The Prevalence of Freshwater Flocculation in Cold Regions: A Case Study from the Mackenzie River Delta, Northwest Territories, Canada

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ABSTRACT. The Mackenzie River Delta (MRD) is used as a case study for evaluating the extent to which flocculation may play an important role in the transport of sediment and associated contaminants in arctic regions. Samples were collected for nondestructive analysis of particle/floc size, major ions, particulate organic carbon (POC), dissolved organic carbon (DOC), bacterial counts, and suspended solid (SS) concentrations. On-site measurements were made for pH, conductivity, and temperature. Results indicate that the dominant form of sediment transport to and within the MRD is flocs, and not traditionally sized primary particles. It is shown that the flocs of the Mackenzie Delta are at times larger in size than those in southern Ontario rivers that have been studied. The sediment distributions were bimodal in nature; the particle-deficient zone potentially represented a preferential particle size for flocculation. Spatial and temporal trends in the grain-size distributions suggest site-specific controlling factors of flocculation, such as source area and sediment characteristics. It is hypothesized that water temperature, suspended solid concentration, and bacteria are the important factors in controlling flocculation within the Delta.

Key words: flocculation, suspended sediment, grain-size distribution, bacteria, transport

INTRODUCTION

The existence of flocculation within the freshwater fluvial environment has been known for some time; however, its significance to sediment and contaminant transport has only recently been explored (e.g., Droppo and Ongley, 1992, 1994; Phillips and Walling, 1995; Nicholas and Walling, 1996; Petticrew, 1996; Droppo et al., 1997). Flocculation is the process whereby smaller particles (inorganic and organic), water-stable soil aggregates, or flocs aggregate to form larger particles (flocs) in a flowing medium. The formation of flocs is a complicated process that is driven by a combination of mechanisms, physical (e.g., turbulence), chemical (e.g., ionic concentration), and biological (bacterial populations and extracellular polymeric material). The flocculation process is significant for sediment and contaminant transport, because it alters the hydrodynamic characteristics of suspended sediment: the effective particle sizes, shapes, porosity, density, water content, and compositional matrices of flocs differ significantly from those of the traditionally assumed primary particles (Droppo et al., 1997). Flocculation also alters the chemical and biological behaviour of sediment in terms of how it interacts with contaminants and the biological community and how it alters or degrades the contaminants or nutrients assimilated within or around the floc. In effect, a floc can be considered a micro-ecosystem capable of modifying not only itself but the aquatic environment as a whole (Liss et al., 1996; Droppo et al., 1997).
Freshwater fluvial sediment studies in arctic climates have focused primarily on delta-building through sedimentation and erosion (Rosenberg and Barton, 1986; Lewis, 1991), contaminants, sediment budgets, and sediment transport (e.g., Gilbert, 1980; Mackiewicz et al., 1984; Ferguson and Marsh, 1991; Jenner and Hill, 1991; Yunker et al., 1993, 1995; Yunker and MacDonald, 1995). Very little comprehensive information is available on the phenomenon of flocculation and how it relates to sediment and contaminant transport in freshwater Arctic regions. In late spring during the mid 1980s, the late Dr. Kate Kranck, a well-known expert on flocculation, visited the Liard River at its confluence with the Mackenzie River at Fort Simpson to examine flocculation. Sediment concentrations were too high to use her Benthos Plankton Camera, but her visual observations at the time (E. Ongley, pers. comm. 1996; T. Milligan, pers. comm. 1997) indicated that a phenomenon which she referred to as “roiling” was occurring. Roiling produces an oil-like sheen on the water surface caused by completely dispersed inorganic clay particles. Dr. Kranck concluded that no flocculation was occurring on the Liard River at the time of her observations. Further towards and within the Mackenzie River Delta (MRD), she suggested that flocculation of the sediment was occurring (T. Milligan, pers. comm. 1997). Other than these unpublished observations, work that has addressed flocculation in cold climates has generally focused on salt/brackish water fjord environments (e.g., Winters and Syvitski, 1992; Domack et al., 1994).

