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

I.G. DROPPO,[1,2] D. JEFFRIES,[1] C. JASKOT[1] and S. BACKUS[1]

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

RÉSUMÉ. Le delta du Mackenzie (DM) sert d'étude de cas pour déterminer l'importance du rôle que peut jouer la floculation dans le transport des sédiments et contaminants connexes dans les régions arctiques. On a recueilli des échantillons pour analyse non destructive de la taille des particules/flocons, des ions majeurs, du carbone organique particulaire (COP), du carbone organique dissous (COD), de la numération bactérienne et des concentrations solides en suspension. Les mesures du pH, de la conductivité et de la température ont été faites sur le terrain. Les résultats indiquent que le transport solide en amont et à l'intérieur du DM s'opère principalement sous forme de flocons et non sous forme de particules élémentaires calibrées de façon traditionnelle. On montre que les flocons du delta sont parfois plus gros que ceux des cours d'eau du sud de l'Ontario qui ont déjà fait l'objet d'une étude. La distribution des sédiments était de nature bimodale: la zone déficitaire en particules représentait potentiellement une grosseur de particules propice à la floculation. Des tendances spatiales et temporelles dans la distribution granulométrique suggèrent l'existence de facteurs de contrôle de la floculation qui sont spécifiques à certains sites, tels que la source d'origine et les caractéristiques des sédiments. On émet l'hypothèse que la température de l'eau, la concentration des matières solides en suspension et les bactéries sont les principaux facteurs qui contrôlent la floculation dans le delta.

Mots clés: floculation, solides en suspension, distribution granulométrique, bactéries, transport

Traduit pour la revue *Arctic* par Nésida Loyer.

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).

[1] National Water Research Institute, Environment Canada, P.O. Box 5050, Burlington, Ontario L7R 4A6, Canada
[2] ian.droppo@cciw.ca

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 1.787×10^6 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 118×10^6 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).
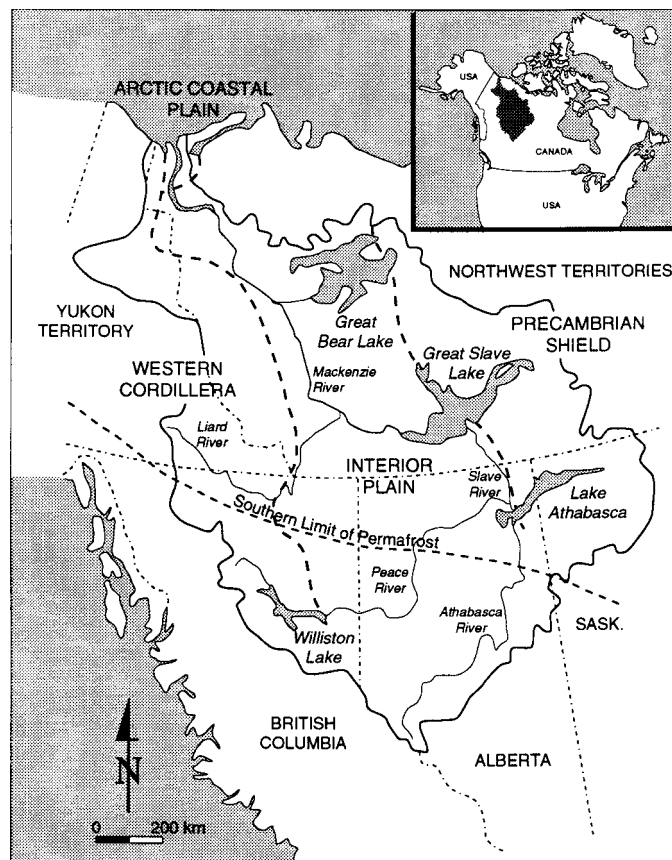

FIG. 1. The Mackenzie River Basin with physiographic regions and southern limit of permafrost. Modified from Rosenberg and Barton (1986).

