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Suspended sediment structure: implications for sediment and contaminant transport modelling

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Abstract This paper examines the influence of sediment (floc) structure (size, shape, porosity and density) on the physical behaviour (e.g. settling and transport) of suspended sediment (flocs) and its implications for sediment and contaminant transport models. Results demonstrate that as floc size increases, the settling velocity increases in a linear fashion. The rate of settling is, however, substantially below that predicted by Stokes' law for solid spherical particles of the same size. Floc density and porosity demonstrate strong negative and positive relationships respectively with floc size. As floc size increases, the density of the flocs approaches that of water. It is found that whilst a change in density can affect floc settling, the size of the floc is a much more important influence on settling. Floc shape also influences floc settling, with elongated flocs settling with their long axis parallel to the direction of settling. This paper concludes that suspended sediment can no longer be viewed and modelled in the traditional manner as solid spherical units. Suspended sediment must be observed and analysed in its natural flocculated form due to its significantly different behaviour (transport/settling) from primary and theoretical solid spherical particles.

INTRODUCTION

Most fine sediment and contaminant transport models make use of grain-size distributions or characteristic parameters such as d_{50}, derived from sizing techniques which do not maintain the integrity of the sediment size structure. It is now well documented that fluvial suspended sediment is preferentially transported in a flocculated (aggregated) form (Droppo & Ongley, 1994; Droppo *et al.*, 1997; Phillips & Walling, 1995; Petticrew, 1996b). As flocculation significantly alters the hydrodynamic characteristics of sediment in suspension by modifying the effective grain size, density, porosity and water content (Droppo *et al.*, 1997), models which do not take into account flocculation will provide erroneous predictions of sediment and contaminant transport/deposition (Nicholas & Walling, 1996).

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MATERIALS AND METHODS

Study site

Samples were collected from Sixteen-Mile Creek, Milton, Ontario, during spring melt (rising limb, 19 February; falling limb, 21 February 1997) and during summer baseflow (7 September 1997). This river has a drainage basin of approximately 276 km^2. The sample site was located 20 km upstream and receives only surface and subsurface flow from forested and low density agricultural land. The site is more fully described in Droppo & Ongley (1992).

Particle size and shape

Samples were collected following the method of Droppo & Ongley (1992). This method allows for the non-destructive direct sampling and observation/measurement of flocculated material within a settling column (plankton chamber). The flocs are imaged (sized) down to a lower resolution of approximately 2 μm (10× objective) using a Zeiss Axiovert 100 microscope interfaced with an image analysis system (Northern Exposure^{TM}—Empix Imaging, Inc.).

Particle settling velocity, settling orientation, density and porosity determination

Settling experiments were performed following the methods of Droppo *et al.* (1997). A drop of sediment collected with a wide mouth pipette (3.74 mm) from a gently homogenized sample bottle was introduced into an insulated 2.5-litre-capacity settling column. As the flocs pass through the field of view of the microscope they are videotaped on a SVHS VCR through a CCD camera interface. Using Northern Exposure^{TM}, the settling velocity was derived by digitally overlaying two video frames separated by a known time interval. In this way the same particle appears on the newly combined image twice and the distance of settling (over a known time), particle size, and settling orientation can be digitized.

The density of a floc [expressed as excess density (1-wet floc density)] was estimated using Stokes' law. As Stokes' law is based on the settling of single impermeable spherical particles in a laminar region (Reynolds number < 0.2), it is not ideal for the determination of floc density due to the heterogeneous structure and irregular shape of flocs (Hawley, 1982). Nevertheless Stokes' law or a modification thereof has often been used to determine the wet density of singular flocs (Li & Ganczarczyk, 1987; Droppo *et al.*, 1997), and does provide an indication of how aggregate settling velocity, density, and porosity are related to aggregate size. The floc porosity can be expressed by a mass balance equation (equation (1)) assuming a typical density of dried silt and clay of 1.65 g cm^{-3}.

$$\varepsilon = (\rho_s - \rho_f)/(\rho_s - \rho_w) \tag{1}$$

where ε = floc porosity, ρ_s = density of the dried solid material, ρ_f = wet density of the floc and ρ_w = density of the water (Li & Ganczarczyk, 1987).

