

OBSERVATIONS ON SEDIMENT-CHEMISTRY INTERACTIONS DURING NORTHERN RIVER BREAKUP

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ABSTRACT

Northern river breakups are the most significant annual hydrological event not only because of their extreme potential for morphological changes, but also because they provide the environmental set point for the coming year. River beds and banks are scoured by rapidly moving ice, which in combination with maximum stage, ice jams and increased stream velocities, result in maximum sediment yield to river systems. It is known that most metal transport is associated with suspended solids; however, there are virtually no data on suspended solids and metal concentrations in northern rivers during actual breakup to determine natural fluxes.

The purpose of this study was to determine sediment and metal fluxes just before, during and immediately after river ice breakup. An intensive sampling program was carried out on the Liard River and Mackenzie River at Fort Simpson during April and May, 1993. Initial observations reveal strong correlations between suspended sediment and metal concentrations and break-up conditions. Recommendations for sampling refinements and further study are presented.

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INTRODUCTION

Northern river breakups present a unique challenge for research in hydrology because of the complexity and dynamics of their physical, chemical, and biological processes. In pre-breakup condition, northern rivers may be characterized by thick ice cover, minimum water levels and discharge, near-zero temperatures, and relatively pristine water quality, especially in relation to suspended sediments. Riverine suspended-sediment transport is important for a number of reasons, including potential ecosystem effects, changes in channel morphology, fish habitat alteration, as well as for general scientific interest (Bird, 1990; Horowitz, 1991; Newcombe and MacDonald, 1991; and Williams, 1989).

Once breakup begins, rapid increases in stage and velocities have the potential to intensify system turbulence, disrupt the biotic community, and yield significant quantities of fine-grain material for river transport (Prowse, 1993; Scrimgeour et al., 1992). Much of the latter is caused by ice scour of beds and banks (e.g., Gatto, 1993; Prowse, 1993; Sherstone, 1981; Wuebben, 1986, 1988). Such suspended matter is also known to be a major source of pollutant transport in river and estuary systems (e.g., Bero and Gibbs, 1990), since many environmental pollutants are adsorbed or complexed to their surface. Breakup therefore also has the potential to be a significant period of, for example, organic and trace-metal contaminant transport. In the case of metals, the greatest concentrations within an aquatic system are associated with bed- and suspended-sediments, particularly the finer grained material (Combest, 1991; Horowitz, 1991; Horowitz and Elrick, 1988; Luoma, 1989; Ongley et al., 1988; Warren and Zimmerman, 1993). In many instances, metal concentrations can be orders of magnitude greater than surrounding water (Horowitz and Elrick, 1988). As stated by Luoma (1989), "...sediments constitute a concentrated pool of metals in the aquatic environment (p. 379)."

Unfortunately, except for Prowse (1993), field data collections of suspended sediment have not been undertaken during breakup events primarily due to safety and extreme logistic problems. This study was undertaken to further evaluate the significance of

river-ice breakup on the seasonal transport of sediment and to make the first assessment of its associated role in modifying water quality parameters, especially those associated with the transport of trace metals.

STUDY LOCATION

The study was centred in the Fort Simpson area of the Northwest Territories on the Liard River just upstream of the Mackenzie River confluence. The Liard River rises in Yukon and drains portions of that territory, British Columbia, Alberta, and the Northwest Territories. With a total drainage area of 277,000 km², the Liard River basin is one of the largest tributaries to the Mackenzie River Basin and is also the largest contributor of water and sediment to the Mackenzie River (MRBC, 1981). Sampling transects were established at Water Survey of Canada's (WSC) gauge 10ED002 on the Liard River near its mouth and gauge 10GC001 on the Mackenzie River at Fort Simpson (Figure 1).

River-ice breakup forms a dominant hydrologic event in the Fort Simpson area, often resulting in spectacular ice jams occur on the Liard and Mackenzie Rivers. Moreover, it is break-up of the Liard River that is the trigger to breakup of the larger Mackenzie River (MRBC, 1981). The morphological setting of the Liard River mouth is highly susceptible to ice jamming because of its rapidly decreasing slope and increasing width, which combine to diminish the energy and downstream progression of rapidly moving break-up fronts that have been observed to travel at velocities in excess of 5 m s⁻¹ (Prowse, 1984; 1986).

Following the release of the Liard River ice jam, breakup continues into the Mackenzie River where it is often again halted just downstream of the town of Fort Simpson. Three factors explain the susceptibility of this site to ice jams: the influx of Liard River ice and water at a time when the Mackenzie ice cover is still often intact and relatively strong; the presence of shoals downstream of Fort Simpson island that constrict ice movement; and the presence of a relatively sharp, narrow bend 15 km downstream of Fort Simpson Island that constricts ice passage (Anderson, 1982).