Through a field survey of suspended solids in the MRD, we examine the importance of flocculation as a mechanism influencing sediment transport in the MRD. This paper discusses the significance of flocculation and the factors that control it on the MRD, compares our results to those of previous flocculation studies on rivers from southern Ontario (Canada), and draws inferences from associated observations of in-stream chemical, biological, and physical characteristics and from “between site” differences in floc size and related data.

**MATERIALS AND METHODS**

**The Mackenzie River**

The Mackenzie River (Fig. 1) is the largest north-flowing river in North America, draining 1.787 x 10^6 km^2 with a mean annual discharge of approximately 10 000 m^3/s and an annual sediment load delivered to the Arctic Ocean of 118 x 10^6 tonnes (Brunskill, 1986; Rosenberg and Barton, 1986). The river basin extends over four physiographic regions (the Western Cordillera, Interior Plain, Precambrian Shield, and Arctic Coastal Plain), and much of the basin is underlain by permafrost (Fig. 1). The climate is either tundra (NE region and the high Cordillera) or subarctic; the river remains under ice cover from late September to late June in the northern part of the basin (Rosenberg and Barton, 1986). The northern third of the MRD supports very few trees, while the southern region supports a boreal forest (Brunskill, 1986).

**The Mackenzie River Delta**

The Mackenzie River Delta (MRD) is the largest in Canada, extending over an area of approximately 12 170 km^2 (Fig. 2). The MRD receives 300 – 350 km^3 of water and 120 x 10^6 tonnes of suspended sediment annually (two million tonnes are deposited in the delta annually). Flow within the delta is primarily within three main channels. Two-thirds of the flow discharges through the Middle Channel into a large distributary system; one-sixth of the flow is through the East Channel (the easternmost channel); and the final one-sixth flows through the West Channel (fed mostly by the Peel, Rat, and Big Fish Rivers). Spring/summer breakup on the Peel, Rat, and Big Fish Rivers generally occurs one to two weeks earlier, causing the West Channel to open up sooner than the Middle or East Channel. Up to 95% of the delta is flooded at this time of year because of ice and log jams. Even with such immense flows, the channels of the MRD appear to have remained quite stable since their original mapping in 1826 by the Franklin Expedition (Brunskill, 1986). This stability likely reflects the influence of permafrost in armouring the river banks against significant erosion and suggests that the significant suspended sediment loads of the MRD owe their origin to southern regions of the Mackenzie River and not to the MRD itself.
Sample Sites

Three freshwater sampling locations were chosen (Arctic Red River, Aklavik, and Inuvik) to provide a range of sediment and flow conditions while affording good accessibility (Fig. 2). The Arctic Red River site provides information on sediment characteristics entering the MRD from the main trunk of the Mackenzie River. The monthly mean discharges during the open water season (time of sampling) at this site range from 11 400 to 21 200 m³/s (Environment Canada, 1992a). The total mass of suspended sediment passing this site during open water season is on average $76.5 \times 10^6$ tonnes (Environment Canada, 1992b). The Aklavik and Inuvik sites provide information on characteristics of the sediment from within the MRD (West and East Channel, respectively). At Aklavik, monthly mean discharges (during open water season) range from 970 to 455 m³/s, with an average of $3.82 \times 10^6$ tonnes of sediment passing the site from June to September (Environment Canada, 1992a, b). (This site is fed mostly from rivers other than the Mackenzie River). Inuvik has monthly mean discharges (during open water season) ranging from 481 to 163 m³/s, with an average of $1.35 \times 10^6$ tonnes of sediment passing the site from June to September (Environment Canada, 1992a, b).

Sediment Sampling and Particle (Floc) Distribution Determination

All samples were collected from a boat in the centroid of flow irrespective of stage. Sampling occurred over the summer of 1993, with samples taken on 23 June, 27 July, and 7 September for the Inuvik site; 23 June, 29 July, and 8 September for the Aklavik site; and 28 July and 9 September for the Arctic Red River site. No June sample was collected for Arctic Red River.

