The influence of floc size, density and porosity on sediment and contaminant transport

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Abstract This paper examines the influence of floc size, porosity and density on the transport of suspended sediment (flocs) and associated contaminants. Results demonstrate that as floc size increases the settling velocity increases. Settling velocity is also influenced by the relationship of floc density and porosity to floc size. As floc size increases, the density decreases and approaches that of water. This relationship is related to the concomitant increase in porosity, and therefore water content. The role of flow through flocs (pores) as a possible explanation for the settling of large low density flocs is discussed. Equations for describing the relationship of floc porosity and density to floc size are provided and discussed in relation to floc transport.

INTRODUCTION

The transport of sediment and associated contaminants is dictated in part by the structure and settling velocity of the sediment (Ongley *et al.*, 1992; Droppo *et al.*, 1997). It is now well documented that cohesive suspended sediment is primarily transported as flocs (Droppo *et al.*, 1997; Phillips & Walling, 1999). As flocculation significantly alters the hydrodynamic characteristics of sediment by modifying the effective grain size, density, porosity and water content (Droppo *et al.*, 1997), models which do not take into account flocculation and the processes influencing it will provide erroneous predictions of sediment and contaminant transport (Nicholas & Walling, 1996). This paper examines the influence that floc size, density and porosity will have on the transport of sediment and associated contaminants.

MATERIALS AND METHODS

Study site

Samples were collected from Sixteen-Mile Creek and Fourteen-Mile Creek (February 1997–May 1998). These sites are located in southern Ontario, Canada and have been described previously. The reader is referred to Ongley (1974) for details of their hydrological and geomorphological characteristics.

Floc size, settling velocity, density and porosity determination

Samples were analysed for floc size, settling velocity, density and porosity using a 2.5 l settling chamber interfaced with a stereoscopic microscope, CCD camera, SVHS VCR and a computer image analysis system (Northern Exposure™) following the methods described in Droppo *et al.* (1997, 1998).

RESULTS AND DISCUSSION

The relationship between floc settling velocity and floc size

It is well documented that flocs do not conform to the assumption of solid spherical particles as required by Stokes' law and have densities well below that of quartz particles (e.g. Li & Ganczarczyk, 1987, 1988; Droppo *et al.*, 1997, 1998). In addition, many of the larger flocs do not settle within the Stokes' region of Reynolds numbers. Droppo *et al.* (1999) examined multiple river and lake sediment samples and found that only flocs less than 100 μm (equivalent spherical diameter) settled within the Stokes' region ($Re < 0.2$). These results pose a problem for modelling sediment and contaminant transport, as the majority of the sediment volume is often accounted for by the larger particles which settle outside the Stokes' region (Droppo & Ongley, 1994). For most of the rivers in southern Ontario, however, the flocs are generally small (< 100 μm) and, as such, will settle within the Stokes' region. Such a finding does not, however, imply that the Stokes' equation is appropriate for models which focus on fine flocculated sediment, as the assumption of solid spherical particles is still not met.

Stokes' equation was consistently found to overestimate the settling velocity of flocculated particles by orders of magnitude for larger flocs, while the values converged only for very small flocs. The poor prediction of settling velocity by Stokes' equation is related to the varying morphology (shape, porosity) and composition (organic/ inorganic composition and water content) of flocs and their deviation from

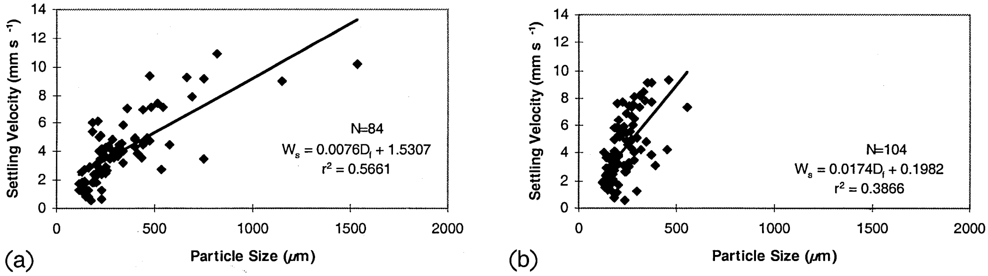

Fig. 1 Example plots of settling velocity *vs* floc size for (a) 16-Mile Creek (18 February 1997) and (b) 14-Mile Creek (3 November 1997).

that of the assumed solid spherical particle (Nicholas & Walling, 1996). While it is evident that floc size is a dominant factor which will influence settling velocity, other characteristics of density, porosity and shape all combine to provide a particle settling velocity which is well below that predicted by Stokes' law.

