the same time under a certain flow condition. The other school of though proposed by Lick implies that the erosion and deposition can occur simultaneously. The fine sediment transport research program now underway at the National Water Research Institute, Burlington, Ontario, Canada, will shed more light on the flocculation process.

RESUME

On examine l'importance des sédiments fins dans le transport des substances chimiques et les connaissances de base nécessaires pour mettre au point des modèles mathématiques du transport de sédiments fins. Le procédé de floculation a été identifié comme étant celui qui, à cause de son importance, doit être étudié plus à fond. Il influe, en effet, sur la vitesse de chute des sédiments à grain fin et sur les caractéristiques du dépôt et de l'érosion de l'interface sédiments/eau.

L'étude de la documentation sur les processus de dépôt et d'érosion des sédiments fins révèle qu'il y a deux différentes écoles de pensée concernant le processus de transport près de l'interface sédiments/eau. D'après le mécanisme proposé par Partheniades, les sédiments fins sont soit déposés soit érodés, mais ils ne sont pas soumis à ces deux processus à la fois dans certaines conditions d'écoulement. L'autre école de pensée soutenue par Lick suppose que l'érosion et le dépôt peuvent se produire en même temps. Le programme de recherche sur le transport des sédiments fins en cours de réalisation à l'Institut national de recherche sur les eaux, à Burlington, en Ontario, Canada, mettra davantage en lumière le procédé de floculation et les contradictions du processus érosion-dépôt.

INTRODUCTION

The role of sediment in chemical transport was widely recognized for metals and phosphorus and has been reviewed by many authors (e.g., Allan, 1986). Especially where sediment transport is high, a large proportion of the total chemical load is associated with the sediment This has been shown world-wide for most metals (Frostrer and phase. Wittmann, 1981), for phosphorus (LEWMS, 1975) and for a wide range of synthetic organic contaminants (Frank, 1981; Kuntz and Wary, 1983). By the mid-1970's, chemical transport models involving the sediment component were not, however, well developed due to inadequate understanding of the dynamics of fine-grained sediment (generally <62 μ m). For example, Blackford and Ongley (1984) show a pronounced decline in sediment-associated metals over a distance of 365 km below a major urban area in the Bow River. The rate of decline is higher dependent upon discharge and sediment concentration which, in this prairie environment, is seasonally dependent. Similar observations have been made in ongoing studies of the North Saskatchewan River (unpublished data). The downstream decline is presumed to relate to sediment deposition and resuspension mechanisms (i.e., particle replacement) and the resulting interactions of metal-rich suspended matter and metal-poor sediments available for resuspension (bank materials, tributary inputs, etc.) during downstream transport. dilution model is inappropriate if a particle replacement mechanism is the major variable.

Studies of phosphorus flux (Verhoff <u>et al.</u>, 1982; Brownlee and Bird, 1988) indicate that particulate-phosphorus transport is a complex deposition/resuspension phenomenon. For phosphorus, the downstream relationship amongst sediment-bound and solute phases, biological uptake, storage, resuspension and discharge, are complex and probably non-linear in time and space (downstream). Because of the reported overwhelming importance of sediment in phosphorus transport in many rivers, successful modelling of phosphorus flux requires a more exact parameterization of fine sediment behaviour in rivers. Verhoff <u>et al</u>. (1982) clearly shows that discontinuous transport of sediment is the norm rather than the conventional view that fine-grained sediments, once suspended, move continuously from source to the outlet of the river system.

Although a large proportion of US-EPA priority synthetic organic contaminants are primarily associated with suspended matter (Chapman <u>et al.</u>, 1982), few data sets have been collected which characterize downstream transport of synthetic organic contaminants. In our own work over a 900 km distance below a major photochemical complex on the North Saskatchewan River (unpublished data), we were unable to detect any continuity of hydrophobic organic contaminants in the downstream direction at higher or low river flows. This suggests a complex interaction of sedimentary, biological and chemical processes leading to chemical and biochemical transportation and in-stream sedimentation and storage. The issue of sediment transport of organic contaminants becomes particularly important in view of the dominance of toxicity associated with the sediment-bound phase (Ongley <u>et al.</u>, 1988).