In order to minimize particle breakage and modification resulting from collection and storage of samples within bottles, water/sediment samples were collected directly within plankton chambers (which double as sampling and analytical chambers) by submerging the column portion of the chamber below the surface, parallel to the direction of flow. The volume of the column (5, 10, 25, or 50 ml) used was dependant on the concentration of suspended solids (Droppo and Ongley, 1992). The column was then capped at both ends (under water) and inverted upright at which point the sediment settled down onto a microscope slide chamber. Once the particles had settled, the column could be removed, leaving only the microscope slide chamber and a small volume (3 ml) of water. If sediment concentrations were high (> 100 mg/l), then only the microscope slide chamber was used for sampling. Keeping the chamber flat and air free prevented the particles from interacting or breaking up. While the time between sampling and analysis ranged from 1 to 3 weeks, Monahan (1997) has shown that, at the observation scale used in this study, no significant change in distribution over time would be expected.

The microscope slide chambers were carried by hand back to the image analysis laboratory at the National Water Research Institute. The flocs were imaged (sized) down to a lower resolution of approximately 2 µm (10× objective) using a Zeiss Axiovert 100 microscope interfaced with a 35 mm camera. Seventeen evenly distributed slides (photographs) were taken of the settled sediment. Each slide was rear-projected onto a Scriptel translucent digitizer, where the perimeters of the particles (primary and flocs) were digitized to yield equivalent spherical diameter. One to three thousand particles were imaged (with primary particles and flocs differentiated), and the distributions were presented as percent by number (i.e., the percentage of total number of particles per size class). All organic and inorganic particles and flocs were included in this distribution, as differentiation was not possible at this magnification. Particles were defined as flocs if they were composed of two or more organic or inorganic particles.

Chemical, Biological, and Physical Analysis

All major ions, particulate organic carbon (POC), and dissolved organic carbon (DOC) were analyzed by the National Laboratory for Environmental Testing following the methods of Environment Canada (1979). Conductivity, pH, and temperature were derived in the field using standard meters. Suspended solid (SS) concentrations were determined by filtering a known sample volume onto a tarred 0.45 µm Millipore filter. Bacterial counts (free-floating and attached) were derived for the September samples only by using a modification of...
TABLE 1. The significance of flocs in relation to the total number and volume of particles in suspension for the Mackenzie River Delta.

<table>
<thead>
<tr>
<th>Date</th>
<th>Inuvik</th>
<th>Aklavik</th>
<th>Arctic Red River</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flocs as % of total</td>
<td>Flocs as % of total</td>
<td>Flocs as % of total</td>
</tr>
<tr>
<td></td>
<td>no. of particles</td>
<td>vol. of particles</td>
<td>no. of particles</td>
</tr>
<tr>
<td>June</td>
<td>48.8</td>
<td>98.8</td>
<td>49.9</td>
</tr>
<tr>
<td>July</td>
<td>66.4</td>
<td>99.9</td>
<td>60.0</td>
</tr>
<tr>
<td>September</td>
<td>47.2</td>
<td>99.2</td>
<td>51.4</td>
</tr>
</tbody>
</table>

TABLE 2. The significance of flocs in relation to the total number of particles in suspension and to the total volume of suspended solids from various rivers in southeastern Canada (reproduced from Droppo and Ongley, 1994).