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 $\times 10^6$ 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 m^3/s (Environment Canada, 1992a). The total mass of suspended sediment passing this site during open water season is on average 76.5×10^6 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 m^3/s, with an average of 3.82×10^6 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 m^3/s, with an average of 1.35×10^6 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
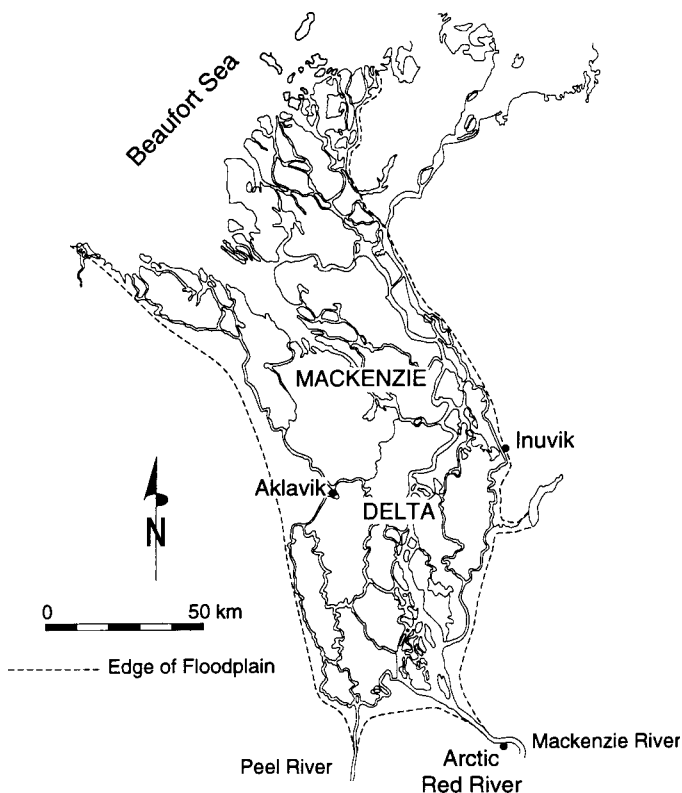

FIG. 2. The Mackenzie River Delta and sampling site locations.

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.

Date	Inuvik Flocs as % of total		Aklavik Flocs as % of total		Arctic Red River Flocs as % of total	
	no. of particles	vol. of particles	no. of particles	vol. of particles	no. of particles	vol. of particles
June	48.8	98.8	49.9	98.5		
July	66.4	99.9	60.0	99.5	56.6	99.4
September	47.2	99.2	51.4	99.6	46.1	99.8

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).

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

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 d_{50} [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 $\alpha = 0.5$, Modified Kolmogorov-Smirnov test, Goldman and Lewis, 1984). Similar results have been observed in temperate climates (Droppo and Ongley, 1994; Irvine, et al., 1995).