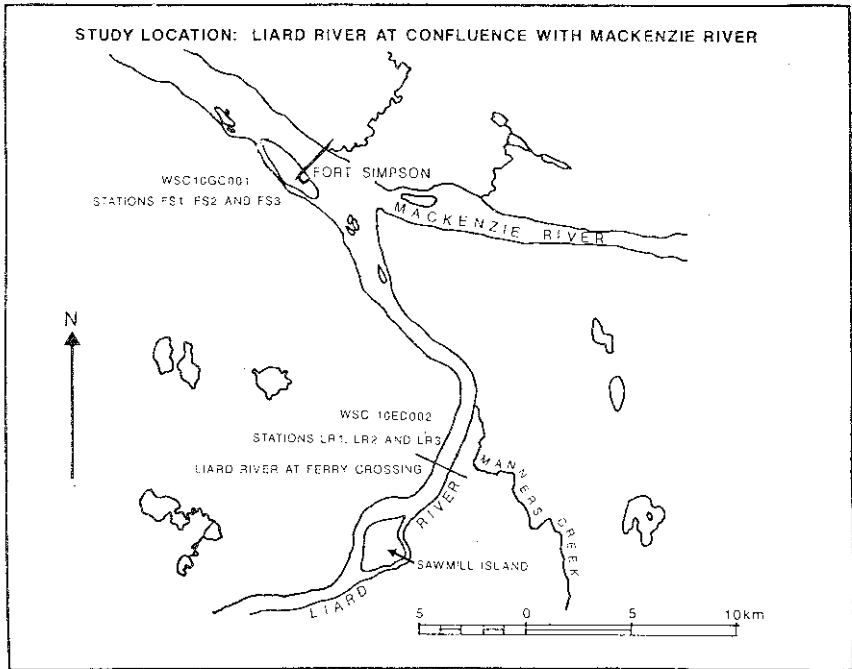


Figure 1. Study Location, Fort Simpson, Northwest Territories

The Liard River is also a significant source of sediment to the Mackenzie River and meets the two most important criteria for maximum sediment transport: a high transport capacity and a large sediment supply (Simon, 1989), most of which comes from bed and bank erosion (Grey, 1981). The combination of river-ice and sediment-regime conditions make this site ideal for studying the interaction of breakup processes and sediment transport.

SAMPLING METHODOLOGY

Three components comprised the sampling program: on-site field measurements of general water-quality parameters; depth-integrated suspended sediment sampling; and associated water-chemistry sampling/analysis for major cations and metals. Sampling was conducted over 15 days in late April to early May 1993 to cover the periods before, during, and immediately following breakup. This report focuses on samples

collected at a transect of three stations (LR1, LR2 and LR3) on the Liard River (Figure 2). Some initial pre-breakup samples were also collected at 3 stations on the

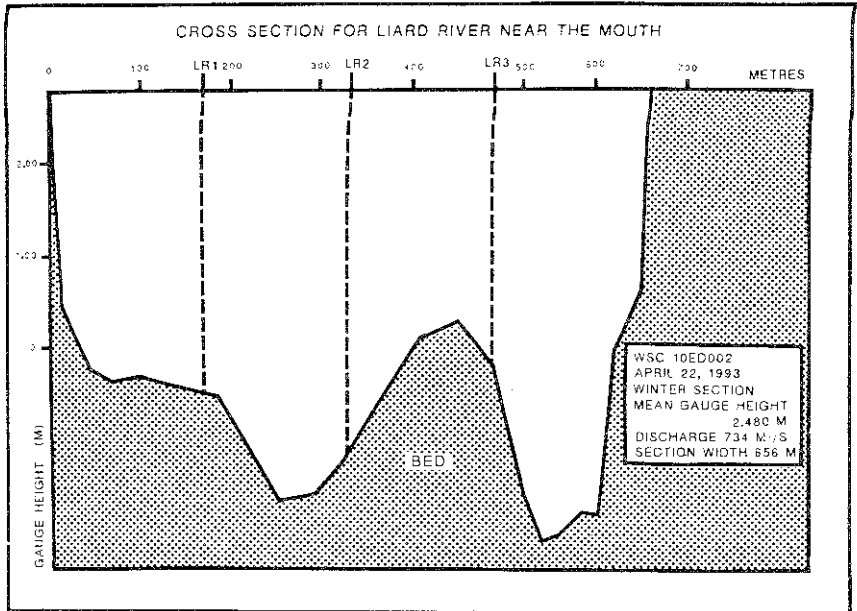


Figure 2. Sampling Transect, WSC gauge 10ED002

Mackenzie River. Unfortunately, this portion of the sampling program had to be discontinued because of logistical problems associated with breakup conditions. Hence, only some general water-quality observations for the Mackenzie River are herein reported. Similarly, sampling difficulties during the active breakup period restricted sampling to the mid-channel site, LR2, on the Liard River.

Water Quality Sampling

All field measurements of general water-quality parameters were made with a Horiba U-10 multi-parameter Water Quality Checker. Conductivity, pH, turbidity, dissolved oxygen, and temperature were recorded by lowering the measuring probe to the ice-water interface and to the river bed: ice thickness and water depth were also recorded. This set of field measurements was terminated when ice conditions became unsafe.