<table>
<thead>
<tr>
<th>River</th>
<th>Sampling Date</th>
<th>Flocs as % of total</th>
<th>no. of particles</th>
<th>vol. of suspended solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Otter Creek</td>
<td>12 Aug 1991</td>
<td>56.6</td>
<td>99.6</td>
<td></td>
</tr>
<tr>
<td>Big Creek</td>
<td>12 Aug 1991</td>
<td>43.1</td>
<td>98.6</td>
<td></td>
</tr>
<tr>
<td>Grand River</td>
<td>6 Nov 1990</td>
<td>48.7</td>
<td>99.9</td>
<td></td>
</tr>
<tr>
<td>Nith River</td>
<td>12 Aug 1991</td>
<td>42.7</td>
<td>98.9</td>
<td></td>
</tr>
<tr>
<td>Sixteen-Mile Creek, Site 1</td>
<td>15 Jun 1988 to 01 Apr 1989</td>
<td>22.5–27.0</td>
<td>95.8–97.0</td>
<td></td>
</tr>
<tr>
<td>Sixteen-Mile Creek, Site 2</td>
<td>15 Jun 1988 to 01 Apr 1998</td>
<td>9.7–12.0</td>
<td>92.0–95.9</td>
<td></td>
</tr>
<tr>
<td>St. Lawrence River, N. Shore</td>
<td>05 Jun 1990</td>
<td>38.3</td>
<td>99.4</td>
<td></td>
</tr>
<tr>
<td>St. Lawrence River, Centre</td>
<td>05 Jun 1990</td>
<td>30.1</td>
<td>99.8</td>
<td></td>
</tr>
<tr>
<td>St. Lawrence River, S. Shore</td>
<td>05 Jun 1990</td>
<td>38.1</td>
<td>99.9</td>
<td></td>
</tr>
</tbody>
</table>

Goulder’s (1976), acridine orange, epifluorescence technique, as described in detail by Droppo and Ongley (1994). This method allows for the separation of free-floating and attached bacteria by passing a sample of sediment/water consecutively through black 1.0 μm and 0.1 μm Nuclepore filters. Sediment/flocs and the attached bacteria were retained on the 1.0 μm filter, while the free-floating bacteria passed through it and were retained on the 0.1 μm filter. Bacterial counts associated with the suspended solids were doubled to yield an attached-bacteria population, as only bacteria on the top side of each particle or floc can be counted. Attached-bacteria counts are a best estimate, as some free-floating bacteria may settle on the sediment during filtration, and bacteria embedded within the matrix of a floc may be missed. Likewise, free-floating bacteria populations may be underestimated because sediment particles settle on top of those free-floating bacteria that are trapped by the 1.0 μm filter. Although this method is not completely effective in separating sediment-bound and free-floating bacteria, it does allow for semiquantitative estimates of bacterial populations.

RESULTS AND DISCUSSION

It is now well documented that fluvial suspended sediment is preferentially transported in a flocculated (aggregated) form (Droppo and Ongley, 1994; Phillips and Walling, 1995; Petticrew, 1996; Droppo et al., 1997). The MRD did not prove exceptional. Table 1 demonstrates that flocs are a significant component of the MRD’s SS transport regime: close to 100% (by volume) of the SS is transported as flocculated material. It also appears that the SS transported in the MRD is more highly flocculated than in some southeastern Canadian rivers (Droppo and Ongley, 1994), as the MRD transports 10 to 40% more flocculated particles (related to the total number of particles transported) and possesses larger flocs (floc d50 [medium particle size] by number > 14 μm compared to < 10 μm from Droppo and Ongley [1994]) than the rivers in southeastern Canada (Table 2). This observation supports Kate Kranck’s visual observation that flocculation was occurring in the MRD (T. Milligan, pers. comm. 1997). This finding has significant implications, as flocculation significantly alters the hydrodynamic characteristics of sediment in suspension by modifying its effective grain size, density, porosity, and water content (Krishnappan, 1990; Ongley et al., 1992; Nicholas and Walling, 1996; Droppo et al., 1997). In general, a floc will settle much faster in a given flow (assuming no disaggregation) than its constituent primary particles (Ongley et al., 1992; Droppo et al., 1997), hence significantly modifying the fate of sediments.