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It is now widely recognized that the role of fine-grained sediment dynamics is central to improved understanding and prediction of chemical transport. The hydrodynamic behaviour of chemicallyactive fine-grained particles is fundamental to further understanding of particle-microbiological interactions (flocculation, biochemical processing), particle contact with channel boundaries (filter-feeders, biofilms, etc.), downstream storage and remobilization (particle replacement), and mid-channel edge-channel exchange of particles (cross-channel change in biological communities and commensurate biochemical cycling of sediment-bound chemistry). Ongley (1987) aggregated these factors in a conceptual model to account for the information content (I_t) of a sediment-chemical measurement model as a function of:

 $I_t = \frac{(information from source)}{(information introduced in transit)} - Loss - Lag$

Clearly, the terms require research before adequate sediment models can be developed for environmental applications.

An example of simplifying assumptions used in toxic contaminant transport models is WASP4 (US-EPA, 1988) which uses an accounting principle based upon continuity of mass where the interactions are calculated by specific kinetic equations. The sediment component is characterized by sediment concentration and by values for settling, scour and sedimentation for three different size fractions or for three types of sediment (organic, inorganic, phytoplankton). The governing assumption is that fine particles exist as conventional size classes (in practical terms, by conventional sizing techniques) and behave as cohesionless particles. A second simplifying assumption is that the interaction of suspended sediment and bed materials is one of erosion, transport or deposition, depending upon particle size and stream velocity. As we show below, fine sediments in open-channel flow behave in a much more complex manner. Simplifying assumptions based upon simple empirical experiments and conventional sedimentological principles are unlikely to be correct. Such errors cascade back into the predictions for toxic chemical transport by assigning the chemistry to the wrong environmental compartment.

Considerable progress has been made in the understanding of sediment transport processes, especially those related to the cohesionless coarse grained fractions (sand size and larger). A number of computer models such as HEC-6 (1977), IALLUVIAL (1982), MOBED (1981) and FLUVIAL II (1982), are extensively used to predict the erosion and deposition patterns of the riverbed and the profile of the free surface under steady and unsteady flow conditions; they are fairly successful in simulating the river response to changes in river geometry and/or sediment inputs associated with certain developments within the river basin (Thomas & Parasuhn, 1976; Karim & Kennedy, 1982; Krishnappan, 1981; Chang, 1984). However, these models are not capable of treating the transport of fine-grained cohesive sediment that is important in the prediction of water quality aspects of river flows.

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The mechanisms controlling the transport of fine grained sediments are much more complex because of the interparticle bonds that cause the particles to flocculate as they are transported. The cohesionless sediment on the other hand behave as individual particles and the mathematical formulations to describe the motion of these particles are relatively simpler.

Sediment source term in conventional models is a channel erosion term and the load is hydraulically determined. In fine sediment the source of fine sediment fractions is mainly from off-channel sources, such as soil erosion. The transport capacity of riverflow virtually always exceeds the supply rate of these sources. Therefore, a quantitative knowledge on the rate of sediment supply is necessary before the transport processes of fine sediments in river channels can be modelled. Such information has to come either from direct field measurements or from other hydrological models capable of simulating the rainfall-runoff and sediment production and transport in overland flows in the river basin.

In the balance of our paper, we review the existing mathematical formulations of fine sediment transport and the basic research that is required to advance the knowledge in this field.

MATHEMATICAL DESCRIPTION OF FINE SEDIMENT TRANSPORT

The transport of fine sediments in a riverflow can be described by a mass balance equation which, for a three-dimensional turbulent flow, can be written as:

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$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x} (uC) + \frac{\partial}{\partial y} (vC) + \frac{\partial}{\partial Z} \{(w - w_s) C\} = \frac{\partial}{\partial x} (\epsilon_x \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y} (\epsilon_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z} (\epsilon_z \frac{\partial C}{\partial z}) + S (x,y,z,t)$$
(1)

where C is the volumetric concentration of fine sediment of any one size fraction, u, v and w are the velocities of sediment-water mixture in the three co-ordinate directions x, y and z respectively. (See Figure 1 for the description of the co-ordinate system). ϵ_X , ϵ_y and ϵ_z are the dispersion coefficients in the three co-ordinate directions. w_S is the settling velocity of sediment, t is time and S is the source term due to reactions if any. The above equation expresses a balance between the advective sediment flux due to time average flow velocity components u, v and w and the sediment settling velocity w_S , and the diffusive flux due to turbulent fluctuations. The boundary conditions are:

 $(w - w_s) C - \epsilon_z \frac{\partial C}{\partial z} = 0$ at z = h (at the free surface) $S_R + (1 - P_d) w_s C = -\epsilon_z \frac{\partial C}{\partial z}$ at z = 0 (at the bed) $vC - \epsilon_y \frac{\partial C}{\partial y} = q_s$ at y = 0 and y = B (at the sides)

(2)

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In equations set (2), h is the depth of flow at a particular crosssection and at a particular vertical, P_d is a coefficient which reflects the probability that a settled particle stays at the bed, S_R is the rate of sediment erosion from the unit area of the bed and q_s is the sediment input rate due to bank erosion.