Suspended Sediment Sampling

Depth integrated samples for suspended sediment were collected according to standard methods described by Tassone et al. (1992). Initially, suspended-sediment samples were collected with a DH 48 depth-integrating sampler and wading rods; however, as river velocities increased, a DH 59 depth-integrating sampler suspended from a handline cable was used.

Just before breakup, a modified water-quality sampler on a weighted handline was used so that a single sample could be collected for both suspended sediments and water quality (Figure 3). This was deemed necessary as stream velocities had

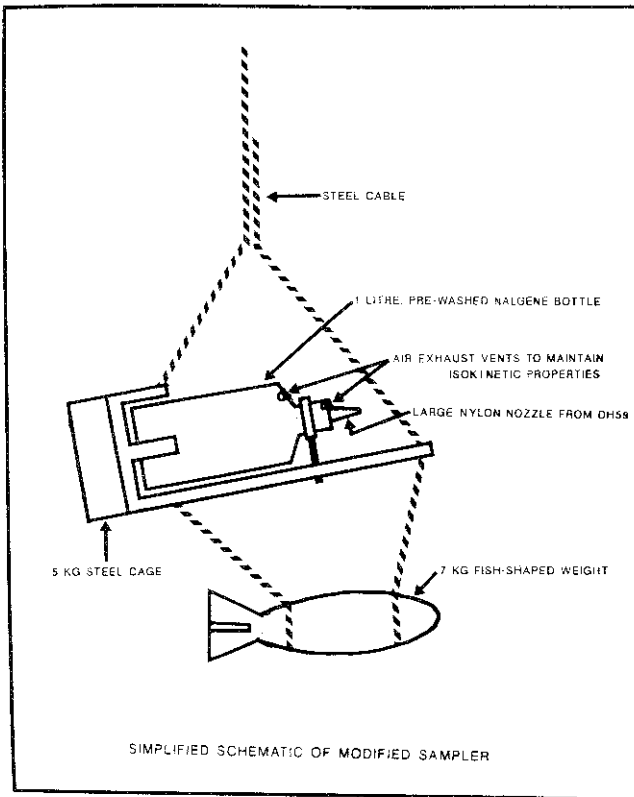


Figure 3. Modified Sampler

increased to the point where there was no assurance of sample consistency over short periods of time; that is, samples collected just minutes apart could have varied significantly in sediment and chemical characteristics. The sampler was modified to place the sample bottle in a near-horizontal position similar to a standard depth-integrating sampler, and it was weighted to overcome stream-velocity effects. The bottle caps were tapped to accept a standard sediment-sampler nozzle. A comparison of results from this sampler, with samples collected with a DH 48, did not reveal any significant differences.

Just prior to and during breakup, when ice integrity was questionable or when open-water conditions existed, samples were collected by lowering the DH 59 or the modified sampler from a stationary helicopter above the sampling site. All samples collected for suspended sediments were analyzed at Environment Canada, Sediment Surveys, Regina, Saskatchewan. Unfortunately, the mass of suspended-sediment samples was not sufficient to permit particle-size distribution analyses.

Water Chemistry Sampling

A number of analytical techniques allow sediment-metal speciation, but these are complex procedures involving a number of tedious steps, and require sample volumes considerably larger than those obtained by a standard depth-integrated sampler (Horowitz, 1991). Luoma (1989) argues that different speciation techniques can show strong correlations with metal bioavailability, but no single approach has been successful in all studies. Nelson and Campbell (1991) offer a more conservative approach by suggesting that lab studies show lowering the pH of the sample will effectively release many trace elements. Therefore, for this study, simple acidification according to standard methods for collection and preservation of samples for total metal analysis was considered to give a first-order understanding of suspended-sediment-induced metal fluxes.

All water-chemistry samples were collected in acid-washed one litre Nalgene bottles. A 125 millilitre portion was transferred to smaller acid-washed Nalgene bottles,

acidified with ultrapure nitric acid and stored in a refrigerator at 4°C. At the end of the field program, all sample bottles were transferred to the National Water Quality Laboratory, Burlington, Ontario, for the analysis of total metals using induced coupled plasma spectroscopy (ICP).

BREAKUP OBSERVATIONS

Ice conditions during the period from April 15 to April 27, 1993, were characterized by gradual ice ablation and structural decay typical of thermal breakups. As seen in Figure 4, water levels rose gradually during this period from 2.0 to 3.4 m. By April 28, ice conditions at the Liard River crossing transect had deteriorated to those typical of a thermal break-up, i.e., extensive small-scale localised ice shunting, exposed ice showing structural decay, and numerous open-water leads. The orifice line of the hydrometric gauging station was also severed by ice on this day (Wood, 1993, pers. comm.).