RESULTS AND DISCUSSION

It is now well known that suspended sediment in any aquatic environment is preferentially transported as flocculated particles (Droppo & Ongley, 1994). The significance of flocculation on the effective grain-size distribution can be seen by sizing the sediment from the baseflow of the Sixteen-Mile Creek (7 September 1997) before and after particle disaggregation by sonication (Fig. 1(a)). Sonication has the effect of significantly shifting (disaggregating) the classical percent by volume distribution (Fig. 1(a)) towards smaller particles sizes (significant difference at α = 0.5, modified Kolmogorov-Smirnov test). The total particle count went from 6639 before sonication to 13 196 after sonication.

The dispersed distribution in Fig. 1(a) (by volume) is close to what traditional sediment sizing techniques (e.g. sedigraph) would provide as the grain-size distribution. As flocculated particles have significantly different hydrodynamic characteristics compared to absolute primary particles (Krishnappan, 1990; Ongley *et al.*, 1992; Droppo *et al.*, 1997), the use of such a disaggregated distribution to characterize sediment for sediment and contaminant transport models would result in erroneous results. It is likely that models based on these traditional absolute grain sizes would overestimate storm event contaminant and sediment loadings to receiving water bodies, since finer particles will be transported further in a turbulent flow than larger flocculated particles. This is exemplified by Ongley *et al.* (1992) who found that by modelling sediment transport with and without accounting for flocculation provided significantly different sediment fluxes. Modelling which did not take into account flocculation essentially showed minimal change in sediment flux, whereas, when flocculation was accounted for, virtually all of the sediment was deposited in a relatively short distance. While their model was overly simplistic (only flocculation and not floc breakage is assumed and only sedimentation occurs and not resuspension), the effect of flocculation on sediment transport is obviously dramatic.

Settling experiments undertaken with Sixteen-Mile Creek samples (as well as numerous lacustrine samples, Droppo *et al.*, 1997) demonstrate the positive relationship of floc size to settling velocity (Fig. 2). While a statistically significant

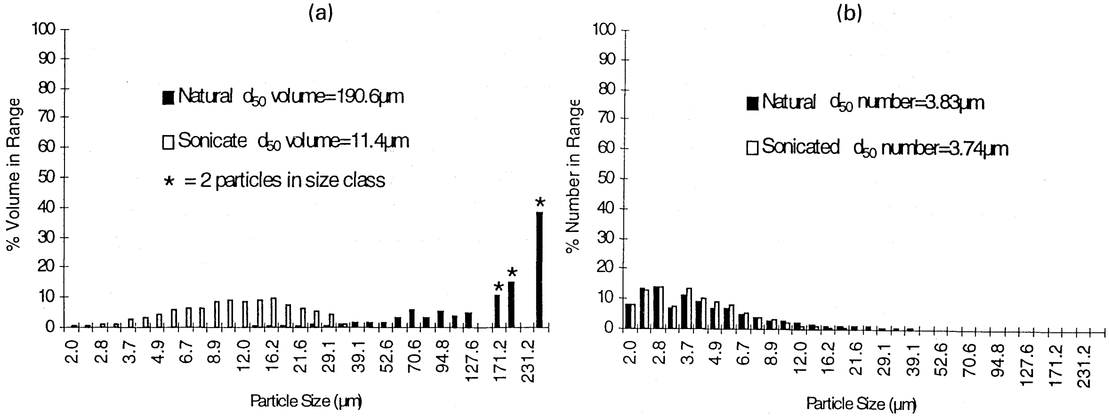

Fig. 1 Natural and sonicated distributions by (a) volume and (b) number (baseflow—7 September 1997).