BASIC KNOWLEDGE REQUIREMENTS

To solve equation (1) for the determination of the concentration of fine sediment, one needs to know, the flowfield, i.e., the velocity components u, v, w as functions of time and space, the turbulent diffusion coefficients ϵ_X , ϵ_y and ϵ_z of the sediment laden flow, the fall velocity of fine sediment particles, w_s, the erosion rate of fine sediment S_R at the sediment-water interface (at the bed) and the parameter, P_d.

Velocity Components

The velocity components can be determined by solving momentum and flow continuity equations with a suitable turbulence closure approximation. A summary of the number of available turbulence closure approximations can be found in Rodi (1980). An example of computation of velocity field in a compound channel using the algebraic stress model of turbulence closures is described in Krishnappan and Lau (1986). It should be pointed out that the three dimensional velocity

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fied is extremely laborious to calculate. A reasonable compromise is to consider the depth-integrated versions of the governing equations (2-dimensional models).

Turbulent Diffusion Coefficients

The turbulent diffusion coefficients can also be determined from turbulence models with the assumption that the turbulent transport of mass is analogous to momentum transport. However, it should be borne in mind that such an approach, strictly speaking, is valid for clearwater flows or flows with very low concentration of suspended sediment. At high concentrations, the fine sediment suspensions tend to "dampen" turbulence and lower the value of the turbulent diffusion coefficient. Lau and Chu (1987) have measured vertical diffusion coefficients in channel flows with suspended sediment and have shown that the reduction of turbulent diffusivities were 57% and 73% for sediment concentrations of 380 ppm and 1900 ppm respectively. Further research is required to quantify the effect of fine sediment concentrations on the turbulent mixing characteristics over a wide range of flow conditions and sediment concentrations.

Fall Velocity of Sediment Particles

The fall velocity of fine sediment particles is the most difficult parameter to quantify. Because of the flocculation process, the

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particle size distribution and the effective density change with time of travel and as a result, the fall velocity of fine particles becomes a function of time and other parameters governing flocculation process. A large number of studies have been reported in the literature on the process of flocculation of estuarine sediments. A review of these studies is given by W. Van Leussen (1988). Much less is known of flocculation in freshwater systems.

A brief account of the flocculation process and its impact on fall velocity is given below:

For flocculation of particles to occur, two separate mechanisms are responsible. One is the collision mechanism which brings the particles close enough so that they collide with each other and the second is the cohesive mechanisms which cause the collided particles to bond together and form flocs.

Collision mechanisms

Under the collision mechanisms, three processes were identified which cause the particles to collide. These processes are:

- 1) Brownian motion
- 2) Shear flow and turbulence
- 3) Differential settling.

The Brownian motion is due to the thermal energy of the fluid and it is random in character. Shear flow causes the particles to collide because of the relative motion of parcels of fluid at different levels. Under differential settling, fast settling larger particles overtake and collide with slower-settling smaller particles. The collision frequency function which is a ratio of number of collisions per unit time and unit volume and the product of the number of particles in the two size fractions that participate in the collision were established for these processes by Smoluchowski as early as 1917. These are:

$$\beta_{b} = \frac{2\kappa T}{3\mu} \frac{(d_{i} + d_{j})^{2}}{d_{i} d_{j}}$$
(3a)
$$\beta_{sh} = \frac{G}{6} (d_{i} + d_{j})^{3}$$
(3b)

and
$$\beta_{ds} = \frac{\pi q}{72\nu} \left(\frac{\rho_s - \rho_w}{\rho_w} \right) \left(d_j + d_j \right)^2 \left| d_j^2 - d_j^2 \right|$$
 (3c)

where β_b , β_{sh} and β_{ds} are the collision frequency functions of Brownian motion, shearflow and differential settling respectively and

and d_1 and d_2 are the size of particles participating in collision.

