Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances
(Proceedings of the Oslo Workshop, June 2002). IAHS Publ. 283, 2003.

A new definition of suspended sediment: implications for the measurement and prediction of sediment transport

IAN G. DROPPO
National Water Research Institute, Environment Canada, PO Box 5050, Burlington, Ontario L7R 4A6, Canada
ian.droppo@ec.gc.ca

Abstract Sediment (floc) structure is discussed in relation to its influence on the measurement and prediction of sediment transport. Structural characteristics of floc size, porosity, density and compositional matrix are investigated with the aim of creating a new paradigm of suspended sediment. This new paradigm is intended to influence the development of new techniques and strategies for the quantification of suspended sediment transport in aquatic environments.

Key words deposition; floc; flocculation; suspended sediment; transport

INTRODUCTION

A river's transport characteristics can have a profound effect on the design of sampling programmes for the measurement and prediction of sediment erosion and transport. Historically, sampling programmes have relied on infrequent sampling protocols in conjunction with continuous water quantity monitoring to estimate contaminant/sediment loads. While monitoring/measuring errors are generally associated with the temporal variance of targeted contaminants/sediment and the relationship between discharge and concentration, little consideration is given to the impact of sediment structure and how this may impact sediment transport.

Sampling programmes have typically relied on the traditionally measured, chemically dispersed, mineral fraction to characterize sediment transport characteristics and for input to numerical models for the prediction of transport. These programmes implicitly or explicitly subscribe to the traditional definition of suspended sediment (i.e. the holding-up of small particles of matter, transported by moving water, by turbulent upward eddies). This traditional definition implies that sediment particles are individual entities with no other function than to be eroded, transported and settled within aquatic systems as individual non-cohesive particles. In today's multidisciplinary approach to ecosystem research and assessment, such a physically-based definition no longer represents the significance of suspended sediment within the environment as a physical, chemical and biological moderator of aquatic systems (Clifford, 2002). Flocs have been shown to be the dominant mode of transport within any aquatic system that carries a significant proportion of cohesive sediment (Petticrew & Droppo, 2000). Flocculation significantly alters the downward flux of sediments due to the cumulative effects of a change in the effective particle size, density, porosity and shape (Li & Ganczarczyk, 1987; Ongley *et al.*, 1992; Phillips & Walling, 1995; Nicholas & Walling, 1996; Droppo *et al.*, 1997, 1998) over that of the primary particle.

Settling velocity (measured, derived or assumed) is a key predictor within all sediment transport models. The knowledge that cohesive particles exist primarily as flocculated particles, and not as the traditionally viewed primary particle, complicates the quantification of particle (floc) settling velocity. The settling velocity/transport of sediment in aquatic systems is controlled to a degree by the structure of the sediment that in turn is influenced by the conditions prevailing in the fluid/sediment medium (e.g. shear, organic content, mineralogy of the sediment). The use of traditionally obtained absolute particle size distributions and Stokes' law derived settling velocities to characterize sediment in sediment transport models will result in erroneous results.

This paper represents a discussion on how the structural characteristics of flocs (floc size, density, porosity and compositional matrix) can influence the measurement and prediction of sediment transport. Towards this end, a new definition/paradigm of suspended sediment is proposed. This new definition provides a new way of thinking of suspended sediment and is intended to be the motivating factor towards the development of new techniques for the quantification of suspended sediment transport within aquatic systems. As this is a discussion paper centred on the general phenomenon of flocculation and how it may influence sediment transport in general, no detailed field descriptions and methods are provided. References to these are, however, provided where appropriate.