Given the inappropriateness of the Stokes' equation for the calculation of floc settling velocity, it is important to measure the fall velocity of flocculated particles directly. While Stokes' law states that the settling velocity of a particle is proportional to the diameter squared, our work suggests that a floc's settling velocity is directly proportional to its diameter (Fig. 1).

While the regression lines fitted to the relationship between settling velocity and floc size are generally significant ($\alpha = 0.05$), the r^2 values are often low, ranging from 0.2 to 0.7 (e.g. Fig. 1). This low r^2 reflects the wide range of morphologies and composition of individual flocs, which result in a high variation in floc settling velocity for a given floc size.

The relationship between floc density and floc settling velocity

The density of a floc is primarily controlled by its composition (inorganic and organic particles, extracellular polymeric substances (EPS), water content, etc.) and its porosity (pore size and structure), and consistently shows a negative relationship with floc size (Fig. 2). Floc densities are typically low, ranging between the density of water and 1.4 g cm^{-3} (the majority of flocs observed were below 1.1 g cm^{-3}). Similar densities have been observed by other researchers for a variety of environments (Tambo & Watanabe, 1979; Li & Ganczarczyk, 1987; Namer & Ganczarczyk, 1993; Droppo *et al.*, 1997, 1999). Variations in floc density between environments reflect the different factors and the relative importance of these in relation to floc growth between environments. As a floc grows and encompasses more and more particles, it also creates more void space (pores) for the entrapment of water. It is this trapping of water which is the primary mechanism resulting in the density of larger flocs approaching that of water (Droppo *et al.*, 1998). The EPS matrix, common in all flocs (Droppo *et al.*, 1997), is responsible for much of the retention of water in flocs due to the very small pores created by the EPS resulting in

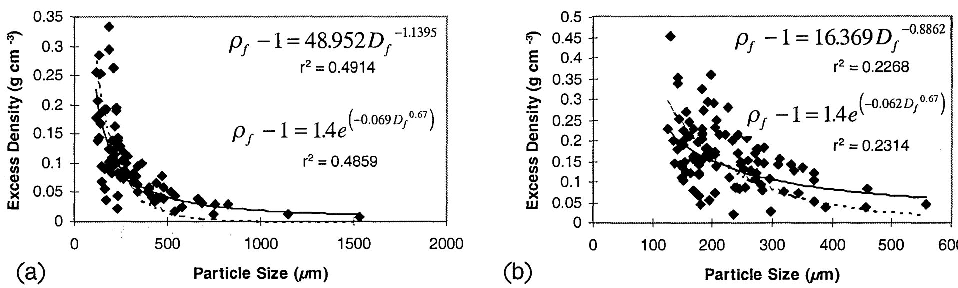

Fig. 2 Examples of the negative relationship between excess density (floc density–water density) and floc size for (a) 16-Mile Creek (18 February 1997) and (b) 14-Mile Creek (3 November 1997). The data have been fitted with a power (solid line) and exponential (dashed line) function (see equation (1)).

strong surface tension (Droppo *et al.*, 1997; Liss *et al.*, 1996). The relative importance of floc density for floc settling may be minimal given (a) that larger flocs generally have the lowest density, and yet, exhibit the greatest settling velocity, (b) the minimal changes in density over the range of floc sizes examined, and (c) the relatively small difference between floc density and water density. As such, it is likely that the size of the floc will have a greater influence over settling than its density. For large flocs with low densities (approaching that of water), it is possible that an open floc matrix with large pores will have a strong influence on floc settling, due to flow through the floc (discussed further below). Because estimates of floc density are derived from the settling velocity, a statistical comparison of these two variables is not possible.

In assessing the relationship of density to floc size, the power function is often used to provide a "good fit" (Fig. 2) (Zahid & Ganczarczyk, 1990). The power function, however, does not have any physical meaning with regard to this relationship. The exponential function is, on the other hand, more physically based in relation to how floc size and density vary and, as such, can be used to explain the relationship between floc size and density.

