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Flocculation of suspended solids in southern Ontario rivers

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ABSTRACT Suspended solids play a primary role in fluvial transport of hydrophobic contaminants. The important components of the suspended load for geochemical transport are silts, clays and particulate organic carbon. The fluid mechanics of fine particles in natural systems are largely unknown because of the common presumption that fine-grained sediment moves as primary particles of silt and clay. Evidence suggests, however, that in many rivers primary particles travel and behave as larger particles due to flocculation. Using a river in southern Ontario, we examine the changes in floc size and shape between sites on the river and in a storm event. Results include methods for handling flocculated solids, a new sizing technique for flocs and substantive findings pertinent to physical modelling of fine particle transport in rivers.

INTRODUCTION

Sediment transport models normally assume that suspended solids are transported as primary particles (absolute particle size; Ongley et al., 1981). Recent findings illustrate that primary particles are frequently and perhaps characteristically transported as flocs within the aquatic medium. This observation may have substantial implications for fine grain sediment and pollutant transport models.

Flocs are a complex matrix of organic and inorganic material which appear as masses or clumps of numerous individual grains (Fig. 1A and B). The may often have planktonic cells (in whole or in part) present in the matrix (Kranck, 1973) and generally contain a representative portion of the fine fraction of the whole suspension (Kranck & Milligan, 1980). Flocs may range from very small sizes to very large matrices of up to a few centimeters in the marine environment (Kranck & Milligan, 1980). Flocculation has a significant effect on effective size, surface area, density, settling velocity and deposition rates of sediment (Tsai et al., 1987).

Flocculation is a dynamic process wherein flocs are in a continual state of change depending on the rate of aggregation and disaggregation of the particles (Zabawa, 1978). The rate of flocculation is dependent upon site specific variables such as fluid shear, suspended solids concentration, mineralogy and grain size distribution, dissolved chemicals and salinity, pH, temperature, particulate organic carbon, and biological organisms (Tsai et al., 1987 and Kranck, 1973). Each of these variables may behave in such a way so as to promote coagulation by phenomena such as collision, sorption and electrochemical flocculation. Despite the importance of sediment flocculation, the processes of aggregation and disaggregation of suspended sediments and their dependence on the above variables are not yet well understood. This is particularly true in the freshwater fluvial medium.

Here we discuss preliminary observations of flocculation in an Ontario river, including floc stability and a new methodology of measuring floc size and shape. The influence of a storm event on floc size and shape in comparison with average floc shape for the summer low flow period is determined. A comparison is made of variations in floc size between an upstream site of low pollution and a more polluted downstream site. Some visual findings of bacteria - floc relationship are also presented. The effect of fluid shear, grain size distribution, pH, temperature, and particulate organic carbon are under investigation but are not reported here.

MATERIALS AND METHODS

Our sizing methods are those developed for analysis of plankton; equipment includes settling chambers, inverted microscope with camera, slide projector and translucent digitizer. In general, a water sample is taken in a settling chamber; suspended solids settle onto a microscope slide within the chamber; photographs (transparencies) are taken of the settled solids through the microscope; the transparencies are projected onto a translucent digitizer and the flocs digitized for size and shape.

The only variable is settling chamber volume which varies in direct proportion to the suspended solid concentration. It is statistically important to utilize the proper chamber volume; too large a volume will result in overlapping of particles with concomitant errors in shape and over-estimation of particle size. Too small a volume results in an insufficient number of flocs for statistically significant counting.

A field turbidity value (NTU) is compared to a predeveloped rating curve of SS concentration, column volume and NTU. Column volumes of 50, 25, 10, 5 and 3 ml are capable of settling different SS concentration ranges with minimum overlap.

Floc Sampling

The fragility of flocs is thought to pose the greatest difficulty in obtaining a representative floc sample (Kranck, 1984; Kranck & Milligan, 1980; Gibbs & Konwar, 1982). Flocs are presumed to be in equilibrium with shearing (turbulent) forces in the water column. The act of sampling alters the turbulence conditions and may have a destructive effect on flocs (Kranck, 1979).