DISCUSSION

A typical floc structure that is composed of what would appear to be sub-flocs made up of thousands of other individual grains is provided in Fig. 1. It is evident that such a particle will be transported in suspension very differently than the primary absolute particles, due to significant differences in effective size, surface area, density, porosity, shape and settling velocity (Li & Ganczarczyk, 1987; Ongley *et al.*, 1992; Phillips & Walling, 1995; Nicholas & Walling, 1996; Droppo *et al.*, 1997, 1998). Given the obvious structural and behaviour differences, and the relative difference in mass

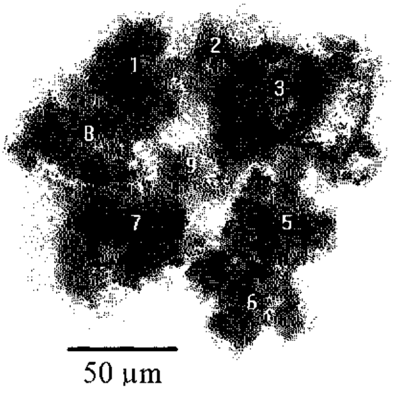

Fig. 1 An example of a floc illustrating a typical diffuse structure composed of thousands of individual grains. Visual observations subjectively suggest that this floc may have developed from 9 sub-flocs (identified on the figure).

transport between the two forms, it is evident that to understand and measure sediment transport correctly, sediment must be viewed and interpreted based on its natural flocculated state and not as absolute (primary) particles. This is particularly true given that: (a) flocculation of cohesive sediment is a universal phenomenon, and (b) that the floc is the dominant mode of sediment transport for rivers with a significant cohesive sediment load (Petticrew & Droppo, 2000).

The influence of floc size on sediment transport

The individual inorganic grains which make up the floc shown in Fig. 1 are on average approximately 5 μm in diameter with a corresponding Stokes' settling velocity of 0.02 mm s^{-1} (Fig. 2). If such particles were present exclusively within the water column (i.e. no flocs) then they would only settle within a quiescent environment (Hjulstrom, 1939). Direct measurement of floc settling velocity yields settling rates up to two orders of magnitude faster than the absolute particles (the majority of natural flocs settle in the range of 1.0 to 2.5 mm s^{-1}; Droppo *et al.*, 1997, 2000) (the method of settling velocity measurement can be found in Droppo *et al.*, 1997). The elevated settling velocity of flocs over constituent particles for a variety of environments and the consistent relationship of increased settling velocity with increasing floc size is illustrated in Fig. 2. The process of flocculation is the only phenomenon that can explain the presence of the cohesive particles on the bed of flowing environments. The mechanism of floc deposition and erosion has been described by Droppo *et al.* (2001) and Droppo & Amos (2001) to be a combination of the cyclic linkage between floc recycling and surficial fine grained lamina (SFGL) recycling.

As flocs become smaller, they approach the particle size of the constituent particles and as such Stokes' law may represent these particles adequately (Fig. 2). However, for large floc particles, Stokes overestimates settling velocity by orders of magnitude (Fig. 2) due primarily to the floc structure (Fig. 1) not supporting the solid spherical particle assumption assumed by the Stokes equation (Droppo, 2001).

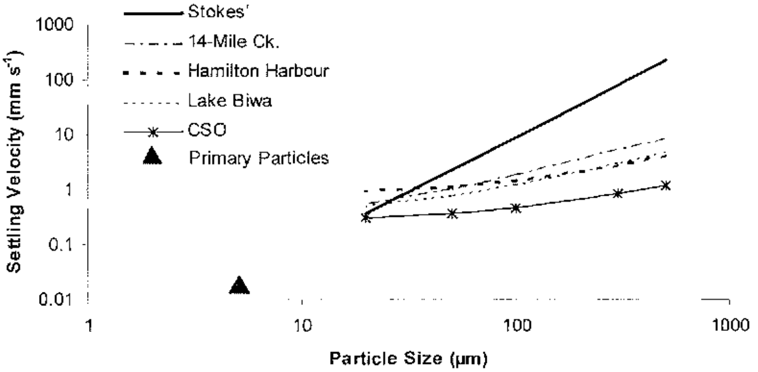

Fig. 2 Relationship between measured and calculated (Stokes) settling velocity and flocs (CSO = combined sewer overflow). Calculated settling velocity is also provided for a 5 μm primary particle. Note that a density of 2.65 g cm^{-3} has been used in the Stokes equation.