As described above, as a floc increases in size, its density approaches that of water. Conversely, as a floc approaches the size of a discrete (absolute) single particle its density approaches that of the density of the sediment. This relationship can be described mathematically below (Lau & Krishnappan, 1997):

$$\rho_f - \rho_w = (\rho_s - \rho_w) e^{-\left(C_1 D_f^{C_2}\right)} \tag{1}$$

where C_1 is constant 1, C_2 is constant 2, D_f is floc diameter, ρ_f is floc density, ρ_s is solid particle density, ρ_w is water density and $(\rho_f - \rho_w)$ is excess density.

As $D_f \rightarrow \infty$ ($e^{-\infty} = 0$) then $\rho_f - \rho_w = 0$ and therefore $\rho_f = \rho_w$

As $D_f \rightarrow 0$ ($e^0 = 1$) then $\rho_f - \rho_w = \rho_s - \rho_w$ and therefore $\rho_f = \rho_s$

A value of 2.4 was assumed for ρ_s given that in the natural environment flocs will be made up of both mineral particles and organic material. The parameter ρ_w was assumed to be 1.0 and, as such, $\rho_s - \rho_w = 1.4$. In order to achieve the best fit to the data, C_1 and C_2 were varied until the lowest sum of squares of the errors was obtained. Clearly, for the representative examples given in Fig. 2 the exponential model provides a reasonable fit relative to the more widely used power function, in describing the relationship of floc density to floc size. This is demonstrated by both fitted lines explaining essentially the similar amounts of variance within the data (i.e. similar r^2). Interestingly, the exponential function under-predicts the density for larger size particles and, to a lesser degree, over-predicts the density of the smaller particles. The under-prediction of floc density for large flocs is of less concern, as generally these particles only represent a small proportion of the overall sediment in transport. The constants of the equations were found to be similar for all fluvial samples, suggesting that factors influencing floc density and size are consistent within a system. Given the physically based nature of equation (1), it is more appropriate to use such a relationship rather than the more commonly used power function for numerical description of the relationship between floc density and size.

The relationship between floc porosity and floc settling velocity

Floc pores are responsible for much of the physical, chemical and biological behaviour exhibited by flocs, as they are the primary physical factor which controls water content (retention within the pores due to surface tension), and therefore density, and water movement within a floc (flow through large pores). As such, floc pores influence floc density and transport, as well as potential advective, diffusional and electrochemical gradients within the floc (Li & Ganczarczyk, 1988; Logan & Hunt, 1987). Porosity cannot be measured directly, due to the three dimensional and tortuous nature of floc geometry, but instead is generally derived through a mass balance of densities (wet and dry density and water density) (Li & Ganczarczyk, 1987).

Figure 3 indicates that as floc size increases, the porosity of the floc also increases, approaching 100% (fitted lines are expressed by equation (2) as discussed below). This finding is consistent with the findings of other researchers (Tambo & Watanabe, 1979; Logan & Hunt, 1987; Li & Ganczarczyk, 1987, 1988). This relationship is reasonable, given that the settling velocity of flocs is not related to the square of the size. This would indicate that the floc density must decrease and the floc porosity increase with

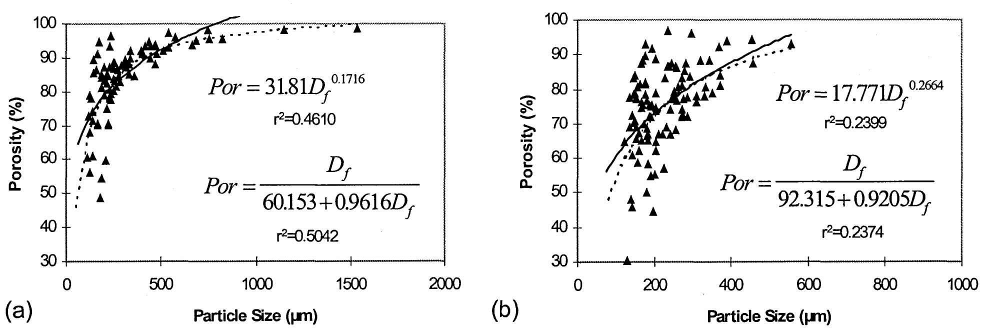

Fig. 3 Examples of the positive relationship between porosity and floc size for (a) 16-Mile Creek (18 February 1997) and (b) 14-Mile Creek (3 November 1997). The data have been fitted with a power function (solid line) and equation (2) (dashed line).