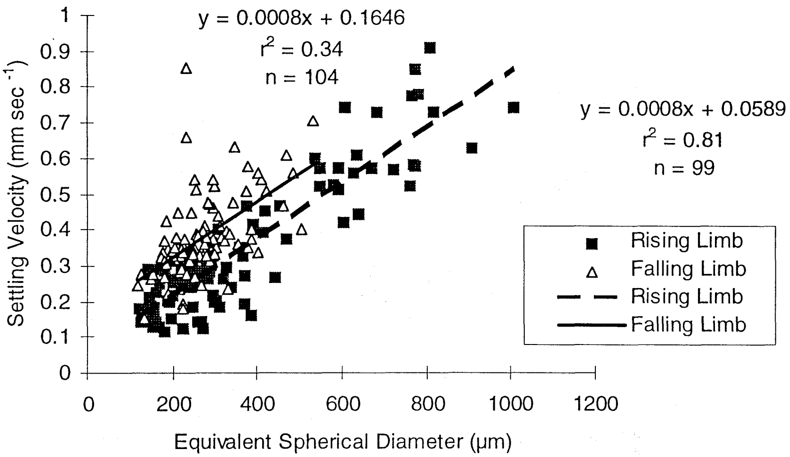

Fig. 2 Settling velocities as related to floc size for the spring melt rising and falling limb.

regression line ($\alpha = 0.05$) can be fitted to such data, the r^2 is characteristically low. This low r^2 is related to variation in the morphology (shape, porosity and settling velocity) and composition (organic/inorganic composition and water content) of individual flocs of the same size. Flocs from Sixteen-Mile Creek were also found to settle at a much slower rate than predicted by Stokes' equation. This too is related to floc morphology being very different from the solid spherical particles assumed by Stokes' law and because of significant density differences between the two particle types (Nicholas & Walling, 1996) [solid spherical quartz particle ~ 2.65 g cm^3; floc ~ 1.001 to 1.03 g cm^3 (Fig. 4)]. (One would, however, not expect to apply Stokes' equation to flocs, as they would generally be disaggregated by traditional sizing techniques.)

Given that flocs settle out of suspension faster than smaller primary particles, why then are there periods where the suspended solid concentrations in river reaches remain relatively constant at a given flow (Ongley *et al.*, 1992)? The answer is likely to be related to two factors: (a) the continual input of new sediment from a variety of sources (i.e. bank erosion, resuspension of bed sediment, overland flow and tributary inputs) and (b) floc breakage in the bed sediment shear zone. Factor (a) has been studied widely (Gregory & Walling, 1973) and will not be discussed here, however, the phenomenon of "floc recycling" is a relatively new area of study. Floc recycling is the process whereby larger, less dense flocs are formed within the water column (zone of lower shear) and settle towards the bottom of the river. Once the flocs reach the high shear zone of the sediment water interface they may break up and be lifted back into suspension as primary particles or smaller flocs (Partheniades, 1986). At this point these particles may once again go through the floc building and break up cycle (Fig. 3).

If the critical shear stress for floc break up is larger than the bed shear stress (generally a condition characteristic of baseflow) then the flocculated particles may settle on the bed (Partheniades, 1986) forming a surficial fine-grained laminae (SFGL) (Droppo & Stone, 1994). SFGL is characterized as a high water content,

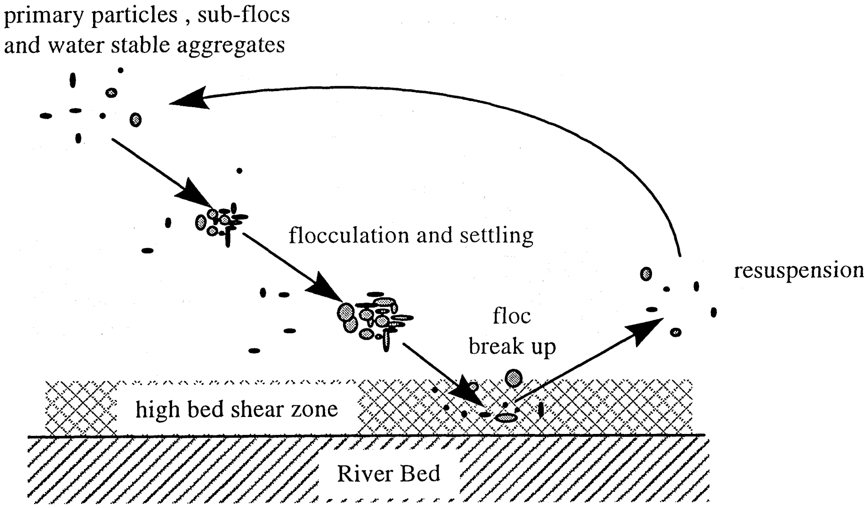

Fig. 3 Simplified model of "floc recycling" within a riverine system.