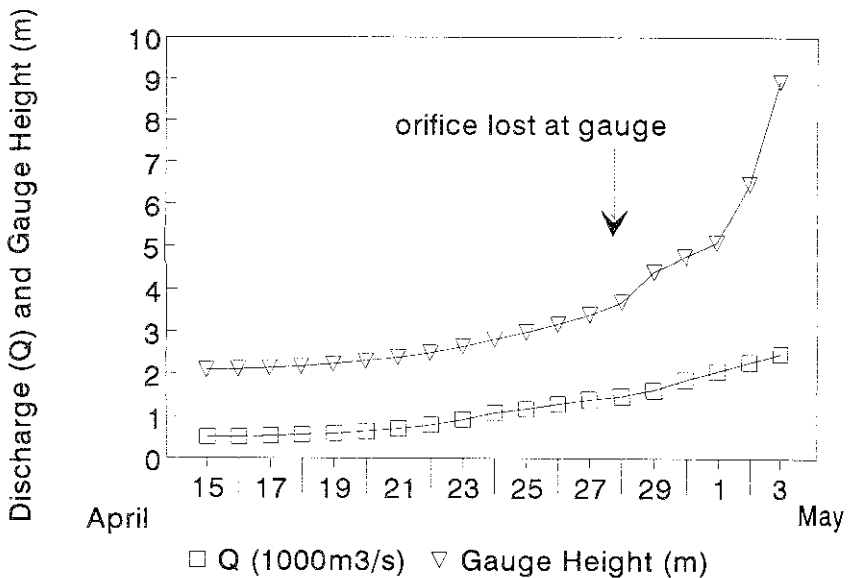


Figure 4. Water Level and Discharge Liard River at Crossing, 1993

The water level rose from 3.4 to 4.4 m in the three-day period from April 27 to 29 when water level measurements by WSC resumed. Ice conditions continued to deteriorate until May 01 with the continued expansion of open-water zones, ablation/decay of the ice cover, and periodic localised downstream shoving. By 2400 MST, however, the ice was moving from bank to bank at an estimated velocity of 2 m s^{-1} . Active breakup continued into May 2 when water levels rose to 6.5 m accompanied by noticeable bank erosion. By 2000 MST of the same day, the ice run had stopped but not before pushing into the Mackenzie River along the right bank of the Liard River. At 0618 MST on May 3, the Mackenzie River ice cover at Fort Simpson had moved enough to break the cable from shore to the timing clock that is used to officially mark breakup, although a full ice was not initiated until 1200 MST. Water levels on the Liard River peaked at 8.9 m. In summary, breakup occurred on the Liard River at the crossing on May 1 and on the Mackenzie River at Fort Simpson on May 3. The 1993 event is considered typical of a thermal breakup.

RESULTS AND DISCUSSION

Results of the field measurements give a clear picture of changes in suspended-sediment levels and water quality parameters. Conductivity, pH, turbidity, dissolved oxygen, and temperature were sampled at near surface, under ice, and near bottom in the pre-breakup phase. None of these parameters exhibit any significant vertical differences or stratification (Table 1). The pH measurements reveal a slightly alkaline condition while the dissolved oxygen values are at near-saturation for temperatures of 0.0 to 1.0°C. Early measurements of turbidity (directly associated with the concentration of sediment particles in suspension) and conductivity produced values consistent with pristine water-quality conditions. As break-up progressed, however, turbidity increased dramatically. Dissolved oxygen also increased, perhaps due to intense mixing during breakup and the number of open leads that developed. By contrast, pH and conductivity decreased slightly, probably because of snowmelt groundwater infiltration.

Table 1. Field Measurements for Physical Parameters

Station LR1 (µmho/cm)	Temperature (°C)		pH		DO (mg/L)		Turbidity (NTU)		Conductivity	
	Surface	Depth	Surface	Depth	Surface	Depth	Surface	Depth	Surface	Depth
Date										
April 15	0.2	0.1	7.06	7.38	12.69	12.53	5	6	.228	.231
April 16	0.4	0.0	8.09	8.00	12.33	11.70	5	5	.238	.246
April 19	0.4	0.2	7.55	7.65	12.18	11.95	10	9	.258	.315
April 21	0.0	0.0	7.87	7.88	11.93	1.81	12	12	.358	.386
April 26	-0.1	-0.1	8.07	8.08	12.78	12.71	74	75	.355	.336
April 27	0.2	0.1	7.89	8.42	12.66	12.68	53	53	.300	.302
April 29			7.86		17.93		106		.277	
May 1			7.77		15.37		95		.265	

Station LR2 (µmho/cm)	Temperature (°C)		pH		DO (mg/L)		Turbidity (NTU)		Conductivity	
	Surface	Depth	Surface	Depth	Surface	Depth	Surface	Depth	Surface	Depth
Date										
April 15	0.1	0.0	6.83	7.69	12.65	12.66	4	4	.260	.259
April 16	0.0	0.0	7.73	7.69	11.68	11.65	4	4	.247	.274
April 19	0.0	0.0	7.66	7.63	11.78	11.85	9	8	.340	.340
April 21	0.0	0.0	8.01	7.95	12.01	11.89	12	12	.380	.384
April 26	0.0	-0.2	8.09	8.07	12.59	12.52	62	62	.314	.334
April 27	-0.1	-0.1	8.06	8.02	12.72	12.75	57	57	.307	.311
April 28			8.15		13.48		85		.260	
April 29			7.67		18.90		334		.274	
May 1			7.81		15.71		95		.265	
May 2			7.79		17.51		326		.259	
May 3			7.61		17.81		396		.251	