The significance of flocculation within the MRD’s suspended sediment can be seen by sizing the sediment before and after particle disaggregation by sonication (Fig. 3). Sonication has the effect of significantly shifting (disaggregating) the distribution (Fig. 3) towards smaller particle sizes (significant difference at α = 0.5, Modified Kolmogorov-Smirnov test, Goldman and Lewis, 1984). Similar results have been observed in temperate climates (Droppo and Ongley, 1994; Irvine, et al., 1995).
1997), the use of such a disaggregated distribution to charac-

terize sediment for sediment and contaminant transport mod-

eels within the MRD could result in erroneous results. It is

likely that models based on these traditional absolute grain

sizes would overestimate storm/snowmelt event contaminant

and sediment loadings to receiving water bodies, since finer

particles will be transported further in a turbulent flow than

larger flocculated particles (Ongley et al., 1992). It is there-

fore imperative that future researchers examine the “true”

particle size distribution of the MRD sediment when examin-

ing sediment- and contaminant-related issues for the delta.

Further evaluation of the “true” distributions indicates that

two populations of sediment are present in all of the MRD

samples (Fig. 4): a primary particle population and a

flocculated population. The bimodal distribution shows a

particle-deficient zone in the 7 –10 µm size range. This result

is similar to that reported by Droppo and Stone (1994) and

Stone and Saunderson (1992) for southern Ontario rivers,

except that their particle-deficient zones were in a smaller

size range (3 –6 µm). These particle deficiencies may be

related to (a) preferential flocculation of this size range; (b)

selective erosional processes resulting in a general absence of

soil aggregates in this size range; (c) the methodology to
determine particle size distribution; (d) a natural sorting

process; and (e) a general deficiency of silt-sized primary

particles in this size range (Stone and Saunderson, 1992). As

primary particles and flocs are differentiated by the optical

methods used (Fig. 4), the 7 –10 µm deficiency may represent

a transition point between primary and flocculated particles

and a possible preferential particle size range for flocculation

(Fig. 4). The rapid reduction in particle numbers in the 6 to

8 µm range and the absence of primary particles larger than

approximately 10 µm (Fig. 4) suggests a potential threshold

at which all particles above 10 µm are flocculated particles

(Droppo and Stone, 1994). This evidence tends to support (a)

above as the possible reason for the observed particle-defi-
cient size range. Figure 4 also suggests that any particles

below approximately 2.5 to 3 µm in size are incorporated into

flocs, although this result could be an artifact of the method-

ology (lower resolution –1 to 2 µm). Higher resolution

microscopic techniques, such as transmission electron

microscopy will be required to elucidate these issues.

Because of the limited data set for this work (a result of
distance, cost, and limited supplies), no statistical analysis

between or within sites such as that provided in Droppo and

Ongley (1994) is possible. The analysis is thus limited to

qualitative assessments. However, we can observe some

apparent trends in the flocculation nature of the MRD and

hypothesize possible explanations qualitatively.

The d₅₀ values for the floc and total distributions were

largest in the July samples at all three sites (Table 3). This may

reflect an adequate supply of SS for particle-to-particle inter-
duction (collisions resulting in flocculation) (Table 4), al-

though July did not have the highest SS concentrations.
FIG. 4. Bimodal distribution of suspended sediment from the July samples at each site. The distribution is divided, showing autonomous primary particles and flocs separately by particle size (in microns) within the sample.

TABLE 3. d_{50} values for the primary particles, flocs, and total distributions (primary + flocs) of SS samples for the Mackenzie River Delta.

| Date     | Inuvik          | Arctic Red River
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary (µm)^1</td>
<td>Total (µm)^1</td>
</tr>
<tr>
<td>June</td>
<td>5.9 15.4 8.2</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>5.7 22.6 15.9</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>3.6 14.6 5.1</td>
<td></td>
</tr>
</tbody>
</table>

\(^1 = d_{50}\) values of those particles present on the microscope slide in their primary form only.

\(^2 = d_{50}\) values of those particles present on the microscope slide in their flocculated form only.

\(^3 = d_{50}\) value of the total distribution (combined primary and flocculated particles).