Knowing the local velocity gradients from a hydrodynamic model, the properties of fluid and sediment and the fluid temperature, one can evaluate these collision functions. Hunt (1980) compared three functions for the collision of 1.0 μ m particle with particles of other sizes ranging from 0.01 μ m to 1000 μ m. He assumed the following fluid and sediment properties and flow conditions for his comparison:

Fluid temperature T = 287°A

relative density difference: $(\rho_S - \rho_W)/\rho_W = 0.02$

velocity gradient G = 3 sec^{-1} .

Hunt's results are reproduced here in Figure 2 and it shows the relative importance of the three processes. For particles less than 1.0 μ m, the Brownian motion is important whereas for particles above 10 μ m, the shearflow and the differential settling become predominant.

The shearflow plays a dual role in the flocculation process. According to equation (3b), the collision rate increases with the increase of the velocity gradient, G, giving rise to the growth of floc size. But this growth cannot continue indefinitely. As the value of G increases, the shearing action of the flow may exceed the shear strength of the flocs and the flocs may break up into smaller sizes and from this point on, any increase in G may result in the reduction of floc size. Therefore, if one plots the size of the floc as a function of the velocity gradient, then one can expect a graph as shown schematically in Figure 3 indicating an initial increase in floc Quantitative descriptions of functional dependency of floc size on the turbulence characteristics of shearflows are not available at the present time. The main reason for this knowledge gap is the lack of instrumentation to measure the size of the flocs under natural state. The traditional method of sediment sampling disrupts flocstructure; moreover conventional sizing techniques require dispersion for reproducible results that measure primary particles - the abolute particle size distribution rather than the in-situ "effective" particle distribution (Ongley et al., 1981). Therefore, the size distributions so measured do not reflect the true distributions (see Gibbs, 1981).

Some progress has already been made in this area. Recently, Bale <u>et al</u>. (1987) have modified a Laser Fraunhoffer diffraction particle size analyzer manufactured by Malvern Instruments Ltd. and have used it to measure the floc size distribution in-situ in Tamar Estuary near Plymouth, England. They compared the size distributions measured with this instruments with those measured using conventional sampling technique. Their results are reproduced here in Figure 4. It is very clear from this figure that the sampling technique has caused a significant disruption of the flocs and altered the particle size distribution.

An extensive research programme is also underway at the National Water Research Institute at Burlington, Ontario, Canada, to study the effect of shearflow characteristics on the size distribution of flocs and other aspects of fine sediment and contaminant transport under laboratory and field conditions. For the laboratory investigation, a rotating circular channel 5.0 metres in outside diameter and 30 cm wide is being constructed. The secondary circulation induced by the rotation of the flume is suppressed by a counter rotating annular ring contacting the water surface in the flume.

By varying the speed of rotation of channel and the ring, it is possible to generate shearflows of different intensity and turbulence characteristics. A two colour, two channel laser doppler anemometer mounted on the rotating platform will be used to measure the turbulence intensities and the time averaged velocity components in the tangential and vertical directions. A Malvern Particle Size Analyzer, also mounted on the rotating platform, will monitor the growth of the particle size distribution of a flocculating sediment. Details of the Malvern Particle Size Analyzer are given elsewhere (Krishnappan & Ongley, in preparation). Besides the investigation of the effect of turbulent shear on the particle size distribution of flocs, a number of other investigations involving processes such as, erosion, deposition, consolidation, resuspension with chemical and biological controls can be carried out with this equipment.

For field investigation, the Malvern Particle Size Analyzer is being modified according to a concept similar to that of Bale. With this instrument we intend to characterize the particle size distribution of suspended sediments in natural state in a number of major rivers in North American Continent and to correlate size with other

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parameters describing the physical, chemical and biological states of river systems.

<u>Cohesive</u> mechanisms

Cohesive mechanisms are responsible for bonding particles together once they are brought in contact because of collision mechanisms. The most widely studied cohesive mechanism is the one governed by the physico-chemical processes. The surface forces involved in this cohesive mechanism under this process are discussed in detail by Lambe as cited in Owen (1970). Briefly, the repulsive force is caused by the clouds of positive cations surrounding the negatively charged suspended particles while the attractive force is provided by the electrical fields formed by dipoles of individual particles. The attractive force, commonly known as the Van der Waal's force is inversely proportional to the seventh power of distance between particles. While the repulsive forces are inversely dependent on the number of positive ions in the fluid medium, the Van der Waal's forces are independent of the properties of the fluid. Therefore, by changing the ion content of the water, it is possible to change the net force between particles and affect the bonds between them. For example, the ion-content of salt water inhibits repulsive forces and increases particles bonding (see Drake, 1976; Einstein & Krone, 1952; Kranck, 1980).

