Spatial distribution of particulate phosphorus forms in the Slave River Delta, Northwest Territories, Canada

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Abstract Deltaic landforms are important sinks for a portion of the suspended sediment flux transported by many large river systems in the world. The trapping and subsequent deposition of fine-grained (< 63 μm) sediment by rooted aquatic plants has implications for the distribution of sediment-associated nutrients and contaminants in these ecologically diverse ecosystems. The present study examines the spatial distribution of chemically defined particulate phosphorus (P) forms [nonapatite inorganic P (NAIP), apatite inorganic P (AP), organic P (OP)] in a remote northern Canadian delta where sediment accumulation rates are influenced by delta morphology and plant assemblages. Sediment samples were collected in three morphological zones (outer, mid, apex) of the delta. The median total particulate P concentration was 329.2 μg P g^{-1} ± 50 μg P g^{-1}. NAIP represented approximately 68% of particulate P in the delta but total particulate P concentrations are considerably lower than reported in the literature for mid-latitude river and lake environments. Macrophytes influence the spatial distribution of particulate P forms in the delta by influencing the patterns of sediment deposition and grain size.

Key words bioavailability; particulate phosphorus; sediment geochemistry; Slave River delta

INTRODUCTION

Deltas of large rivers are among the most productive and environmentally sensitive ecosystems in northern Canada. These deltas include the Mackenzie River delta, the Slave River delta and the Peace-Athabasca delta. The Slave River delta, which is located at the confluence of the Slave River and Great Slave Lake, supports a highly productive and diverse aquatic ecosystem and is ecologically important at the local, regional and international scale (Thompson *et al.*, 1979; Tripp *et al.*, 1981). The people of Fort Resolution rely on local harvests from the Slave River delta to provide income and a supply of country food (Geddes, 1981). The productivity of this landform is related to the supply of sediment-associated nutrients derived from upstream sources that deposit in channels as well as perched and riparian habitats of the delta. Morphology of the delta is controlled by a series of complex geomorphic and hydraulic factors that influence sediment erosion and deposition (Vanderburg & Smith, 1988; Milburn & Prowse, 1998). Aquatic macrophytes play an important role in establishing and stabilizing deltaic features (English *et al.*, 1997).

The geochemical cycling and distribution of particulate phosphorus has been well documented, particularly in the context of mid-latitude lakes (Bird, 1986; Boers *et al.*, 1993) and rivers (Miller *et al.*, 1982; Stone & English, 1993; Stone *et al.*, 1991) that receive higher inputs of nutrient from point and non-point sources. However, very little is known about the source, chemical speciation and spatial distribution of particulate phosphorus in remote northern rivers and its role in nutrient cycling within these ecologically diverse northern habitats (Ruttenberg & Goni, 1997). Given the importance of vegetation for sediment trapping and its potential for nutrient uptake (Kairesalo & Matilainen, 1994; Schulz *et al.*, 2003; Vargo *et al.*, 1998), this study examines the distribution of particulate phosphorus forms (NAIP, AP, OP) in depositional zones within three morphological areas of the Slave River delta. The distribution of particulate P forms is related to delta morphology as well as the geochemical composition and grain size characteristics of sediment.

METHODS

Study area

The Slave River Delta is located in the Northwest Territories at the confluence of the Slave River with Great Slave Lake (Fig. 1). Three morphological areas of the delta (outer, mid and apex) are distinguished by increasing levee height, botany and geomorphology (English *et al.* 1997). The outer delta is a large flat marsh, which serves as an important staging, breeding and feeding ground for migratory bird species. *Equisetum fluviatile* and other emergent species of aquatic vegetation attract a diverse range of wildlife including muskrat

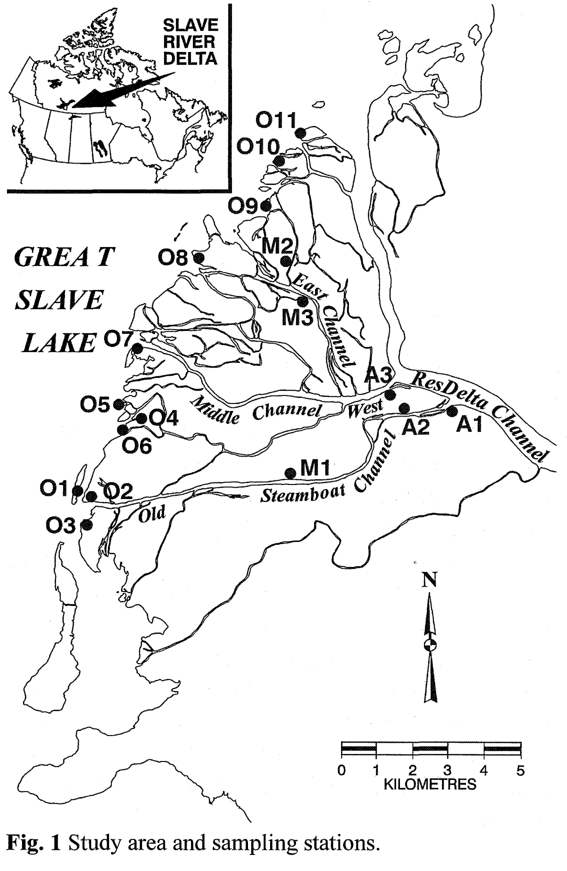

Fig. 1 Study area and sampling stations.