Electrochemical flocculation does not appear to be a dominant factor, as the July samples had major ion concentrations below those of the September samples (Table 5). Contrary to traditional thinking (van Olphen, 1963; Tsai et al., 1987), conductivity and many of the major ions (Table 5) exhibit many negative relationships with total and floc median diameters. This further suggests a lack of importance of major ions in the flocc-building process for the MRD. In addition, the variations within the major ions between both sample dates and sites (Table 5) are small and generally within the range of those variations created experimentally by Tsai et al. (1987), who found that small variations in ionic strength did not affect the steady-state d_{50}. Thus, the degree of variability in water chemistry exhibited within the MRD is not expected to influence floc size. DOC was highest for the July samples at Aklavik and Arctic Red River, with Inuvik showing a moderately high level. POC showed higher variability with no real trends associated between sites and sampling dates. Water temperatures were the highest in July for all sites (Table 4). Although the POC, which incorporates bacteria populations, showed no trends, the warmer temperatures may increase metabolism and the production of extracellular polymeric substances (EPS) (Droppo and Ongley, 1994). In addition, as DOC (commonly absorbed onto particulate matter) is the
TABLE 4. Physical and biological data for the sampling sites of the Mackenzie River Delta.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>SS conc. (mg l⁻¹)</th>
<th>POC (mg l⁻¹)</th>
<th>DOC (mg l⁻¹)</th>
<th>pH</th>
<th>Temp. (°C)</th>
<th>Bacterial counts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>attached counts ml⁻¹</td>
</tr>
<tr>
<td>Inuvik</td>
<td>23 Jun 1993</td>
<td>155.0</td>
<td>5.700</td>
<td>8.8</td>
<td>8.75</td>
<td>12.8</td>
<td>5.97 × 10⁵</td>
</tr>
<tr>
<td></td>
<td>27 Jul 1993</td>
<td>70.8</td>
<td>1.580</td>
<td>7.8</td>
<td>8.46</td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>07 Sep 1993</td>
<td>62.8</td>
<td>1.300</td>
<td>7.6</td>
<td>7.84</td>
<td>12.3</td>
<td>5.97 × 10⁵</td>
</tr>
<tr>
<td>Aklavik</td>
<td>23 Jun 1993</td>
<td>76.0</td>
<td>0.056</td>
<td>4.5</td>
<td>8.75</td>
<td>13.4</td>
<td>5.66 × 10⁵</td>
</tr>
<tr>
<td></td>
<td>29 Jul 1993</td>
<td>31.2</td>
<td>0.734</td>
<td>6.3</td>
<td>8.79</td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>08 Sep 1993</td>
<td>107.0</td>
<td>2.450</td>
<td>5.6</td>
<td>7.80</td>
<td>9.5</td>
<td>6.89 × 10⁵</td>
</tr>
<tr>
<td>Arctic Red River</td>
<td>28 Jul 1993</td>
<td>107.0</td>
<td>2.160</td>
<td>7.4</td>
<td>8.57</td>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>09 Sep 1993</td>
<td>60.0</td>
<td>2.140</td>
<td>5.3</td>
<td>7.83</td>
<td>13.1</td>
<td>6.89 × 10⁵</td>
</tr>
</tbody>
</table>

TABLE 5. Conductivity and major ion data for the sampling sites of the Mackenzie River Delta.¹