In natural waters, the particles are often coated with metallic and/or organic materials which in turn affect the surface charge of suspended particles and consequently the bonding between particles. (Micro)Biological control is another cohesive mechanism which is receiving considerable attention in recent years. For example, Kranch considers that biological bonding may be the most important flocculating agent in freshwater (personal communication). In this process, the particles are bridged together by the polymers produced by the microorganisms present in natural waters. An elaborate discussion of the studies on bioflocculation can be found in the review paper of Van Leussen (1988).

Effect of Flocculation on Fall Velocity of Sediment Particles

The flocculation changes the particle size, shape and density and hence the prediction of fall velocity of suspended sediment requires the prediction of all these parameters as functions of governing factors of flocculation. Such knowledge is non-existent at the present time, and the approach currently being used is to determine the fall velocity by direct measurements either in the laboratory or in the field. The apparatus commonly used to measure fall velocity of suspended sediment in the field is known as "owen-tube" developed in the late sixties by Owen (1971). This consists of a tube 1.0 m long and 5 cm in diameter with two end caps. The tube is pivotted near its centre so that it stays in the horizontal position when immersed in water and in vertical position in air. Samples are collected by lowering the tube to the sampling location and closing the end caps. The tube is then pulled out of water and held in vertical position to perform the settling velocity measurements using the bottom withdrawal technique (see Guy, 1969).

The drawback of the above method is that during the measurement period, the sample is not subjected to the turbulence of the flowfield and hence the floc size may start to increase as the particles descend in the tube. No satisfactory method has been developed so far to measure the fall velocity of suspended sediment in natural state.

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

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their calculation of suspended sediment distribution using a two dimensional, laterally averaged model. The results of Markofsky are reproduced in Figure 6 which shows the turbidity distributions computed using two different fall velocities. The top distribution is computed using a fall velocity of 0.01 mm/s whereas the bottom distribution is computed using a fall velocity of 0.05 mm/s. A fivefold increase in fall velocity has resulted in a substantially different turbidity distribution.

EROSION AND DEPOSITION RATES OF FINE SEDIMENTS

Also required for modelling fine sediment transport is the mathematical description of the sediment erosion and deposition processes at the sediment water interface near the streambed. Unlike conventional models for cohesionless sediment, this is not the source term for cohesive sediment; it does, however, bear closely on the mechanism of particle replacement by deposition and resuspension. A number of laboratory investigations had been carried out using straight and rotating circular flumes to quantify erosion and deposition rates as a function of bed shear stress and other physico-chemical properties of fluid and bed. A brief review f these studies is given in this section.

<u>Erosion rate of fine sediment beds</u>. Unlike cohesionless sediment beds, the erosion characteristic of cohesive beds depends on a number of physico-chemical properties of sediment and fluid in the water column and in the sediment bed. Hayter (1987) has listed the principle controlling factors of erosion of saturated cohesive sediment beds in tabular form as shown in Table 1. Because of the larger number of parameters involved and the complexity of the process, it is not possible to derive analytical expressions for erosion rate. The approach taken to tackle this problem was to derive empirical relationships based on laboratory experiments using straight and circular flumes.

Ariathurai and Arulanandan (1978) obtained the following relationship for the erosion rate of a consolidated bed:

(4)

$$S_R = M \bullet (\frac{\tau_b}{\tau_c} - 1)$$

where τ_b is the bed shearstress and τ_c is the critical shear for the erosion of the sediment bed. M is termed the erodibility constant and its value has to be determined by conducting laboratory experiments in a straight or circular flume for the sediment-water mixture under investigation.

For flow-deposited (stratified) beds, the experimental investigations of Partheniades (1962), Mehta and Partheniades (1974), Mehta <u>et</u> <u>al</u>. (1982), Parchure (1980), and Dixit (1982) in straight and rotating circular flumes have resulted in the following expression for erosion rate:

$$S_{R} = S_{R_{oi}} \exp \left[\alpha_{i} \frac{\tau_{i} - \tau_{c} (Z_{b})}{\tau_{c} (Z_{b})}\right]$$
(5)

Table 1.