Given the inappropriateness of the Stokes equation for the calculation of floc settling velocity, this variable must be measured directly (Droppo *et al.*, 1997). Such measurements are, however, not without their problems as generically the r^2 of the least-squares regression lines are low owing to the wide range of morphologies and compositions of individual flocs. Nonetheless, direct measurement does allow for the assessment of the factors which influence settling, and has demonstrated a direct relationship between floc settling velocity and floc diameter. Such a relationship is counter to that prescribed in the Stokes equation (i.e. that particle settling velocity is proportional to the particle diameter squared) and is once again a testament to the structural and behavioural differences between flocs and primary particles.

Despite the above knowledge, primary particles are still the most common sediment parameter measured by sediment monitoring programmes. This arises from a lack of a standard defining equation to explain the process of flocculation and due to a lack of simple and cost effective standard techniques for the sampling, measurement and analysis of flocculated material. Given the primary particle's significantly different transport properties, it is evident that such measurements and models will yield erroneous results and that sediment management decisions based on primary particle characteristics will be flawed.

The influence of floc density and porosity on sediment transport

The impact of flocculation on the downward flux of sediment is in part related to the change in the effective density and porosity of the particles. As floc size increases the number of contacts between particles increases, thus increasing the porosity. Increasing porosity is linked to the concomitant effect of decreasing the density, due to the propensity for the pores to trap water within the floc. This negative relationship between floc size and density is consistent for all floc populations, regardless of environment (Fig. 3).

The significance of water trapping can be seen in Fig. 4 which illustrates the very small pores developed within the floc due to the secretion of extracellular polymeric

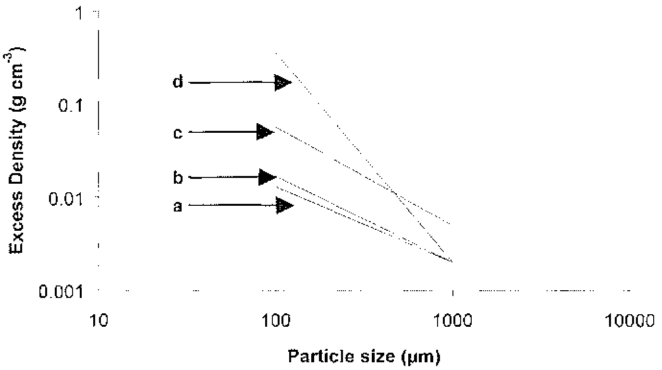

Fig. 3 Comparative results of excess density (wet density of the floc minus the density of the water) with floc size for different environments. a = Fennessy *et al.* (1994) (marine), b = Gibbs (1985) (estuarine) c = Hawley (1982) (lacustrine), d = Droppo *et al.* (2000) (river).

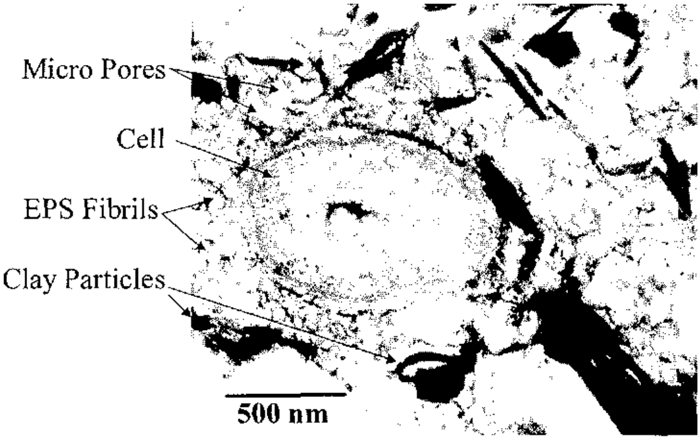

Fig. 4 Transmission electron microscope micrograph of a typical floc with inorganic and organic particle interactions.

fibrils (EPS) by the bacterial population of the flocs. The average diameter of an EPS fibril is 4–20 nm (Leppard, 1997) and as such, each pore will have a high surface tension for the retention of water. Large macro pores are possible within large open matrix flocs, with the effect of increased settling velocity due to the movement of free water through the floc pores reducing mechanical drag on the floc (Masliyah & Polikar, 1980). However, Liss *et al.* (1996) suggest that such macro pores may in fact be filled with EPS that cannot be seen by standard microscopic methods. In addition, given the likely "tumbling" nature of flocs transported in a turbulent environment, flow through pores as a result of vertical settling is likely to have a limited impact on floc settling.