We believe it to be least destructive to flocs if suspended solid samples are collected directly in a settling chamber. The chamber was held under the surface of the water parallel to the direction of the current to reduce shearing. The chambers are filled to capacity, capped under water to reduce wave motion and transported to our laboratory for settling in an upright position. This transporting method was found by Cleary et al. (1987) to be the least destructive to soil aggregates suspended in water.

Floc Size and Shape Analysis

The method used to determine floc size and shape is a combination of microscopy, photography and digitization. The settling chamber slide is placed on an inverted Wild Leitz microscope and the flocs photographed in color at 100X magnification using a Zeiss 35 millimeter camera (Fig. 1A). Flocs are identified and digitized on the basis of Quinn's (1980) electron microscope work. Figure 1B illustrates a typical (laboratory prepared) freshwater floc. It appears similar in structure to those in Fig. 1A. Seventeen evenly distributed stage

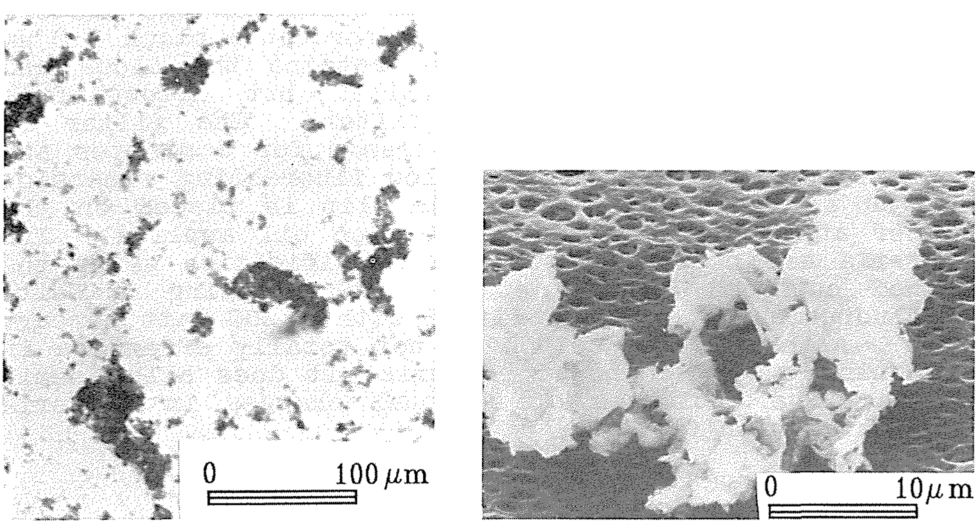

Fig. 1A Flocs photographed at 100X magnification.
Fig. 1B Freshwater floc aggregate (Quinn, 1980).

positions (fields of view) are used for all samples. A photograph of a known grid size (1/16 mm^2) is used as a standard grid scale reference for floc size and shape calculations. These slides were kept for later analysis.

Each transparency is rear-projected onto a translucent Scriptel digitizer and the flocs in each field digitized. An equivalent spherical diameter (D) and a shape factor (C) for each floc is calculated from the digital data as:

$$D_i = \sqrt{\frac{4A_i}{\pi}} \qquad (1)$$

where D_i = equivalent diameter of floc i and A_i = the digitized area of floc i. This permits calculations of size distributions.

$$C = (4\pi)(\text{AREA})/\text{PERIMETER}^2 \qquad (2)$$

This ratio of floc area to the area of a circle with the same perimeter as the floc, is close to 1.0 for a circular floc and close to 0.0 for a linear floc.

Floc-Bacteria Analysis

The analysis of bacterial associations with flocs uses a modification of Rao et al. (1984) for counting living and dead cells. Bacteria in freshwater and sediments are generally small, ranging from 0.3 to 0.7 µm in diameter (Hobbie et al., 1977). The flocs analyzed by the digitizer are far larger than this range. Bacteria in suspension are separated from the bacteria attached to the flocs by filtration. River samples are diluted into a known volume of low response type 1A reagent in order to produce an even distribution of solids on the filter. The sample and reagent is filtered through a black 1.0 µm Nuclepore filter. This process retains the flocs and floc-bound bacteria on the filter but allows free bacteria to pass through the filter. The filter is stained with 3 ml of acridine orange for 3 minutes and then placed on 1 drop of very low fluorescing immersion oil on a clean slide. A cover slip is placed on the filter and another drop of immersion oil applied. The bacteria are counted at 1562.5X magnification using the method outlined by Rao et al. (1984) using a Leitz epifluorescent microscope fitted with a 200 watt mercury lamp. Although this method is not totally effective in retaining only floc-bound bacteria, it does allow semi-quantitative estimates of seasonal changes in bacteria associated with flocs.