The dispersed (sonicated) distributions in Figure 3 are close to what traditional sediment sizing techniques (e.g., sedigraph, pipette analysis) would provide as the grain size distribution for the MRD. Indeed, these are the type of distributions provided by Environment Canada (Environment Canada, 1992b) and used in many river sediment studies including those of the MRD. As flocculated particles settle substantially differently than do primary particles (Krishnappan, 1990; Ongley et al., 1992; Droppo et al.,
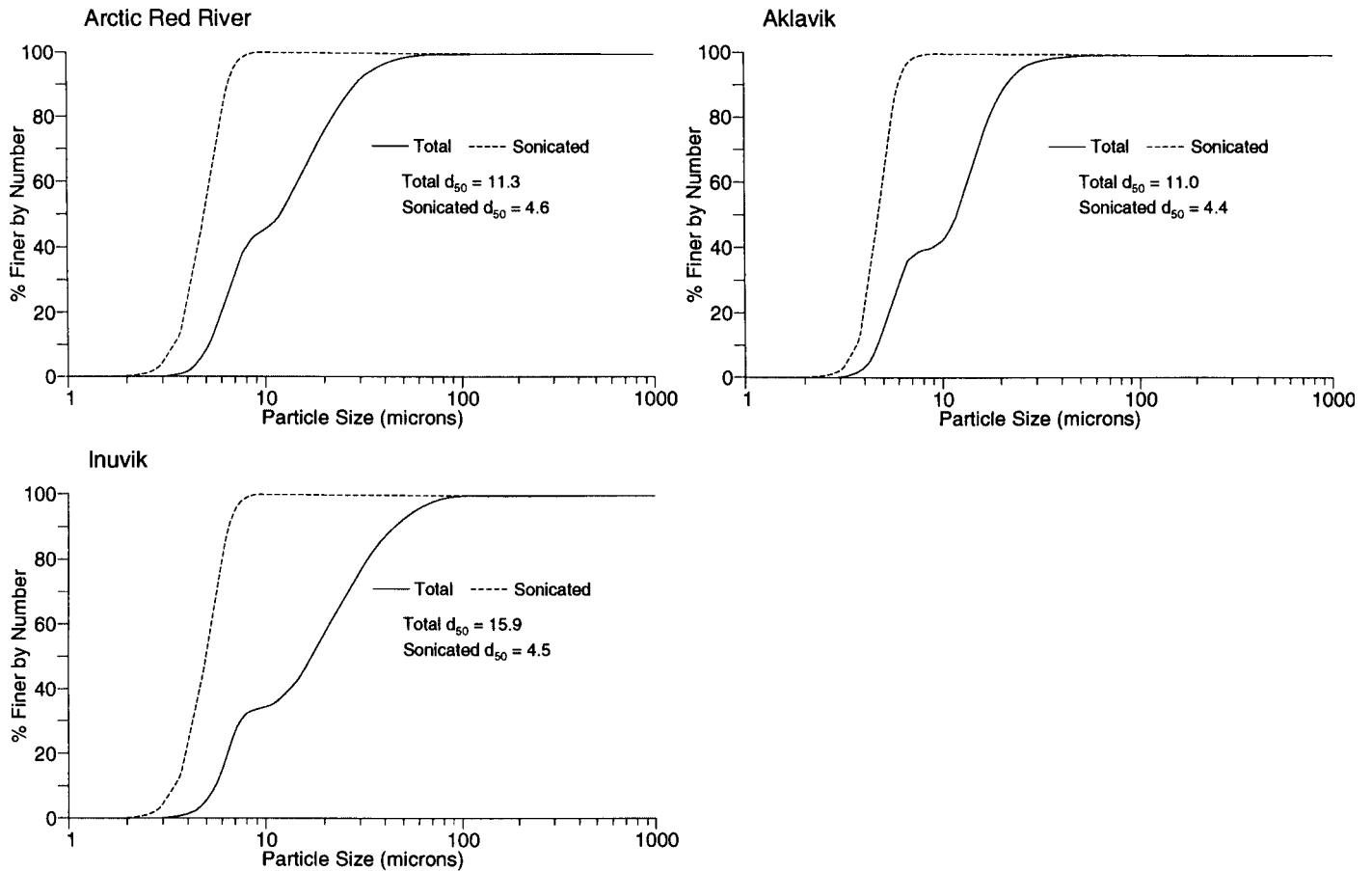
FIG. 3. Comparison of total (natural) and sonicated (dispersed) particle size distributions for the July samples at each site.