"fluffy", "buoyant" layer with substantial inter-particle/inter-floc spaces/pores with a density of approximately 1.1 g cm^{-1} (Droppo & Stone, 1994). Because of these structural characteristics, the layer is easily eroded by the next storm event which increases the bed shear stress beyond the critical shear stress for erosion. As such, SFGL is a transient depositional feature which is highly related to flocculation within the water column and critical bed shear stress.

Floc strength is therefore a critical characteristic which will dictate its transport history within a riverine system. A number of experiments have demonstrated that flocs are inherently unstable and prone to break up (Bale & Morris, 1987). The outcomes of these experiments, however, are biased by their exclusive use of percent by volume distributions. Typical sediment distributions will have the highest sediment volume within the largest size classes. These particles may only represent a few particles relative to the total number of particles within a distribution (Fig. 1(a)). These few large volume flocs, if disturbed (i.e. sampled), may be more prone to disaggregation and as a result will significantly change the percent by volume distribution (Fig. 1(a)) but will have a limited impact on the percent by number distribution (Fig. 1(b)) (no significant difference at $\alpha = 0.5$, modified Kolmogorov-Smirnov test). Phillips & Walling (1995) have demonstrated that sampling riverine suspended sediment in a bottle does not significantly affect the floc size distribution (by number and volume) provided that size measurements are made immediately after sampling. We suggest that while large flocs may be more unstable, the total floc distribution (by number) may be relatively stable (shear dependent). It is therefore important that both the percent by number and by volume distributions be evaluated in order to better understand and model the transport of sediment and contaminants.

Extreme variations in flow occurred during the 1997 spring melt and samples were collected on both the rising limb and falling limb of the hydrograph. A significant difference and no significant difference was found between the two hydrograph limbs for the percent by volume and number distributions respectively (modified Kolmogorov-Smirnov test, $\alpha = 0.05$). The significant difference between

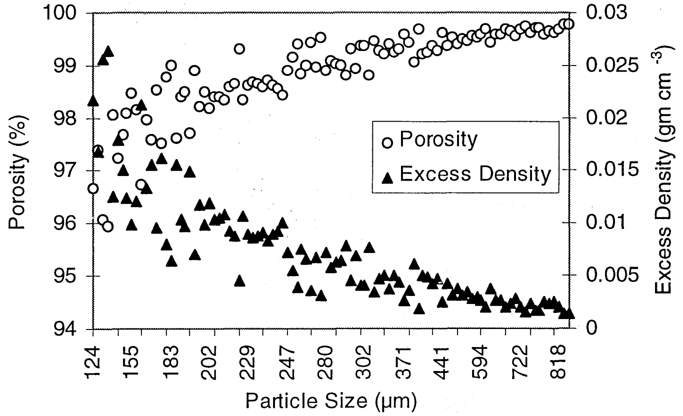

Fig. 4 Relationship between floc size, porosity and excess density for the spring melt rising limb.

the volume distributions is related to their sensitivity towards the variation of only a few large volume particles. A distinct difference was found between the two hydrograph limb's settling velocities (Fig. 2). While the rate of change is constant (i.e. same slopes), particles on the rising limb have lower settling rates which may indicate lower densities, more irregular shapes and higher porosity. The differences are likely to reflect the changing source material over the spring melt hydrograph. For example, the rising limb may contain more low density biofilm flocs ripped up from the bed while the falling limb sample may contain more high density eroded water stable soil aggregates (the source of biofilm would be depleted by this time). Density estimates from statistically significant regression lines ($\alpha = 0.05$) confirm an increase in floc densities for the falling limb (rising limb, excess density = 6.021 × floc diameter$^{-1.212}$ r^2 = 85%; falling limb, excess density = 23.971 × floc diameter$^{-1.402}$ r^2 = 78%). Petticrew (1996a) found two distinct populations of particle densities within western Canadian streams which exhibited differences in settling velocities. It was hypothesized that the denser flocs/aggregates were derived from the cobble bed while the less dense flocs were derived from flocculation within the water column. Figure 4 illustrates that there is a strong relationship between porosity, density and floc size. As floc size increases, the density approaches that of water, reflecting the inverse relationship with porosity which approaches 100%.