Principle Factors Controlling Erosion of Saturated Cohesive Sediment Beds

HYDRODYNAMIC FACTORS (Erosive Force)



BED AND FLUID PROPERTIES (Resistive Force)



where $S_{R_{01}}$ and α_{1} are empirical coefficients to be determined through experiments. The variation of the critical shearstress for erosion as a function of bed-depth τ_{c} (Z_b) has to be determined also by experiments.

Based on experimental works of Lick (1982), Lea <u>et al</u>. (1981), Ziegler & Lick (1986) formulated the net erosion of sediment as:

$$z = a \left[\frac{\tau - \tau_c}{\tau_c} \right]^m \quad \text{for } \tau > \tau_c \qquad (6)$$

$$= 0 \qquad \qquad \text{for } \tau > \tau_c$$

where $a = a_0/t_d^n$ and ϵ is the net erosion per unit bed area. n and m are empirical constants, approximately equal to two, t_d is the time after deposition in days and a_0 is an empirical constant equal to $8x10^{-3}$ and it depends on the type of sediment.

<u>Deposition rate of fine sediment</u>. The rate at which the deposition of sediment takes place is given by the product of the settling rate (w_sC) and the probability of a settled particle bonding and staying at the bed (P_d) i.e.,

$$S_D = w_s C \bullet P_d$$

(7)

where Sp denotes the deposition rate.

The deposition process of fine sediment was also studied extensively by a large number of investigators under laboratory conditions using straight and rotating circular flumes. Notable investigations are those of Krone (1962), Partheniades (1965) Partheniades <u>et al</u>. (1966), Mehta and Partheniades (1975), Mehta <u>et al</u>. (1982), Lick (1982) and Lee <u>et al</u>. (1981). These investigations involved suspending the fine sediment into the main body of flow in a laboratory channel at a high shearstress, letting it deposit at a lower shearstress and monitoring the concentration as function of time. Under conditions of negligible concentration gradient in the flow direction, the deposition rate can be equated to the time-rate of change of depth-average concentration, \overline{C} of the suspended sediment, i.e.

$$S_{D} = -h \frac{dC}{dt}$$

(8)

Krone (1962) hypothesized that the probability P_d is a function of the bed shearstress τ and can be expressed as:

$$Pd = (1 - \frac{\tau}{\tau_{cd}})$$
 (9)

where τ_{cd} is the critical shearstress for deposition defined as the shearstress above which no deposition would occur. Using this hypothesis and the relations (7) and (8), Krone developed an equation for concentration distribution as:

$$\frac{C}{C_0} = \exp\left[-\frac{P_d \bullet W_s}{h} \bullet t\right]$$

for concentrations below 0.30 gm/litres. C_0 is the initial concentration. For higher concentrations in the range 0.3 g/L < C < 10 g/L and C > 10 g/L, Krone derived a different relationship which is:

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$$\log C = -K [\log (t)] + constant$$
(11)

where K is a function of P_d and h.

The investigations of Partheniades (1965), Partheniades <u>et al</u>. (1966) and Mehta and Partheniades (1975) and Mehta <u>et al</u>. (1982) revealed that above a certain critical shearstress, the concentration of suspended sediment reached a constant value (equilibrium concentration) and the ratio of this concentration to the initial concentration remained constant for a given shearstress. When the shearstress was increased, the ratio of equilibrium concentration to the initial concentrations increased. Based on these observations, Partheniades <u>et al</u>. (1966) concluded that there is no continuous interchange between suspended and bed sediment (as in the case of cohesionless sediment transport) and the equilibrium concentration had resulted from the breakage and resuspension of weakly bonded flocs that cannot withstand the high shearstress in the flow region near the bed.

(10)

Using their experimental results, Mehta and Partheniades (1975) derived a log normal relationship for concentration of suspended sediment as:

$$C_{\star} = \frac{C_{o} - C}{C_{o} - C_{eq}} = \frac{1}{2} \{1 + erf(\frac{T}{\sqrt{2}})\}$$
(12)

where erf is the error function, C_{eq} is the equilibrium concentration and T = $\log_{10} (t/t_{50})^{1/\sigma_2}$. σ_2 is the standard deivation of the log-normal relationship and t_{50} is the geometric mean. By differentiating (12) with respect to t, the deposition rate can be derived as:

$$\frac{dC_{\star}}{dt} = \frac{0.434}{\sqrt{2\pi} \cdot \sigma_2} \frac{\exp(-T^2/2)}{t}$$
(13)