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Conductivity (µS cm⁻¹)</th>
<th>Ca (mg l⁻¹)</th>
<th>Mg (mg l⁻¹)</th>
<th>Na (mg l⁻¹)</th>
<th>K (mg l⁻¹)</th>
<th>SO₄ (mg l⁻¹)</th>
<th>Cl (mg l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inuvik</td>
<td>23 Jun 1993</td>
<td>228</td>
<td>28.86</td>
<td>7.26</td>
<td>4.54</td>
<td>0.39</td>
<td>29.0</td>
<td>5.40</td>
</tr>
<tr>
<td></td>
<td>27 Jul 1993</td>
<td>189</td>
<td>32.10</td>
<td>8.50</td>
<td>6.40</td>
<td>0.90</td>
<td>42.0</td>
<td>7.03</td>
</tr>
<tr>
<td></td>
<td>07 Sep 1993</td>
<td>293</td>
<td>34.47</td>
<td>8.87</td>
<td>7.63</td>
<td>0.94</td>
<td>41.7</td>
<td>7.90</td>
</tr>
<tr>
<td>Aklavik</td>
<td>23 Jun 1993</td>
<td>290</td>
<td>35.76</td>
<td>11.33</td>
<td>3.00</td>
<td>0.57</td>
<td>61.7</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>29 Jul 1993</td>
<td>249</td>
<td>44.90</td>
<td>14.60</td>
<td>4.20</td>
<td>0.60</td>
<td>69.0</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>08 Sep 1993</td>
<td>378</td>
<td>43.60</td>
<td>13.70</td>
<td>5.10</td>
<td>0.67</td>
<td>86.0</td>
<td>1.65</td>
</tr>
<tr>
<td>Arctic Red River</td>
<td>28 Jul 1993</td>
<td>219</td>
<td>32.30</td>
<td>8.70</td>
<td>6.70</td>
<td>0.90</td>
<td>41.0</td>
<td>7.31</td>
</tr>
<tr>
<td></td>
<td>09 Sep 1993</td>
<td>311</td>
<td>35.40</td>
<td>9.40</td>
<td>7.70</td>
<td>0.91</td>
<td>51.0</td>
<td>7.86</td>
</tr>
</tbody>
</table>

¹ Detection limits (mg l⁻¹): Ca = 0.04, Mg = 0.01, Na = 0.04, K = 0.05, SO₄ = 3.0, Cl = 0.08.

dominant food source for bacteria (Wotton, 1990), bacteria and their by-products may be the dominant factor contributing to the observed floc sizes (i.e., largest d₅₀ in July samples). No bacterial counts are available for July, however, to verify this assumption. The pH values did not vary substantially from site to site (7.8 – 8.7), and it is therefore difficult to infer cause and effect relationships.

The September samples possessed the smallest d₅₀ in all three size categories (Table 3). This fact may be related to (1) smaller SS concentrations reducing the potential for particle-particle interactions (with the exception of Aklavik); (2) higher concentrations of PP below 3 µm, resulting in the formation of smaller flocs; and (3) colder temperatures influencing bacterial populations and the potential for bioflocculation. Interestingly, the September samples possessed the highest conductivity and generally the highest ionic concentration (Table 5). This high concentration of ions, combined with the lower floc sizes for September, suggests once again that electrochemical flocculation may not be a dominant mechanism for floc building in the MRD.

Aklavik had an unusually high SS concentration (107 mg l⁻¹, Table 4), which corresponded with the largest total d₅₀ value for September (Table 3). This correspondence supports the traditional view that SS is an important factor in controlling flocculation (Krone, 1978; Kranck, 1979; Droppo and Ongley, 1992, 1994; Skarbovik, 1993).

While the primary and total distributions of the Aklavik site (Table 3) generally have an intermediate d₅₀ with respect to the other sites, its floc d₅₀ is consistently the smallest for each month sampled, perhaps because the source areas of sediment and water (primarily the Peel River) are physically, chemically, and biologically different from those associated with the other sites. This difference is reflected by (1) the lowest attached and free-floating bacteria counts for September (limiting bioflocculation) (Table 4); (2) the lowest SS concentration, except for the September sample (limiting particle-particle interactions) (Table 4); and (3) the high Ca and Mg concentrations relative to the other sites (Table 5). While the interrelationships of these factors are complicated and cannot be easily explained, it is evident that the sites’ physical, chemical, and biological differences may be responsible for the different floc d₅₀ results.