and moose. Cleavage bar islands are the principal deposition features in the outer delta where emergent plant species such as *Equisetum fluviatile*, *Carex rostra* or *Carex aquatilis* invade and enhance sediment trapping (English, 1984). The mid delta is a transitional area between the water-dominated landscape of the outer delta and the elevated, relatively dry apex area. The mid delta represents approximately 45% of the active delta and average levee height is approximately 1 m above summer lake water levels. This portion of the delta supports plant species adapted to a mesic environment including *Equisetum arvense*, *Cornus Stolonifera*, *Salix* spp., *Alnus tenuifolia* and *Populus balsamifera*. The *Alnus–Salix* plant assemblage is by far the most representative in the mid delta. In the apex, the average elevation of levees above summer water levels is approximately 2 m. Flood frequency in the apex is approximately 35 years (English, 1984). About 6% of the apex is classified as aquatic and most of these areas are elevated and cut-off from the Slave River. A significant portion of this zone has reached the climax forest stage of *Picea glauca* that is underlain by permafrost.

Sample collection and chemical analysis

Surface sediment samples (top 10 cm) were collected from depositional features in 17 locations across the delta (Fig. 1), including 11 outer delta sites (O1–O11), three mid delta sites (M1–M3) and three apex sites (A1–A3). Surface sediment samples were stored for 1 month at 4°C before analysis. The grain size distribution was determined with a combination of sieve and hydrometer techniques and the organic matter content was determined by loss on ignition (Environment Canada, 1979).

The concentration of major elements (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O, TiO_2, MnO and P_2O_5) was determined using a Phillips PW1480 XRF spectrometer in the Geology Department at McMaster University, Hamilton, Ontario, Canada. The practical detection limit of the instrument is 50 ppm. Precision of the analysis was determined by analysing three pellets made from a homogenized sediment sample. Accuracy of the analysis was verified by running Canadian Reference Standards and comparing the results with the stated reference values for major elements. The mineralogical composition of sediments was investigated by powder X-ray diffraction using a Cu-target with a Ni-filter. Mineralogy of the sediment is reported as percent dry weight.

A sequential extraction scheme was used to provide quantitative and qualitative assessment of the relative fractional composition of particulate P forms in delta sediment. The fractionation scheme yields five operationally defined fractions of particulate P (Stone & English, 1993). In order of extraction the particulate P fractions are: (a) loosely sorbed P; (b) reductant soluble P; (c) reactive P sorbed to metal oxides; (d) P bound to carbonates, apatite P and P released by the dissolution of oxides; and (e) non-reactive organic P extractable in hot (85°C) NaOH. The first three fractions combined are considered bioavailable and referred to collectively as non-apatite inorganic P (NAIP). Fractions four and five are referred to as apatite P (AP) and organic P (OP), respectively. The OP fraction is potentially available after mineralization (Bostrom *et al.*, 1988). Extractions were performed in triplicate. After centrifugation, extracts were analysed on a Technicon Autoanalyzer using the stannous chloride ammonium molybdate method (Environment Canada, 1979). Detection limit of the analytical method is 1 $\mu g\ l^{-1}$.

RESULTS AND DISCUSSION

Mineralogy and major element composition

Sediment mineralogy is remarkably consistent in the three morphological zones of the delta. Sediments are primarily composed of quartz (60–82%) with lesser proportions of calcite (2–6%), feldspars (8–15%), micas (3–7%), montmorillonite (2–9%), dolomite/ankerite (2–4%) and kaolinite (3–5%). Differences in sediment mineralogy are related to variation in the textural composition of the samples. Fine grained deposits typically have less quartz but higher percentages of feldspar and montmorillonite.