While the floc properties of high porosity and low density will have some impact on the settling velocity of a floc, their significance is limited relative to that of floc size, due to: (a) the density of the floc being close to the density of the water (due to the high porosity of flocs) and (b) the range in floc densities being relatively small (Fig. 3). As such, a change in floc density/porosity will have a minimal impact on the settling velocity of a floc. This also suggests that water temperature effects on water density will have little mechanical impact on floc settling. However, temperature will influence floc development and structure (and therefore transport) by influencing the microbial community and its metabolic function (primarily EPS production).

The influence of overall floc structure/composition on sediment transport

In conjunction with flow characteristics, the transport of a floc is largely related to its complex composition and structural matrix. The above has discussed the gross scale influences of floc size, density and porosity on sediment transport. However, to fully understand the transport behaviour of a floc it is important to also examine floc structure and composition at the micro-scale. To this end, Droppo (2001) has broken the floc down into four different structural components: (a) inorganic particles (Fig. 5);

(b) biota and biorganic particles with an EPS sub-class (Figs 6 and 7); (c) pore structure (Fig. 8); and (d) water (Fig. 9). Each of these components have autonomous and yet linked physical, chemical and biological processes which will influence the sediment's transport within the water column. This section borrows heavily from the Droppo (2001) paper entitled "Rethinking what constitutes suspended sediment" and as such Figs 5–9 are reproduced with permission from this source (John Wiley and Sons Limited, ©2001).

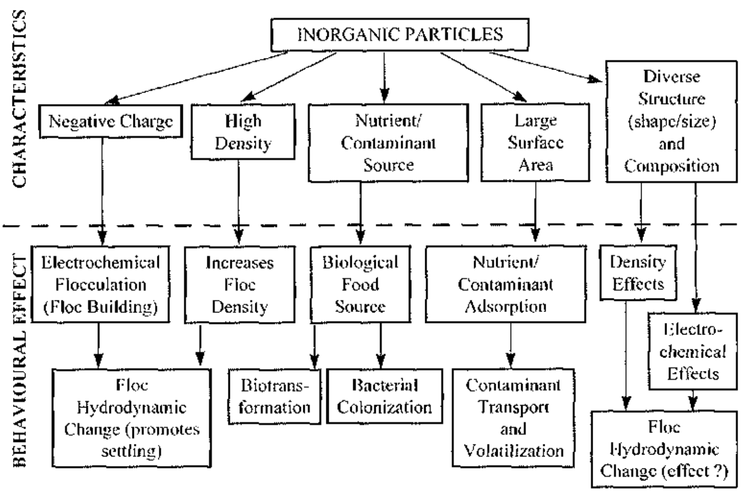

Fig. 5 The characteristics of inorganic particles that will influence the internal and external (transport) behaviour of flocs.

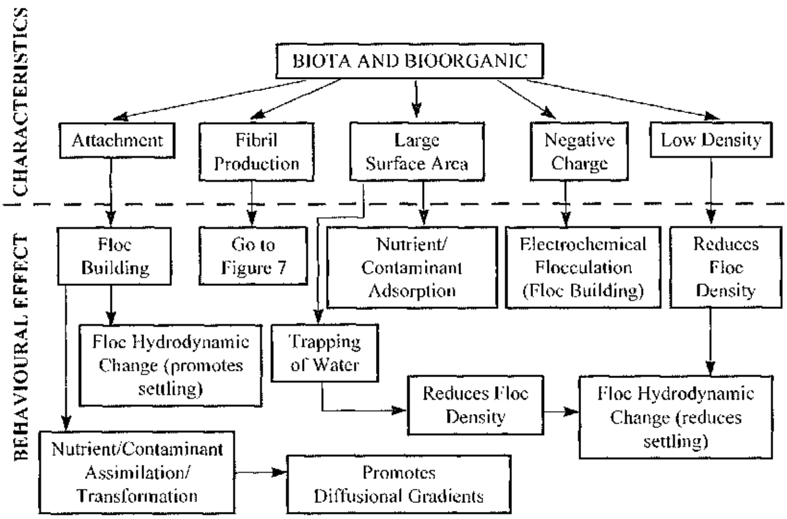

Fig. 6 The characteristics of the microbial community/organic particles that will influence the internal and external (transport) behaviour of flocs.