1997), the use of such a disaggregated distribution to characterize sediment for sediment and contaminant transport models 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 therefore imperative that future researchers examine the "true" particle size distribution of the MRD sediment when examining 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 $7-10\,\mu m$ 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 ($3-6\,\mu m$). 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 $7-10\,\mu m$ 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-deficient 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 methodology (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 d_{50} 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 interaction (collisions resulting in flocculation) (Table 4), although July did not have the highest SS concentrations.
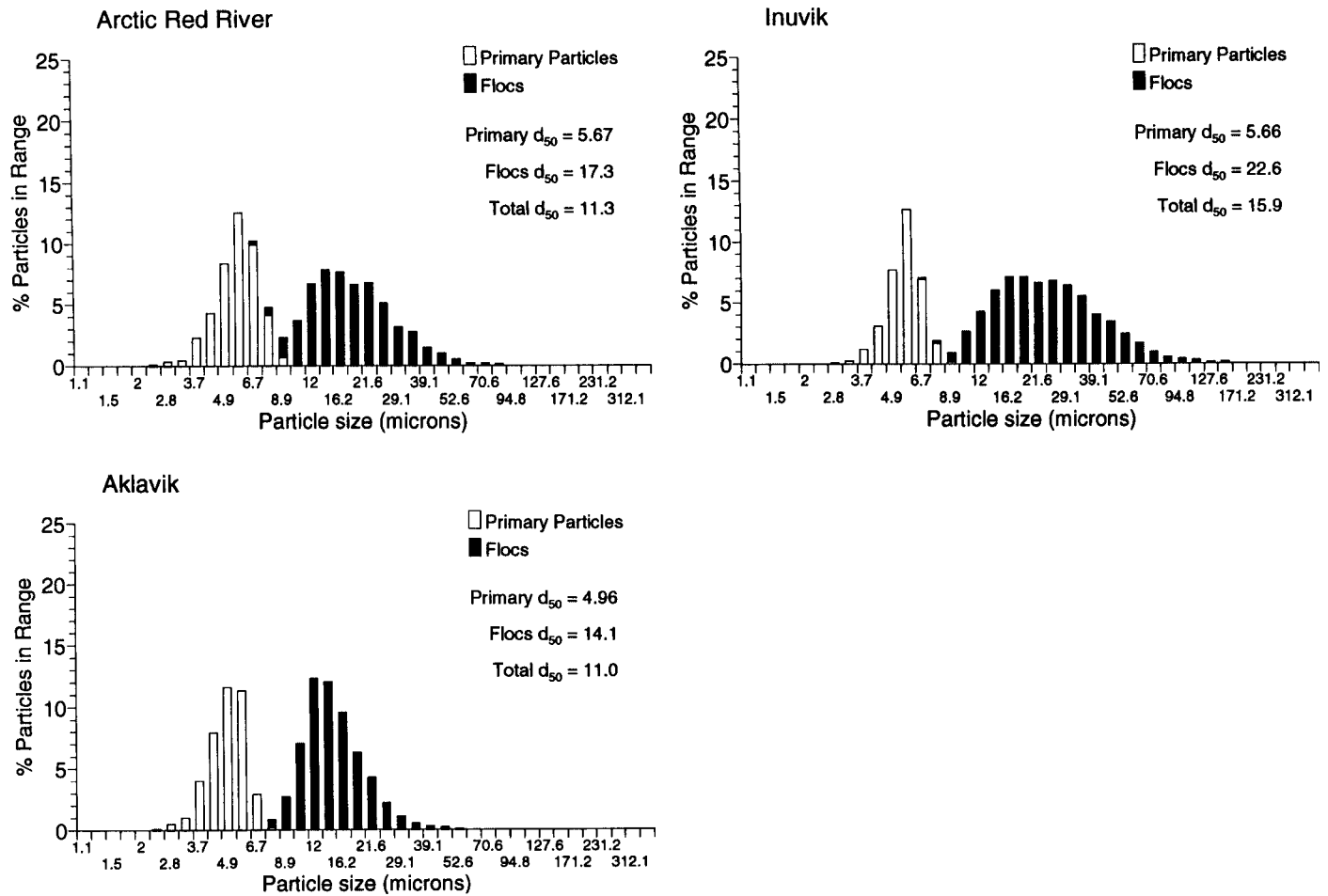
FIG. 4. Bimodal distribution of suspended sediment from the July samples at each site. The distribution is divided, showing autonomous primary particles and flocs separately by particle size (in microns) within the sample.

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

	Inuvik			Aklavik			Arctic Red River		
Date	Primary (μm)[1]	Floc (μm)[2]	Total (μm)[3]	Primary (μm)	Floc (μm)	Total (μm)	Primary (μm)	Floc (μm)	Total (μm)
June	5.9	15.4	8.2	5.9	14.1	8.3			
July	5.7	22.6	15.9	5.0	14.1	11.0	5.7	17.3	11.3
September	3.6	14.6	5.1	3.6	13.6	8.1	4.1	16.1	5.9

[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 floc-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.