RESULTS AND DISCUSSION

A significant methodological problem is the degree of stability of flocs during sampling and in transport between field sites and the laboratory. This was examined by two separate experiments. In the first experiment, photographs of specific stage positions were taken of a laboratory settled sample (control sample). The control slide was driven a normal sampling distance in a car after which the same stage positions were photographed. Before and after photos revealed that the flocs remain stationary on their slide during transport and did not break up due to the vibrations of the road. A two sample two tail T-test with a 95% confidence interval for floc areas confirmed that there was no significant difference in the mean areas of the control and transported floc photos.

In the second experiment, two identical chambers (10 ml) were filled with the same river grab sample. One was allowed to settle in the laboratory while the other was driven around during which time the flocs were in the process of settling. The same stage positions for each column had their photos taken. A two sample two tail T-test with a 95% confidence interval for floc areas revealed that there was no significant difference between the floc areas. We infer that flocs should remain relatively stable during sampling and transportation.

The measured size of flocs is a 2-dimensional representation of a 3-dimensional structure. Therefore the size of the floc in the photo is highly dependent on the depth of field and focussing of the microscope. To test the effect of shifts in focus on floc size a number of photos were taken of the same flocs in and out of focus. A two sample two tail T-test with a 95% confidence interval indicates no significant difference between the floc area means of two slides in and out of focus. Hence small variations in the depth of field tend to have little effect on the statistical analysis of floc size.

This method of sizing and shape determination is not capable of replicating grain size distributions produced by automatic sizing techniques such as the Malvern laser particle analyzer. Figure 2 compares the primary grain size distribution of a granite till as measured both by the Malvern laser instrument and by microscopy/digitizing. A factor which limits representation by digitization is sample size. Direct comparability of the two techniques should not, however, be expected due to the wholly different nature of the techniques as a result of simplifying assumptions used in Malvern (and other) technology such as sphericity of particles. Only digitization permits direct measurement of floc shape.

Two sample sites on the Oakville Sixteen Mile Creek were used to examine the effect of variation of those variables believed to control flocculation. The first site, 22 km upstream from the mouth, is in a primarily rural, forested area which receives no sewage effluent. The second site, located in the harbour, is surrounded by an urban area of approximately 50 km^2 and receives treated sewage effluent and stormwater runoff. The results presented here are for the summer low flow period only.

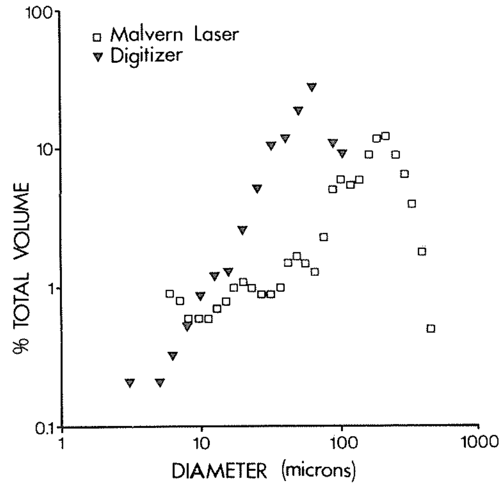

Fig. 2 Comparison of the Malvern laser particle sizer and the digitizer in producing grain size distributions.

Preliminary results show that while there are far fewer flocs than primary particles in suspension (flocs only compose 10 to 27% of the total number of particles) the flocs comprise over 90% of the total suspended solid volume (results range from 92 to 98%). This is consistent with earlier estuarine findings by Schubel & Kana (1972) who found that flocs of 3 primary grains or more made up only 11% of the total number of particles but nearly 97% of the total sediment volume.