The concentrations of major elements are relatively uniform across the delta (Table 1). The grain size characteristics of deposited sediment in the delta are controlled by sediment supply and transport dynamics which are related to variable energy conditions and water level fluctuations (Vanderburg & Smith, 1988). In addition, floral succession plays a significant role in establishing and stabilizing deltaic features such as lateral accretion bars and cleavage bar islands (English, 1984). The major element composition was influenced by grain size (median diameter, D_{50}). The D_{50} was positively correlated with SiO_2 (0.95, $P = 0.01$), CaO (0.76, $P = 0.01$) and Na_2O (0.93, $P = 0.01$) but inversely correlated with Al_2O_3 (–0.96, $P = 0.01$), Fe_2O_3 (–0.88, $P = 0.01$) and MnO (–0.77, $P = 0.01$). Similar relationships between grain size and sediment chemistry have been previously reported (Stone & Mudroch, 1989; Stone & English, 1993). The data show that concentrations of Al_2O_3, Fe_2O_3, and MnO increase with decreasing grain size, which is related to the abundance of clay minerals present in fine grained sedimentary deposits. Conversely, coarse grained deposits contain higher concentrations of SiO_2.

Particulate phosphorus forms

Previous studies report that total particulate P concentrations in a variety of calcareous and non-calcareous lakes range from 580 to 7000 μg P g^{-1} (Williams *et al.*, 1976; Peterson *et al.*, 1988; Ostrofsky & McGee, 1991; White & Stone, 1996). In contrast, the median total particulate P concentration in the Slave River delta is 329.2 ± 50.3 μg P g^{-1} and the range

Table 1 Concentration of major elements in morphological zones of the delta (percent dry weight).

	Outer Delta			Mid delta			Apex		
	Mean	Range	CV (%)	Mean	Range	CV (%)	Mean	Range	CV (%)
SiO_2	74.3	69.4–77.3	3.8	72.9	71.1–76.2	3.89	72.8	67.7–80.5	5.41
Al_2O_3	10.9	9.1–14	16.67	11.1	8.4–13	21.73	11.8	6.9–15.8	23.59
Fe_2O_3	3.5	2.9–4.8	20.47	3.8	3.2–4.2	14.37	3.9	2.2–5.6	28.5
MgO	2.3	2.1–2.7	9.81	2.3	1.9–2.6	16.23	2.4	1.8–2.8	11.26
CaO	4.4	3.9–4.7	7.38	4.8	4.3–5.6	14.58	4.2	2.8–5.6	20.53
Na_2O	0.53	0.41–0.63	15.81	0.49	0.44–0.57	14.29	0.49	0.34–0.72	23.87
K_2O	2.1	1.8–2.5	12.82	2.1	1.8–2.3	12.18	2.2	1.5–2.8	18.44
TiO_2	0.71	0.58–0.86	14.94	0.62	0.41–0.76	29.74	0.7	0.5–0.88	18.05
MnO	0.059	0.043–0.084	26.05	0.047	0.025–0.074	82.67	0.057	0.031–0.11	41.2
P_2O_5	0.3	0.27–0.32	6.09	0.29	0.27–0.32	9.12	0.29	0.27–0.32	5.34

varied from 195 μg P g $^{-1}$ at Site O3 to 390 μg P g $^{-1}$ at Site O1. The Peace and Athabasca rivers erode parent materials from northern Alberta that provides an upstream source of sediment to the Slave River. The eroded parent materials contain approximately 440 μg P g^{-1}, which is lower than the average crustal abundance of 1050 μg Pg^{-1} (Spiers *et al.*, 1981). Because phosphorus levels are low in parent source materials, particulate P concentrations in the delta are also low. Higher particulate P levels in mid-latitude rivers and lakes cited above are due to high deposition rates of atmospheric P as well as increased loading due to point and diffuse source inputs from agricultural and urban sources (Wall *et al.*, 1982).

The distribution of particulate P forms by sample location is shown in Fig. 2. The median concentration of each particulate P form is NAIP (227.7 ± 49.1 μg P g^{-1}), AP (38.4 ± 7.2 μg P g^{-1}) and OP (65.8 ± 16.7 μg P g^{-1}). The average concentrations of NAIP in the apex, mid and outer delta are 241.8 μg P g^{-1}, 222.2 μg P g^{-1} and 205.7 μg P g^{-1}, respectively. While total particulate P levels in sediment from the Slave River delta are much lower than values reported in the literature, NAIP represents 68% ± 8 of the total particulate P. This value is higher than the 40 to 55% NAIP observed in calcareous lakes (White & Stone, 1996) and indicates while total particulate P levels are low; a significant fraction of the particulate P in sediment of the Slave River delta is potentially bioavailable. In a study of nutrient composition of sediments in the Mackenzie River delta, Ruttenberg & Goni (1997) reported the total P:inorganic P ratio was 0.77. They attributed the higher proportion of inorganic P to low weathering rates of particulate matter in arctic environments.