Site	Date	SS conc. (mg l^{-1})	POC (mg l^{-1})	DOC (mg l^{-1})	pH	Temp. (˚C)	Bacterial counts	
							attached counts ml^{-1}	free-floating counts ml^{-1}
Inuvik	23 Jun 1993	155.0	5.700	8.8	8.75	12.8		
	27 Jul 1993	70.8	1.580	7.8	8.46	16.0		
	7 Sep 1993	62.8	1.300	7.6	7.84	12.3	5.97×10^5	9.09×10^5
Aklavik	23 Jun 1993	76.0	0.056	4.5	8.75	13.4		
	29 Jul 1993	31.2	0.734	6.3	8.79	16.0		
	8 Sep 1993	107.0	2.450	5.6	7.80	9.5	5.66×10^5	4.92×10^5
Arctic Red River	28 Jul 1993	107.0	2.160	7.4	8.57	16.5		
	9 Sep 1993	60.0	2.140	5.3	7.83	13.1	6.89×10^5	5.58×10^5

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

Site	Date	Conductivity (μS cm^{-1})	Ca (mg l^{-1})	Mg (mg l^{-1})	Na (mg l^{-1})	K (mg l^{-1})	SO$_4$ (mg l^{-1})	Cl (mg l^{-1})
Inuvik	23 Jun 1993	228	28.86	7.26	4.54	0.39	29.0	5.40
	27 Jul 1993	189	32.10	8.50	6.40	0.90	42.0	7.03
	7 Sep 1993	293	34.47	8.87	7.63	0.94	41.7	7.90
Aklavik	23 Jun 1993	290	35.76	11.33	3.00	0.57	61.7	1.83
	29 Jul 1993	249	44.90	14.60	4.20	0.60	69.0	1.93
	8 Sep 1993	378	43.60	13.70	5.10	0.67	86.0	1.65
Arctic Red River	28 Jul 1993	219	32.30	8.70	6.70	0.90	41.0	7.31
	9 Sep 1993	311	35.40	9.40	7.70	0.91	51.0	7.86

[1] Detection limits (mg l^{-1}): Ca = 0.04, Mg = 0.01, Na = 0.04, K = 0.05, SO$_4$ = 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 d$_{50}$ 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 d$_{50}$ 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 d$_{50}$ 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 d$_{50}$ with respect to the other sites, its floc d$_{50}$ 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 d$_{50}$ 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) (10^5 versus 10^6 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.

REFERENCES

BELL, C.R., and ALBRIGHT, L.J. 1981. Attached and free-floating bacteria in the Fraser River Estuary, British Columbia, Canada. Marine Ecology Progress Series 6:317–327.

BRUNSKILL, G.J. 1986. Environmental features of the Mackenzie system. In: Davis, B.R., and Walker, W.F., eds. The ecology of river systems. Dordrecht, The Netherlands: Dr. W. Junk Publications. 435–471.

DOMACK, E.W., FOSS, D.J.P., SYVITSKI, J.P.M., and McCLENNEN, C.E. 1994. Transport of suspended particulate matter in an Antarctic fjord. Marine Geology 121:161–170.

DROPPO, I.G., and ONGLEY, E.D. 1989. Flocculation of suspended solids in southern Ontario rivers. In: Hadley, R.J., and Ongley, E.D., eds. Sediment and the environment. International Association of Hydrological Sciences Pub. No. 184. 95–103.

———. 1992. The state of suspended sediment in the freshwater fluvial environment: A method of analysis. Water Research 26:65–72.

———. 1994. Flocculation of suspended sediment in rivers of southeastern Canada. Water Research 28:1799–1809.

DROPPO, I.G., and STONE, M. 1994. In-channel surficial fine-grained sediment laminae (part I): Physical characteristics and formational processes. Hydrological Processes 8:101–111.

DROPPO, I.G., LEPPARD, G.G., FLANNIGAN, D.T., and LISS, S.N. 1997. The freshwater floc: A functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. Water, Air and Soil Pollution 99:43–53.

ENVIRONMENT CANADA. 1979. Analytical methods manual. Ottawa: Inland Waters Directorate, Water Quality Branch.

———. 1992a. Historical streamflow summary: Yukon and Northwest Territories - 1990, Ottawa: Inland Waters Directorate, Water Resources Branch, Water Survey of Canada.