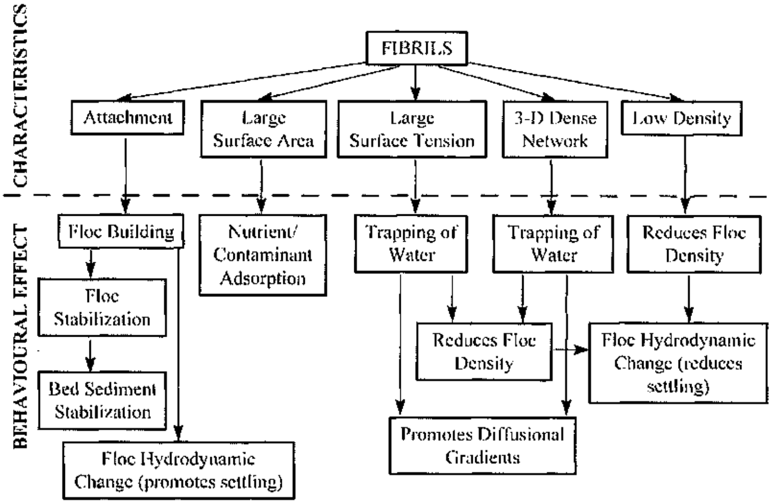

Fig. 7 The characteristics of microbial EPS fibrils and their influence on the internal and external (transport) behaviour of flocs.

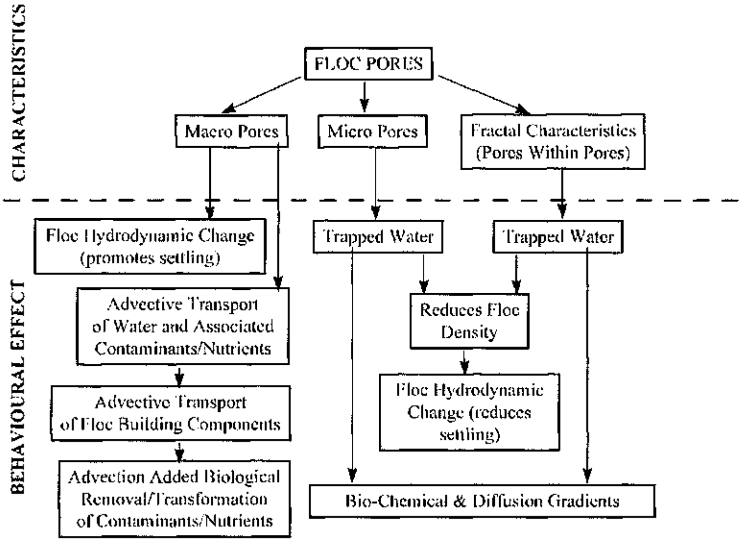

Fig. 8 The characteristics of water within a floc and its influence on the internal and external (transport) behaviour of flocs.

Figures 5–9 by Droppo (2001) are not intended to include all behaviour or structural/constituent characteristics for flocs. There are just too many to account for them all. Rather, this series of flow charts is intended to demonstrate the complex link between the physical, chemical and biological structures (gross and fine scale) of a floc, and the outward physical, chemical and biological behaviour. In this regard, information is provided in the figures demonstrating how various characteristics will influence floc building and the subsequent transport of sediment (hydrodynamic effects).