Station LR3 (µmho/cm)	Temperature (°C)		pH		DO (mg/L)		Turbidity (NTU)		Conductivity	
	Surface	Depth	Surface	Depth	Surface	Depth	Surface	Depth	Surface	Depth
Date										
April 15	0.0	0.0	6.30	6.84	12.62	12.58	4	4	.423	.424
April 16	0.0	0.0	7.65	7.63	11.60	11.52	5	5	.415	.415
April 19	0.0	0.0	7.66	7.64	11.82	11.84	7	7	.400	.402
April 21	0.0	0.0	8.02	7.93	11.89	11.85	11	11	.380	.380
April 26	-0.1	-0.1	8.14	8.06	12.56	12.44	42	47	.327	.328
April 27	-0.1	-0.1	8.16	8.10	12.81	12.80	62	62	.314	.316
April 29			7.59		19.02		85		.261	
May 1			7.72		15.19		111		.244	

Suspended Sediment

Levels of suspended sediment for the three stations on the Liard River increased with breakup activity and correlated strongly with measured turbidity (Table 1). Excluding one anomalous turbidity value for April 29, the correlation coefficient was 0.96 ($p \leq 0.05$) for data collected from LR2 (longest period of record) and 0.72 ($p \leq 0.5$) for data from all three Liard sampling sites. Notably, stations LR1 and LR3 had suspended sediment concentrations similar to that for LR2 but much lower turbidity readings for the same sampling time.

Initial or background suspended-sediment concentrations were less than 10 mg/L. This period is characterized by relatively clear water (low turbidity) and precedes the formation of an under-ice sediment plume that usually forms before breakup. The plume results from the increased input of suspended sediment from spring runoff and from upstream breakup activity. The plume was quite evident by April 26 (5 days before breakup at the sampling sites), with values in the order of 50 mg/L and reaching as high as approximately 100 mg/L immediately prior to breakup (Figure 5). As breakup occurred, values increased dramatically. For example, at LR2 or the mid-channel station, suspended sediment increased from a pre-breakup condition on May 01 of 54 mg/L to 291 mg/L on May 2 during active breakup. As breakup advanced into the Mackenzie River on May 03, and as water levels and discharge began to rapidly decline at the sampling transect, it was assumed that suspended sediment concentrations would decline to levels more typical of open-water conditions. For example, the open-water data reviewed by Prowse (1993) suggests a value in the order of 200 mg/L for an open-water flow of approximately 2500 m³/s, as occurred on May 03. Subsequent laboratory analysis, however, revealed that the concentrations actually increased to 331 mg/L on May 03, approximately 130 mg/L more than expected for open-water conditions. The temporal extent of this apparent lag in breakup sediment concentrations is unknown but is probably relatively short-lived.

It is interesting to compare the suspended-sediment results from this thermal breakup with those reported for a dynamic breakup at this same site in 1987 (Prowse, 1993).

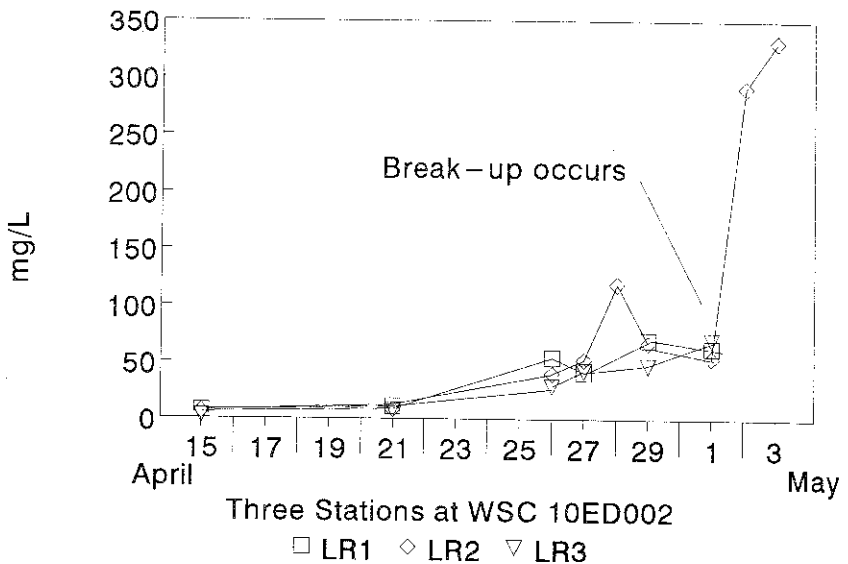


Figure 5. Liard River Suspended Sediment Results

Although a similar trend in pre-breakup values exists (Figure 6), peak concentrations recorded during the dynamic breakup are dramatically higher than the results reported for the station LR2 under thermal breakup conditions; 1067 mg/L in 1987 compared to 331 mg/L in 1993.