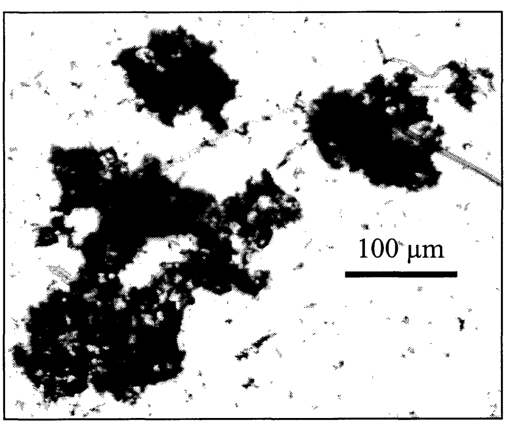

Fig. 4. Representative micrograph of an open matrix floc from 14-Mile Creek.

increasing floc size (Logan & Hunt, 1987). As a floc grows, the amount of open void space increases simply due to the nature of the contact points between particles (organic and inorganic) forming the matrix. In the hundreds of images observed, no floc was found to be completely devoid of pores, but rather were characterized as having an open matrix such as that illustrated in Fig. 4.

Numerous studies (e.g. Masliyah & Polikar, 1980; Adler, 1981; Logan & Hunt, 1987) have investigated flow through flocs and its influence on settling with varying results due to floc specific characteristics. In general, however, a solid sphere, having the same size and density as a highly porous sphere, will settle more slowly than the porous sphere, because the flow through the porous sphere will reduce the hydrodynamic resistance that will be experienced by the solid sphere (Namer & Ganczarczyk, 1993). Zahid & Ganczarczyk (1990) concluded that the traditional computation of settling velocity by Stokes' law from size and density measurements may lead to erroneous results if particle permeability is not considered. Given that, for the floc sizes studied, there is a continuous increase in settling velocity with size (Fig. 1), even though the density is approaching that of water (Fig. 2), it is reasonable to expect that such a mechanism (flow through pores) allows large, low density flocs to settle. As described above, however, the majority of pores in a floc are generally small due to the EPS within the floc (Liss *et al.*, 1996) and, as such, much of the water held in the floc will be bound and not free to move. More details on this issue can be found in Droppo *et al.* (1997, 1999).

As with floc density, a power function (Fig. 3) is often used to describe the relationship of porosity to floc size. Such a function did not provide an adequate fit and performed very poorly for both the larger and smaller floc sizes. As with density, the power function fit has no physical basis. A new function for describing the relationship between sample specific floc porosity and floc size was therefore developed based on the following observations: (a) as floc size increases, porosity approaches unity (or 100%) and (b) as the floc size approaches a single individual particle, the porosity approaches zero (or 0%). Such physical constraints can be adequately represented in the following equation:

$$Por = \frac{D_f}{C_1 + C_2 D_f} \tag{2}$$

where *Por* is porosity (as a decimal), and C_1, C_2 are constants 1 and 2, respectively.

The empirical constants are derived through a spurious correlation of D_f/Por to D_f, which, from a truly statistical perspective, should be avoided. However, as this spurious relationship is only used for the derivation of constants for fitting a line based on equation (2) to the observed data, such a statistical rule can be relaxed. The constants C_1 and C_2 are derived from the regression of the above relationship in the form:

$$\frac{D_f}{Por} = C_1 + C_2 D_f \tag{3}$$

It is evident from the examples provided in Fig. 3, that equation (2) fits the data better than the power function, particularly for the larger size classes where the power function predicts values in excess of 100% much sooner than equation (2).

Equation (2) predicts porosity better than the power function for the smaller floc sizes, although there is still room for improvement. In 85% of the samples analysed, equation (2) resulted in a slightly higher explanation of the variance than did the power function.

CONCLUSION

The transport of sediment and associated contaminants is influenced in part by the symbiotic relationship between floc structure and settling velocity. While it has been shown that floc size is the dominant floc characteristic affecting settling, density and porosity will also have some influence. As such, models for the prediction of the transport of sediment and associated contaminants will produce erroneous estimates if these floc characteristics are not integrated into the model computations.

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