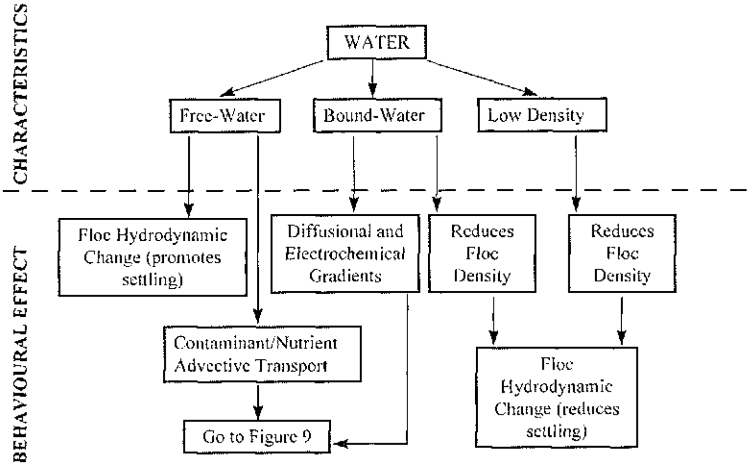

Fig. 9 The characteristics of floc pores and their influence on the internal and external (transport) behaviour of flocs.

Figures 5–9 also provide information on the chemical behaviour effects, such as the promotion of chemical diffusion, transformation and volatilization and biological behaviour, including nutrient and contaminant assimilation, transformation, and EPS production. These flow charts suggest that flocs can be viewed as individual microecosystems with autonomous and interactive, physical, chemical and biological behaviours operating within a floc matrix. The figures also suggest that the flocs are continuously interacting with their environment, as the medium in which they are transported provides the flocs with building materials, energy, nutrients and chemicals for biological growth, chemical reactions and morphological evolution. While flocs can function as individual microecosystems, they have also been shown to have an ability to regulate the surrounding water quality (Leppard, 1985; Decho, 1990).

There are too many structural and behavioural linkages within Figs 5–9 to expand on them all. As such, given that floc biology is believed to be the dominant factor in promoting, controlling, stabilizing and modifying the physical, chemical and biological behaviour of flocculated material (Decho, 1990; Liss *et al.*, 1996; Droppo, 2001), the role that bacteria play in floc development and transport is described here to demonstrate the complexity of the floc microecosystem. In the floc building process, bacteria will often preferentially attach to suspended particles, as this is a beneficial association for their survival, since the sediment represents physical protection and a food source due to adsorbed dissolved organic mater, nutrients and contaminants (Logan & Hunt, 1987, 1988). The main mechanism of attachment is through the bacteria's production of EPS that sticks the bacterium to the sediment (some bacteria have stock attachment). As the bacteria and the EPS are both "sticky" in nature, subsequent collisions in suspension will result in additional particles (organic and inorganic) entering into the floc matrix forming larger faster settling particles. Of course, floc breakage may also occur due to high shear forces. The EPS fibrils themselves are very fine and form dense porous networks within the floc. These fibrils will facilitate further nutrient and contaminant adsorption (further bacterial food source) due to their large surface area and the small pores will result in the trapping of water. The trapping of water reduces the floc density, with possible effects on floc settling in addition to promoting electrochemical and diffusion gradients within the floc (Costerton *et al.*, 1987). The bacteria themselves are of low density and, as such, a highly colonized floc will have a lower density than a less colonized floc, assuming similar floc sizes and compaction. As much of the EPS will be concentrated within the core of the floc (Liao *et al.*, 2002), it may also result in the occurrence of anaerobic processes within the floc and aerobic process on the outer edges of the floc, where the EPS is more diffuse. The cumulative effects of the above will also influence floc hydrophobicity (Finlayson *et al.*, 1998; Liao *et al.*, 2000), surface charge (Liao *et al.*, 2001, 2002), "stickiness" (Logan & Hunt, 1988; Logan, 1993) and organic coatings (with concomitant electrochemical and biological effects) (Gibbs, 1983; van Leussen, 1988; Muschenheim *et al.*, 1989). Although the above scenario is obviously oversimplified and difficult to quantify, it demonstrates that the floc does actually function as a microecosystem within aquatic systems.