———. 1992b. Sediment data: Yukon and Northwest Territories - 1990. Ottawa: Inland Waters Directorate, Water Resources Branch, Water Survey of Canada.

FERGUSON, M., and MARSH, P. 1991. Discharge and sediment regimes of lake channel systems in the Mackenzie Delta, N.W.T. In: Marsh, P., and Ommanney, C.S.L., eds. Mackenzie Delta: Environmental interactions and implications of development. Proceedings of the Workshop on the Mackenzie Delta, 17–18 October 1989, Saskatoon, Saskatchewan. 53–68.

GEESEY, G.G., and COSTERTON J.W. 1979. Microbiology of a northern river: Bacterial distribution and relationship to suspended sediment and organic carbon. Canadian Journal of Microbiology 25:1058–1062.

GILBERT, R. 1980. Observations of the sedimentary environments of fjords on Cumberland Peninsula, Baffin Island. In: Freeland, H.J., Farmer, D.M., and Levins, C.D., eds. Fjord oceanography. New York: Plenum Press. 633–638.

GOLDMAN, A.S., and LEWIS, H.D. 1984. Particle size analysis: Theory and statistical methods. In: Fayed, M.E., and Otten, L., eds. Handbook of powder science and technology. New York: Van Nostrand Reinhold Company. 1–30.

GOULDER, R. 1976. Relationships between suspended solids and standing crops and activities of bacteria in an estuary during a neap-spring tidal cycle. Oecologia 24:83–90.

IRVINE, K.N., PETTIBONE, G.W., and DROPPO, I.G. 1995. Indicator bacteria-sediment relationships: Implications for water quality modelling and monitoring. In: James, W., ed. Modern methods for modeling the management of storm-water impacts. Guelph, Ontario: Computational Hydraulics International Publications. 205–230.

JENNER, K.A., and HILL, P.R. 1991. Sediment transport at the Mackenzie Delta-Beaufort Sea interface. In: Marsh, P., and Ommanney, C.S.L., eds. Mackenzie Delta: Environmental interactions and implications of development. Proceedings of the Workshop on the Mackenzie Delta, 17–18 October 1989, Saskatoon, Saskatchewan. 39–51.

KASIMIR, G.D. 1992. Microbiological investigations in the river Danube: Measuring microbial activities and biomass. Archiv für Hydrobiologie Supplement 84:101–114.

KIRCHMAN, D. 1983. The production of bacteria attached to particles suspended in a freshwater pond. Limnology and Oceanography 28:858–872.

KRANCK, K. 1979. Dynamics and distribution of suspended particulate matter in the St. Lawrence Estuary. Naturaliste Canada 106:163–173.

———. 1984. The role of flocculation in the filtering of particulate matter in estuaries. In: Kennedy, V.S., ed. The estuary as a filter. New York: Academic Press. 159–175.

KRISHNAPPAN, B.G. 1990. Modelling of settling and flocculation of fine sediments in still water. Canadian Journal of Civil Engineering 17:763–770.

KRONE, R.B. 1978. Aggregation of suspended particles in estuaries. In: Kjerfve, B., ed. Estuarine transport processes. Columbia: University of South Carolina Press. 177–190.

LEWIS, P. 1991. Sedimentation in the Mackenzie Delta. In: Marsh, P., and Ommanney, C.S.L., eds. Mackenzie Delta: Environmental interactions and implications of development. Proceedings of the Workshop on the Mackenzie Delta, 17–18 October 1989, Saskatoon, Saskatchewan. 37–38.

LIND, O.T., and LIND, L.D. 1991. Association of turbidity and organic carbon with bacterial abundance and cell size in a large, turbid, tropical lake. Limnology and Oceanography 36:1200–1208.

LISS, S.N., DROPPO, I.G., FLANNIGAN, D., and LEPPARD, G.G. 1996. Floc architecture in wastewater and natural riverine systems. Environmental Science and Technology 30:680–686.

LOGAN, B.E., and HUNT, J.R. 1987. Advantages to microbes of growth in permeable aggregates in marine systems. Limnology and Oceanography 32:1034–1048.