Water-Chemistry Samples

Analysis for water chemistry was conducted by direct aspiration by ICP for 20 elements. These elements and the corresponding detection limit are shown in Table 2. Because of the high water quality of the Liard River at the sampling site, many elements were below detection limits. Only those elements recorded consistently above detection limits throughout the sampling period are discussed below.

Two distinct trends are observed in the water chemistry results: a) rapidly increasing concentrations of some trace metals that tend to parallel the progression of breakup and associated changes in suspended-sediment concentrations; and b) slightly decreasing trace-metal concentrations for the entire sampling period. Discussion

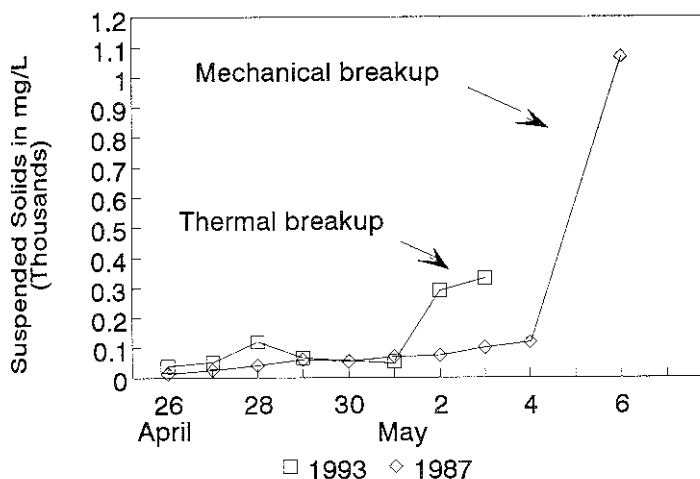


Figure 6. Comparison of 1993 and 1987 Breakup of Liard River

Table 2. Summary of Parameters Analyzed by ICP and Corresponding Detection Limits, National Water Quality Laboratory, Burlington, Ontario.

Parameter	Detection Limit (mg/L)	Parameter	Detection Limit (mg/L)
Aluminum (Al)	0.01	Lithium (Li)	0.001
Barium (Ba)	0.0005	Magnesium (Mg)	0.1
Beryllium (Be)	0.0002	Manganese (Mn)	0.005
Cadmium (Cd)	0.001	Molybdenum (Mo)	0.001
Calcium (Ca)	0.1	Nickel (Ni)	0.002
Chromium (Cr)	0.001	Potassium (K)	0.2
Cobalt (Co)	0.001	Sodium (Na)	0.2
Copper (Cu)	0.001	Strontium (Sr)	0.0005
Iron (Fe)	0.001	Vanadium (V)	0.001
Lead (Pb)	0.005	Zinc (Zn)	0.001

herein focusses on the longest term record from LR2, although LR1 and LR3 showed similar results prior to sampling being discontinued at these sites.

An increase in trace-metal concentrations is evident for concentrations of Aluminum (Al), Copper (Cu), Iron (Fe), Manganese (Mn), and Zinc (Zn) (Figures 7a,b), matching that for suspended-sediment concentrations (Figure 5). The large, episodic increase in concentrations of these trace elements coincides with the initial shunting of ice. The most significant observation, however, is the more than order-of-magnitude increase over the measurement period. Four sets of trace-metal data correlate strongly with that for suspended-sediment, i.e., Al, $r^2=.94$; Fe, $r^2=.90$; Zn, $r^2=.82$; and Cu, $r^2=.78$; whereas Mn correlates poorly with an $r^2=.54$ (all at $p \leq 0.05$).

The strong positive correlation between aluminum and iron, and suspended-sediment concentrations is expected because these elements are normally soil derived (Horowitz, 1991; and Horowitz and Elrick, 1988). The reason for the poor correlation for manganese (another soil-derived metal, is not immediately evident although it is known that manganese is poorly correlated with decreasing grain size and with surface area (Horowitz, 1991). Combust (1991) also reports that manganese is closely related to clay content, thus, one reason for the poor correlation is that under-ice plume samples have a tendency to be higher in fine clay materials, whereas break-up samples would include clays, silts and sands. Another reason is that the primary source of manganese may not be the Liard River but some minor tributary overwhelmed during breakup.

From a biological perspective, the results for copper and zinc are of greatest significance. Both of these trace metals become readily bioavailable under reduced pH conditions and can have toxic effects on aquatic and terrestrial biota. The biological impacts of the rapid increase in these elements during the early spring period (breakup) has never been evaluated.