CONCLUSION

The above discussion represents a new paradigm of suspended sediment which encompasses the knowledge that suspended sediment is not made up of discrete sediment particles, but rather of complex microecosystems (flocs) with an active biological community and microprocesses controlling the structure and transport of sediment. Droppo (2001) provides a useful definition of flocs. He states that a floc is an "individual microecosystem represented as a composite particle composed of a matrix of water, inorganic and organic (viable and non-viable) particles, with autonomous and interactive physical, chemical and biological functions or behaviours operating within the floc matrix". When suspended sediment is viewed as being composed of such "microecosystems", then our interpretation of the suspended sediment and the role that it plays within our environment changes. Not every sediment monitoring programme will need to assess sediment structure, nor will many programmes at this time have the ability to do so, however, this paradigm of suspended sediment is suggestive of a new way of thinking of suspended sediment and is intended to be the motivating factor towards the development of new techniques for the quantification of suspended sediment transport. Such developments will greatly improve our ability to effectively manage our water resources in the future.

Acknowledgements This paper was composed while the author was on a Leverhulme Trust Visiting Fellowship at the University of Exeter, Exeter, Devon, UK. The author would like to thank C. Jaskot, G. Leppard and M. West for assistance with image analysis.

REFERENCES

Clifford, N. J. (2002) Hydrology: the changing paradigm. *Prog. Phys. Geog.* **26**, 290–301.

Costerton, J. W., Cheng, K.-L., Geesey, G. G., Ladd, T., Nickel, J. C., Dasgupta, M. & Marrie, T. J. (1987) Bacterial biofilms in nature and disease. *Ann. Rev. Microbiol.* **41**, 435–464.

Decho A. W. (1990) Microbial exopolymer secretions in ocean environments: their role(s) in food webs and marine processes. *Oceanogr. Mar. Biol. Ann. Rev.* **28**, 73–153.

Droppo, I. G. (2001) Rethinking what constitutes suspended sediment. *Hydrol. Proc.* **15**, 1551–1564.

Droppo, I. G. & Amos, C. L. (2001) The structure, stability and transformation of contaminated lacustrine surface fine-grain laminae. *J. Sed. Res.* **71**, 718–727.

Droppo, I. G., Leppard, G. G., Flannigan, D. T. & Liss, S. N. (1997) The freshwater floc: a functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. *Water Air Soil Pollut.* **99**, 43–53.

Droppo, I. G., Walling, D. E. & Ongley, E. D. (1998) Suspended sediment structure: implications for sediment and contaminant transport modelling. In: *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes* (ed. by W. Summer, E. Klaghofer & W. Zhang) (Proc. Symp., Vienna, Austria July 1998), 437–444. IAHS Publ. 249.

Droppo, I. G., Walling, D. E. & Ongley, E. D. (2000) The influence of floc size, density and porosity on sediment and contaminant transport. In: *Role of Erosion and Sediment Transport in Nutrient and Contaminant Transfer* (ed. by M. Stone) (Proc. Symp., Waterloo, Canada, July 2000), 141–147. IAHS Publ. 263.

Droppo, I. G., Lau, Y. L. & Mitchell, C. (2001) The effect of depositional history on contaminated bed sediment stability. *Sci. Total Environ.* **266**, 7–13.

Fennessy, M. J., Dyer, K. R. & Huntley, D. A. (1994) INSSEV: An instrument to measure the size and settling velocity of flocs *in situ*. *Mar. Geol.* **117**, 107–117.

Finlayson, J. C., Liao, B., Droppo, I. G., Leppard, G. G. & Liss, S. N. 1998. The relationship between the structure of activated sludge flocs and the sorption of hydrophobic pollutants. *Water Sci. Technol.* **37**(4–5), 353–357.

Gibbs, R. J. (1983) Coagulation rates of clay minerals and natural sediments. *J. Sed. Petrol.* **53**, 1193–1203.

Gibbs, R. J. (1985) Estuarine flocs: their size, settling velocity and density. *J. Geophys. Res.* **90**(C2), 3249–3251.

Hawley, N. (1982) Settling velocity distribution of natural aggregates. *J. Geophys. Res.* **87**(C12), 9489–9498.