Bacteria have been shown to be an integral part of most natural floc structures (Logan and Hunt, 1987; Droppo and Ongley, 1989, 1992, 1994; Muschenheim et al., 1989; Liss et al., 1996) and were observed to be an important constituent of MRD flocs for the September samples. While often the majority of bacteria are free-floating in freshwater environments (Geesey and Costerton, 1979; Kirchman, 1983), there are reports of environments and conditions where the attached bacteria are dominant (Goulder, 1976; Bell and Albright, 1981; Lind and Lind, 1991). Bacteria often show an affinity for flocs because of their protective support as a beneficial microhabitat and because organic nutrients adsorb onto particulate surfaces and thus represent a nutrient source and colonization site for the bacteria (Paerl, 1975; Goulder, 1976; Logan and Hunt, 1987). While attached bacteria may not always be dominant, the significance of this
sediment–bacteria relationship lies in the fact that bacteria associated with particulate surfaces demonstrate greater metabolic activity than free-floating bacteria (Logan and Hunt, 1987; Kasimir, 1992). Liss et al. (1996) have demonstrated that it is the bacteria’s metabolic production of EPS which is the dominant mechanism controlling floc development, structure, stability, and behaviour.

Free-floating and sediment-bound bacteria counts for the September samples were found to be an order of magnitude below those of Droppo and Ongley (1989, 1994) for a small creek in southern Ontario (Table 4) ($10^6$ versus $10^9$ per ml$^{-1}$). The lower population of bacteria associated with the MRD’s SS may not necessarily imply that bacteria and EPS are any less significant to the production of flocculated material. The fact that bacteria are associated with the SS at all three sites and that, in particular, the Aklavik and Arctic Red River sites possess more attached than free-floating bacteria (Table 4) suggest that bacteria are likely to be important to the floc ecology and floc-building process of the MRD.

As deltas in cold-climate zones generally have a pronounced increase in organic accumulation (Lewis, 1991), and since particulate organic matter (POM) is believed to enhance the flocculation process because it is highly cohesive (Kranck 1979, 1984; Droppo and Ongley, 1989, 1994), we anticipated larger floc sizes in the delta than at the Arctic Red River site. No consistent spatial (between sites) trends were observed, however, for the July and September samples (Table 3). In fact, contrary to the above hypothesis, the Arctic Red River generally had the highest POC concentrations at all sampling times (with the exception of the September Aklavik sample), an intermediate DOC concentration, and the highest attached-bacteria counts for the September samples (Table 4). This nonconformity may be related to (1) the limited data set; (2) the close proximity of the Arctic Red River site to the delta; and (3) the location of Inuvik and Aklavik sampling sites on significant flow channels, which reduces the residence time for the accumulation and transport of significant quantities of POM compared to distributaries, lakes, and marsh areas of the MRD. Significant changes in the particulate, colloidal, and dissolved organic carbon of the main channels of the MRD may not occur until the freshwater reaches the salt intrusion zone, significantly north of Inuvik (Whitehouse et al., 1989).

CONCLUSIONS

Flocculation of freshwater riverine sediments appears to be a widespread geographical phenomenon. It has been demonstrated that flocs play a significant role in the transport of fine-grained sediment in the MRD and that, for the sample times, the sediment may be more flocculated than in more southerly rivers. As in the southeastern Canadian rivers previously studied, distributions were bimodal in nature, with the particle-deficient zone representing a possible transition point between particle modes and a potential preferential particle size range for flocculation. Some evidence suggests site-specific controlling factors of flocculation, such as source area (different sediment characteristics, water chemistry, etc.). The apparent larger proportion of flocs and general larger size of the MRD flocs, compared to the southeastern rivers studied, suggests that (1) there may be different factors contributing to the development of flocs in the MRD, or (2) that the factors (SS concentration, particle size, bacteria, bacterial exudate, turbulence, water and sediment chemistry, etc.) are the same, but that their order of significance in terms of their relative contributions to floc formation is different.

It is important for researchers and water resource managers to understand the “true” state of the SS in transport within the MRD (and other freshwater river systems), as sediment (floc) form significantly affects sediment (floc) function. That is, the traditionally analyzed inorganic primary particle will behave differently—physically, in how it is transported and settled; chemically, in how it interacts with contaminants/nutrients; and biologically, in how it affects microbial activity within a river system—than the more representative flocculated particle. Sediment and contaminant transport models, to better predict reality, should take into account the phenomenon of flocculation.

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