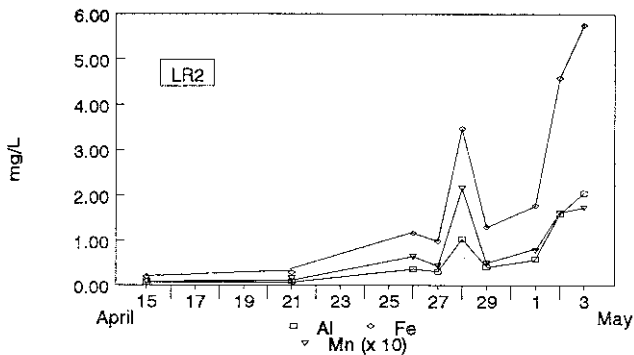


Figure 7a. Total Aluminum, Iron and Manganese

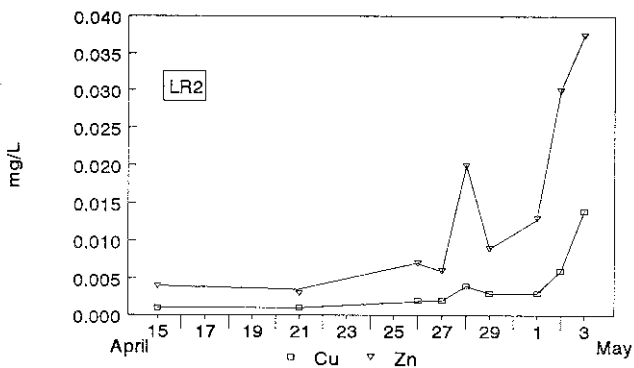


Figure 7b. Total Copper and Zinc

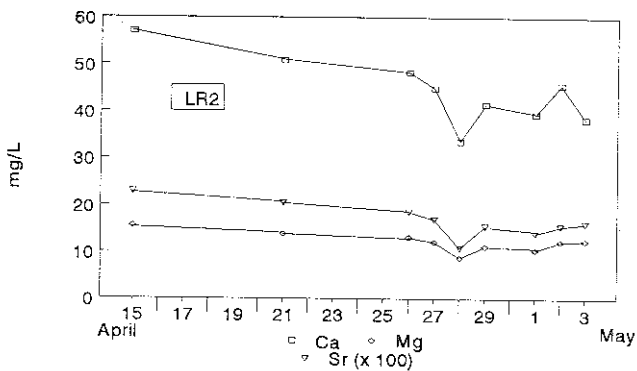


Figure 7c. Total Calcium, Magnesium and Strontium

The second trend in trace metals is one of decreasing concentrations over breakup (Figure 7c). This is exhibited by Calcium (Ca), Magnesium (Mg), and Strontium (Sr) which also have generally poor correlations with suspended sediment, i.e., Ca, $r^2=.23$; Mg, $r^2=.11$; and Sr, $r^2=.21$ (all at $p \leq 0.05$). Notably, however, the rate of decrease in concentrations for these elements is much smaller than for the rate of increase in concentrations for the other trace metals (Figures 7a,b) and is not statistically significant. Possible reasons for this decreasing trend focus on the effects of dilution with increasing flow supplied by snowmelt runoff, groundwater infiltration, and river-ice melt, although the latter contribution is probably minor. It is interesting to note, however, that the small decrease in concentrations of these elements on April 28, 1993 is mirrored by the small rise in suspended-sediment concentrations.

SUMMARY AND FUTURE RESEARCH

This study has presented a unique set of data regarding the flux of sediment and trace metals during breakup; a period that is usually overlooked in evaluating water-quality conditions on rivers. Although breakup was a thermal event, significant changes occurred in most water-quality parameters. Immediately prior to breakup, water quality conditions were characterized by a near-neutral pH, high degree of oxygen saturation, high clarity, and low ionic activity. As breakup commenced, the first noticeable change was in reduced clarity as suspended sediment and associated turbidity increased. Concentrations of suspended sediment and a number of trace-metals, particularly those that tend to adsorb on sediment particles, increased by more than an order-of-magnitude over the whole breakup period.

Although the peak suspended-sediment concentration was almost twice that for equivalent flow under open-water conditions, it was only approximately 30% of that recorded during a previous, more dynamic breakup at this same site. It is theorized that under such dynamic conditions, trace-metal concentrations would also be significantly greater.

Because of the limitations imposed by both sampling equipment and site accessibility, the results should be considered conservative. Even so, the order-of-magnitude changes in concentrations that occurred were temporally dramatic. These may produce significant biological impacts, especially in the case of potentially toxic metals such as copper and zinc. In general, river-ice breakup has significant potential to alter the freshwater aquatic ecosystem, not only due to physical processes such as ice scouring and bed/bank erosion, but also because of rapid changes in important water-quality parameters.