Lick (1982) conducted similar experiments using a stationary circular flume with a rotating annular ring touching the water surface. He also obtained equilibrium concentrations that are proportional to the initial concentrations. But he offered a totally different explanation for his observations. He explained that the equilibrium concentration is due to the gradation of particle size of suspended sediment. As the suspended sediment undergoes deposition, the coarser particles settle out and the finer fraction stay in suspension. The intermediate size particles undergo deposition and reentrainment processes and attain an equilibrium similar to the cohesionless sediment transport. The end result is an equilibrium concentration that is proportional to the initial concentration. As the shearstress is increased, entrainment of recently deposited sediment increases thereby increasing the ratio of equilibrium to initial concentration.

The above explanation of Lick is in total contradiction to the explanation offered by Partheniades. There is an urgent need to resolve this controversy because, it has implications in the development of mathematical models of sediment associated contaminant transport. According to Lick's hypothesis, since there is constant exchange of bed and suspended particles, the dispersion of the contaminated sediment in a stream will be high and the concentration of a sediment associated contaminant will decrease at a much faster rate in the downstream direction compared to a model based on Partheniades' hypothesis. According to Partheniades, the sediment particles undergo either deposition or erosion and are likely to preserve their chemical identity over a larger distance in the downstream direction.

The resolution of the controversy should be fairly simple. According to Lick's arguments, the size distribution of suspended sediment has to become coarser from a lower shearstress condition to a higher shearstress condition because of the entrainment of coarser fraction from the bed. Whereas, according to Partheniades, the grain size distribution of suspended sediment has to become finer because the higher shearstress will breakup the flocs further into even smaller flocs. Therefore, by monitoring the grainsize distribution of

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suspended sediment under different shearstress condition, it should be possible to draw conclusions regarding the validity of the two hypothesis. We expect to resolve this question by developing uniform, turbulent shearflows in the rotating channel apparatus described earlier with continuous monitoring of the particle size distributions.

Another aspect of fine sediment transport that needs further research is the consolidation process of the deposited sediments. This has implication in the erosion resistance and the vertical transport of contaminants within the streambed. A very good review of the research on the bed formation and the consolidation process is given by Hayter (1986). The presently available consolidation theories are based on a number of simplifying assumptions and further work is needed to improve our understanding in this area.

SUMMARY

The basic knowledge requirements for developing mathematical models of fine sediment transport are reviewed and the need for further research is demonstrated. The parameter that needs the most attention is the fall velocity of the fine-grained sediments as it effects the sediment settling in the water column and also the depositional process at the sediment-water interface. It is also the most difficult parameter to quantify at the present time because of our poor understanding of the floccuation process. The review of literature on the erosion and depositional processes of fine sediment reveals that there exist two different schools of thought regarding the transport process near the sediment-water interface. The mechanism proposed by Partheniades suggests that the fine sediments undergo either deposition or erosion but not both at the same time under a certain flow condition. The other school of thought proposed by Lick implies that the erosion and deposition can occur simultaneously. The fine sediment transport research program now underway at the National Water Research Institute, Burlington, Ontario, Canada, will shed more light on the flocculation process and on the contradictions regarding the erosion-deposition process.

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FIGURES

Figure 1. Co-ordinate system to describe river flows.

Figure 2. Comparison of the collision functions for Brownian, shear and differential-sedimentation processes (after Hunt, 1980).

Figure 3. Schematic illustration of effect of turbulence on floc size.

- Figure 4. Particle size distributions measured <u>in situ</u> compared with size distributions measured in discrete samples obtained from the same depth at seven stations of various salinities and turbidities in the Tamar Estuary. Also shown are the size distributions of the primary particles that comprise the aggregated particles at each station.
- Figure 5. Changes in total concentration with time for experiment of Kranck (1980).
- Figure 6. Example of suspended sediment distribution, calculated by a two dimensional laterally averaged model; effect of the settling velocity w_s on the turbidity maximum; from Markofsky <u>et al</u>. (1986).





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Figure 2. Comparison of the collision functions for Brownian, Shear and Differential-Sedimentation processes. (after Hunt, 1980.)





Figure 4. Particle size distributions measured in situ compared with size distributions measured in discrete samples. (after Bale et al)



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Figure 5. Changes in total concentration with time for experiment of Kranck (1980)



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