The shape of a floc is known to affect settling due to resistance effects against flow (fluid drag forces) (Li & Ganczarczyk, 1987). The shape of a floc is generally influenced by its origin/source and composition and by the flow field in which it is transported. Flocs in the quiescent settling column experiments were found to generally settle with their long axes parallel or close to the direction of settling, as indicated by the bell shape distribution in Fig. 5. Figure 6 illustrates that elongated flocs (aspect ratios above 2) settle slower than many of the flocs which exhibit a more stubby stature. While there are many flocs within the overlap of the spheres plotted in Fig. 6, suggesting a weak relationship (or possibly representing a different sediment source), this trend has been observed with numerous other samples. This finding is consistent with that of Li & Ganczarczyk (1987) who found that in quiescent settling column experiments, spherical flocs generally settled faster than

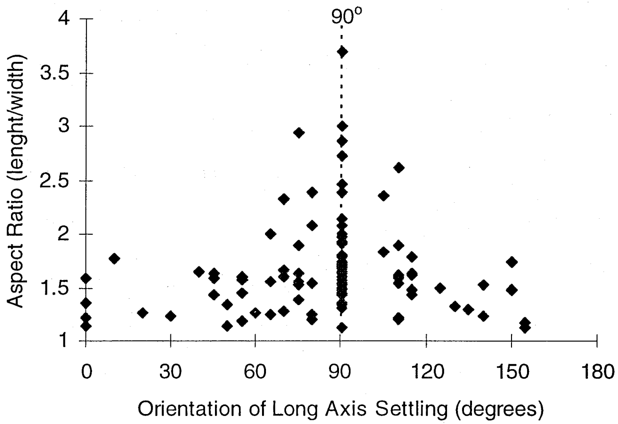

Fig. 5 Relationship between settling orientation in relation to particle shape (aspect ratio) for the spring melt rising limb.

cylindrical or disk shape flocs with similar mass and density.

CONCLUSION

The transport of sediment and associated contaminants in fluvial systems is strongly influenced by the velocity and shear of the flow and by the structure of the sediment. Suspended sediment is preferentially transported as flocculated particles and as such behaves hydrodynamically differently from individual grain particles due to differences in its effective size, shape, porosity, water content and density. Although flocs can have densities as low as water due to high porosity and organic content, they settle relatively fast compared to their constituent primary particles due to their larger size. Flocs generally settle with their long axes parallel to the direction of settling, with elongated flocs settling slower than stubby flocs. As flocculated sediment behaves (transports/settles) differently from the traditionally sized and modelled disaggregated particles, it is critical that predictive models for sediment and contaminant transport take account of the phenomenon of flocculation.

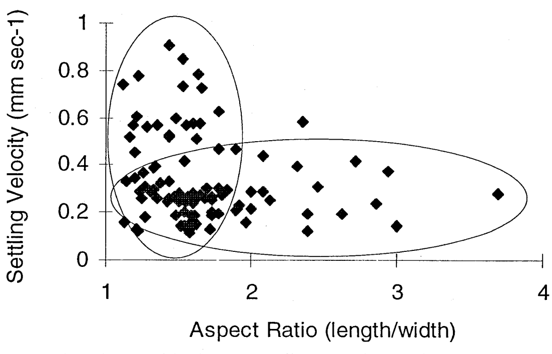

Fig. 6 Relationship between floc settling velocity and floc shape (aspect ratio) for the spring melt rising limb. Spheres represent potential different populations.

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