MACKIEWICZ, N.E., POWELL, R.D., CARLSON, P.R., and MOLNIA, B.F. 1984. Interlaminated ice-proximal glacimarine sediments in Muir Inlet, Alaska. Marine Geology 57:113–147.

MONAHAN, K. 1997. The effects of storm events on sediment flocculation in a river basin. Unpubl. M.S. thesis, State University of New York at Buffalo.

MUSCHENHEIM, D.K., KEPKAY, P.E., and KRANCK, K. 1989. Microbial growth in turbulent suspension and its relation to marine aggregate formation. Netherlands Journal of Sea Research 23:283–292.

NICHOLAS, A.P. and WALLING, D.E. 1996. The significance of particle aggregation in the overbank deposition of suspended sediment on river floodplains. Journal of Hydrology 186:275–293.

ONGLEY, E.D., KRISHNAPPAN, B.G., DROPPO, I.G., RAO, S.S., and MAGUIRE, R.J. 1992. Cohesive sediment transport: Emerging issues for toxic chemical management. Hydrobiologia 235/236:177–187.

PAERL, H.W. 1975. Microbial attachment to particles in marine and freshwater ecosystems. Microbial Ecology 2:73–83.

PETTICREW, E.L. 1996. Sediment aggregation and transport in northern interior British Columbia streams. In: Walling, D.E., and Webb, B.W., eds. Erosion and sediment yield: Global and regional perspectives. International Association of Hydrological Sciences Pub. No 236. 313–319.

PHILLIPS, J.M., and WALLING, D.E. 1995. Measurement *in situ* of the effective particle-size characteristics of fluvial suspended sediment by means of a field-portable laser backscatter probe: Some preliminary results. Marine Freshwater Research 46:349–357.

ROSENBERG, D.M., and BARTON, D.R. 1986. The Mackenzie River system. In: Davis, B.R., and Walker, W.F., eds. The

ecology of river systems. Dordrecht, The Netherlands: Dr. W. Junk Publications. 425–433.

SKARBOVIK, E. 1993. On the transport of phosphorus and fine grained sediments in rivers. PhD. thesis. Report No. 37. University of Oslo, Norway.

STONE, M., and SAUNDERSON, H. 1992. Particle size characteristics of suspended sediment in southern Ontario rivers tributary to the Great Lakes. Hydrological Processes 6:189–198.

TSAI, C.H., IACOBELLIS, S., and LICK, W. 1987. Flocculation of fine-grained lake sediments due to a uniform shear stress. Journal of Great Lakes Research 13:135–146.

VAN OLPHEN, H. 1963. An introduction to clay colloid chemistry. New York: John Wiley and Sons, Inc.

WHITEHOUSE, B.G., MACDONALD, R.W., ISEKI, K., YUNKER, M.B., and McLAUGHLIN, F.A. 1989. Organic carbon and colloids in the Mackenzie River and Beaufort Sea. Marine Chemistry 26:371–378.

WINTERS, G.V., and SYVITSKI, J.P.M. 1992. Suspended sediment character and distribution in McBeth Fiord, Baffin Island. Arctic 45:25–35.

WOTTON, R.S. 1990. The biology of particles in aquatic systems. Boca Raton: CRC Press.

YUNKER, M.B., and MACDONALD, R.W. 1995. Composition and origins of polycyclic aromatic hydrocarbons in the Mackenzie River and on the Beaufort Sea Shelf. Arctic 48:118–129.

YUNKER, M.B., MACDONALD, R.W., CRETNEY, W.J., FOWLER, F.R., and McLAUGHLIN, F.A. 1993. Alkane, terpene, and polycyclic aromatic hydrocarbon geochemistry of the Mackenzie River and Mackenzie shelf: Riverine contributions to Beaufort Sea coastal sediment. Geochimica et Cosmochimica Acta 57:3041–3061.

YUNKER, M.B., MACDONALD, R.W., VELTKAMP, D.J., and CRETNEY, W.J. 1995. Terrestrial and marine biomarkers in a seasonally ice-covered Arctic estuary: Integration of multivariate and biomarker approaches. Marine Chemistry 49:1–50.