The bioavailability of sediment-associated P for plant uptake depends upon several inter-related physical, chemical and biological factors (Bird, 1986). Grain size is one factor that

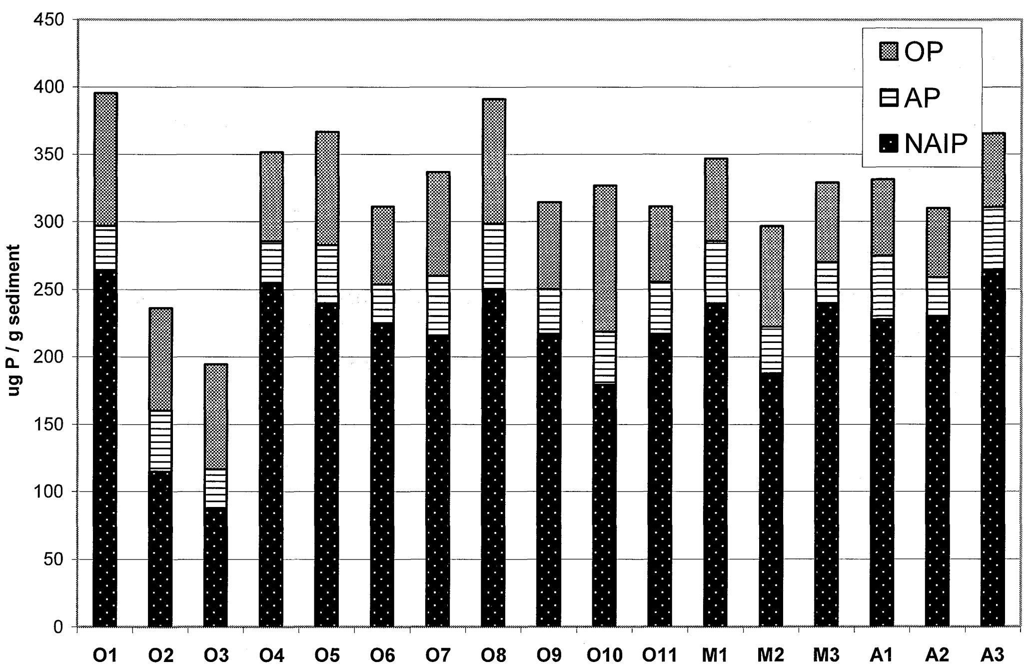

Fig. 2 Distribution of particulate phosphorus forms in the Slave River delta.

Table 2 Slave River water quality data at Fort Smith, NWT (1982–2002).

Variable	*n*	Mean	Range
Suspended solids (mg l^{-1})	59	245	18–2800
pH	64	7.92	7.3–8.4
TP (μg P l^{-1})	61	237	22–4400
Total Fe (μg P l^{-1})	63	4786	8–24700
Total Mn (μg P l^{-1})	41	86	6–482

strongly influences the major element composition and distribution of particulate phosphorus forms in aquatic sediment (Stone & Mudroch, 1989; Stone & English, 1993). The NAIP fraction was positively correlated with Al_2O_3 (0.68, $P = 0.05$), Fe_2O_3 (0.78, $P = 0.01$) and inversely correlated with SiO_2 (–0.70, $P = 0.05$) and suggests that P is primarily bound to metal oxy-hydroxide surfaces of the sediment (Stone & Mudroch, 1989). The mean dissolved P concentration in the Slave River at Fort Resolution is low (5μg P l^{-1}) and levels of total Fe and total Mn are relatively high (Table 2). In rivers with low calcium levels, phosphate concentrations are regulated by the solubility of a solid-solution of ferric-hydroxide in colloidal suspensions or suspended sediments (Fox, 1993). High concentrations of total Fe and low levels of dissolved P suggest that ferric-hydroxide coatings on colloidal suspensions and particulate matter is the dominant factor controlling the kinetics of phosphate in the Slave River.

Much of the sand and coarse-silt fraction of the Slave River is transported through Res Delta channel directly into Great Slave Lake (English *et al.*, 1997). However, finer grained materials enter delta distributaries and a portion of these materials are trapped by vegetation in deposits such as lateral accretion bars, mid-channel bars, channel entrance bars and levees. Results of the present study show that higher particulate P concentrations were found in finer-grained deposits that are stabilized by macrophytes. Further studies are required to estimate nutrient loading to the delta and to quantify the availability of particulate P for plant uptake.

CONCLUSION

The Slave River delta is a remote and environmentally sensitive landform in northern Canada. The present study is the first to quantify the spatial distribution of particulate phosphorus in morphological regions of the delta. The bioavailable NAIP fraction represented approximately 68% of particulate P in the delta but total particulate P concentrations are considerably lower than reported in the literature for mid-latitude river and lake environments. The distribution of particulate P is controlled by sediment grain size which was partly influenced by floral succession and delta morphology.

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