Hjulstrom, F. (1939) Transportation of detritus by moving water. In: *Recent Marine Sediments: a Symposium* (ed. by P. Trask) (Proc. Tulsa, Oklahoma, USA). Am. Assoc. Petroleum Geologists.

Leppard, G. G. (1985) Transmission electron microscopy applied to water fractionation studies – a new look at DOC. *Water Pollut. Res. J. Can.* **20**, 100–110.

Leppard, G. G. (1997) Colloidal organic fibrils of acid polysaccharides in surface waters: electron-optical characteristics, activities and chemical estimates of abundance. *Colloid Surf.* **120**, 1–15.

Li, D. H. & Ganczarczyk, J. (1987) Stroboscopic determination of settling velocity, size and porosity of activated sludge flocs. *Water Res.* **21**, 257–262.

Liao, B. Q., Allen, D. G., Droppo, I. G., Leppard, G. G. & Liss, S. N. (2000) Bound water content of activated sludge and its relationships to sludge retention time, floc structure and surface properties. *Water Environ. Res.* **72**, 722–730.

Liao, B. Q., Allen, D. G., Droppo, I. G., Leppard, G. G. & Liss, S. N. (2001) Surface properties of activated sludge and their role in bioflocculation and settling: extracellular polymeric substances, hydrophobicity and surface charge. *Water Res.* **35**, 339–350.

Liao, B. Q., Allen, D. G., Leppard, G. G., Droppo, I. G. & Liss, S. N. (2002) Interparticle interactions affecting the stability of sludge flocs. *J. Colloid Interface Sci.* **249**, 372–380.

Liss, S. N., Droppo, I. G., Flannigan, D. & Leppard, G. G. (1996) Floc architecture in wastewater and natural riverine systems. *Environ. Sci. Technol.* **30**, 680–686.

Logan, B. E. (1993) Theoretical analysis of size distributions determined with screens and filters. *Limnol. Oceanogr.* **38**, 372–381.

Logan, B. E. & Hunt, J. R. (1987) Advantages to microbes of growth in permeable aggregates in marine systems. *Limnol. Oceanogr.* **32**, 1034–1048.

Logan, B. E. & Hunt, J. R. (1988) Bioflocculation as a microbial response to substrate limitations. *Biotechnol. Bioeng.* **31**, 91–101.

Masliyah, J. H. & M. Polikar (1980) Terminal velocity of porous spheres. *Can. J. Chem. Eng.* **58**, 299–302.

Muschenheim, D. K., Kepkay, P. E. & Kranck, K. (1989) Microbial growth in turbulent suspension and its relation to marine aggregate formation. *Nether. J. Sea Res.* **23**, 283–292.

Nicholas, A. P. & Walling, D. E. (1996) The significance of particle aggregation in the overbank deposition of suspended sediment on river floodplains. *J. Hydrol.* **186**, 275–293.

Ongley, E. D., Krishnappan, B. G., Droppo, I. G., Rao, S. S. & Maguire, R. J. (1992) Cohesive sediment transport: Emerging issues for toxic chemical management. *Hydrobiologia* **235/236**, 177–187.

Petticrew, E. L. & Droppo, I. G. (2000) The morphology and settling characteristics of fine-grained sediment from a selection of Canadian rivers. In: *Contributions to IAP-V by Canadian Experts. IHP-V—Technical Documents in Hydrology*, 111–126. UNESCO Publ. no. 33, Paris, France.

Phillips, J. M. & Walling, D. E. (1995) An assessment of the effects of sample collection, storage and resuspension on the representativeness of measurements on the effective particle size distribution of fluvial suspended sediment. *Water Res.* **29**, 2498–2508.

Tsai, C. H., Iacobellis, S. & Lick, W. (1987) Flocculation of fine-grained lake sediments due to a uniform shear stress. *J. Great Lakes Res.* **13**, 135–146.

Van Leussen, W. (1988) Aggregation of particles, settling velocity of mud flocs: a review. In: *Physical Processes in Estuaries* (ed. by J. Donkers & W. van Leussen), 347–403. Springer, Berlin, Germany.