An analysis of floc size between sites revealed that there was no significant difference in floc area (two sample two tail T-test, 95% confidence) for 5 August 1988. A possible explanation, and contrary to expectations, may be the lack of a significant difference in particulate organic carbon between the sites. The significance of an increase in Cl^-, SO_4^{2-} and Na^+ for the harbour site is not yet known. As we have no direct measure of turbulence (shearing forces) we cannot speculate on the resistance of flocs to potential differences in turbulence between sites.

The higher suspended solid concentration of the harbour (2.8 times higher than the upstream site) does not appear to have an effect on floc size (on 5 August 1988). This contradicts Tsai's et al. (1987) findings that a high suspended solid concentration will result in smaller floc sizes.

Storm events appear to influence floc size. During a dry period (5 August 1988) mean floc area at the upstream site was 173.5 μm^2. After a high intensity rainstorm lasting approximately 45 minutes, followed by light rain on 11 August 1988, mean floc area decreased to 94.97 μm^2. This difference is statistically significant and is possibly attributed to an increase in turbulence during stormflow resulting in greater shearing of the flocs. According to Tsai et al. (1987) the increased suspended solid concentration during the storm event (2.5 times that of the dry period) should be a contributing factor in smaller floc size. This is, however, disputed by other researchers such as Partheniades (1986) who feel that the opposite will occur. Although our dry weather sample contradict Tsai et al. (1987), additional data are needed to resolve this issue. In addition, we also observed a shift to lower values for major ions during the storm event which may affect floc size.

The analysis of floc shape, for a combined total of over 1000 flocs from both sites during a low flow period revealed that the flocs tend to be closer to a circular shape than to an elongated shape. The mean shape factor was 0.702. A two sample two tail T-test illustrated that there was no significant difference in floc shape between the upstream and harbour sites. The floc shape analysis for the storm event revealed more elongated flocs with a ratio of 0.656. This was significantly different than floc shape for the dry flow period.

The role of bacteria in suspended solid flocculation is believed to be very significant as demonstrated by a number of researchers (e.g., Zabawa, 1978; Schubel & Kana, 1972). Their ability to stabilize the floc structure and to build larger flocs relates largely to the ability of some bacteria to secrete an extracellular fibrillar polymer which binds particles together and traps others (Zabawa, 1978). There may also be an electrostatic attraction of positively charged cells to predominantly negative surface charges of suspended solids (Marshall, 1971). The bacteria's ability to sorb onto particles varies with the physical and chemical composition of the particles, and with the species and

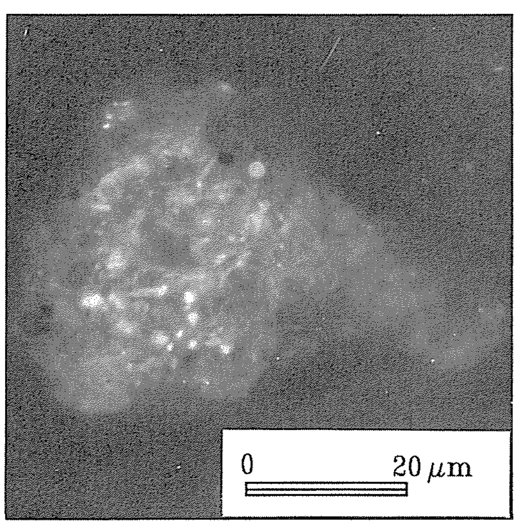

Fig. 3 Photograph of a floc colonized by bacteria (1562.5X magnification).

growth environment of the microorganisms (Marshall, 1971). Figure 3 illustrates a floc which is highly colonized by bacteria (the bright fluorescing dots and rods). There is not yet enough data to present any statistical summary of bacteria counts relative to floc size.

CONCLUSION

While the digitizing method has some limitations especially for grain size distributions, it is very useful in evaluating physical and biological controls over flocculation. The methods of sampling and handling appear to maintain floc structure and is adequate for analysis of floc size and shape. We have demonstrated a method for investigating the relationship of bacteria with suspended solids. The effect of a storm event on mean floc size and shape relative to low flow is illustrated. Future data will provide primary information for more accurate characterization of fine particle transport in rivers.

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