Further studies of this kind are needed to verify the presented results and to better quantify the differences in suspended-sediment and trace-metal concentrations that can occur under varying breakup conditions, e.g., thermal versus dynamic events. Moreover, sampling methodologies should be modified to permit the analysis of suspended-sediment particle-size distribution and of the related metal speciation (c.g., with the use of centrifuges). As per the suggestions of Scrimgeour et al. (1992), the suite of sampled parameters should be expanded to include nutrients, total organic carbon, and organic contaminants in other northern rivers where significant levels of these compounds may be found.

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REFERENCES

- Anderson, J.C., 1982. Liard and Mackenzie River ice break-up, Fort Simpson, N.W.T., 1982. Water Resources Division, Department of Indian Affairs and Northern Development, Ottawa, Ontario.
- Bero, A.S. and R.J. Gibbs, 1990. Mechanisms of pollution transport in the Hudson Estuary. *The Science of the Total Environment*, 97/98(1990), 9-22.
- Bird, G., 1990. Impact of Sediment on River Ecosystems. In: *Managing Ontario's Streams*, J. FitzGibbon and P. Mason (Editors). Canadian Water Resources Association, 60-76.
- Combest, K., 1991. Trace metals in sediment: spatial trends and sorption processes. *Water Resources Bulletin*, 27(1), 19-28.
- Gatto, L.W., 1993. Physical effects of river ice: Section 2.6: Effects of ice on shorelines. In *Environmental Aspects of River Ice*, T.D. Prowse and N.C. Gridley (Editors), National Hydrology Research Institute, Saskatoon, 42-55.
- Grey, B.J., 1981. Suspended Sediment. In: *Mackenzie River Basin Study*, Vol. 3. Spring breakup. Mackenzie River Basin Committee, Ottawa, 124-202.
- Horowitz, A.J., 1991. A primer on sediment-trace element chemistry. Lewis Publishers Inc: Chelsea, Michigan.
- Horowitz, A.J. and K.A. Elrick, 1988. Interpretation of bed sediment trace metal data: methods for dealing with the grain size effect. *Chemical and Biological Characteristics of Sludges, Sediments, Dredge Spoils and Drilling Muds*, ASTM STP 976, J.J. Lichtenberg, J.A. Winter, C.I. Weber and L. Franklin, (Editors), 114-128.
- Luoma, S.N., 1989. Can we determine the biological availability of sediment-bound trace elements? *Hydrobiologica*, 176/1977, 379-396.
- Mackenzie River Basin Committee, 1981. *Mackenzie River Basin Study Report*. Ottawa, Ontario.
- Nelson, O.N. and P.G.C. Campbell, 1991. The effects of acidification on the geochemistry of Al, Cd, Pb, and Hg in freshwater environments: a literature review. *Environmental Pollution*, 71, 91-130.
- Newcombe, C.P. and D.D. MacDonald, 1991. Effects of suspended sediments on aquatic ecosystems. *North American Journal of Fisheries Management*, 11, 72-82.

- Ongley, E.D., D.A. Birkholz, J.H. Carey and M.R. Samoiloff, 1988. Is water a relevant sampling medium for toxic chemicals? An alternative environmental sensing strategy. *Journal of Environmental Quality*, 17(3), 391-401.
- Prowse, T.D., 1984. Liard and Mackenzie River ice break-up, Fort Simpson region, N.W.T., 1983., National Hydrology Research Institute, Environment Canada, report for Water Resources Division, Department of Indian Affairs and Northern Development, 72pp.
- Prowse, T.D., 1986. Ice jam characteristics, Liard-Mackenzie rivers confluence, *Canadian Journal of Civil Engineering*, 13(6), 653-665.
- Prowse, T.D., 1993. Suspended sediment concentrations during river ice breakup, *Canadian Journal of Civil Engineering*, 20(5), 872-875.
- Scrimgeour, G.J., T.D. Prowse, J.M. Culp and P.A. Chambers, 1992. Ecological effects of river ice breakup: a perspective. *Proceedings of 9th International Northern Research Basins Symposium/Workshop*, Whitehorse, Yukon.
- Sherstone, D., 1981. Ice break-up in the Liard Basin. In: *Mackenzie River Basin Study*, Vol. 3. Spring breakup. Mackenzie River Basin Committee., Ottawa, 49-123.
- Simon, A., 1989. The discharge of sediment in alluvial streams, *Water Resources Bulletin*. 25(6), 1177-1188.
- Tassone, B., F. Lapointe and P. Zrymiak, 1992. Field procedures for sediment data collection, Vol. 1 Suspended Sediment. Department of Environment, Ottawa.
- Warren, L.A. and A.P. Zimmerman, 1993. Trace metal-suspended particulate matter associations in a fluvial system: physical and chemical influences. In: *Particulate and matter and aquatic contaminants*, S.S.Rao (Editor). Lewis Publishers, Boca Raton, 127-155.
- Water Survey of Canada, 1993. Streamflow data (unpublished). Inland Waters Directorate, Environment Canada, Ottawa.
- Williams, G.P., 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. *Journal of Hydrology*, 111(1989), 89-106.
- Wood, P., 1993. Pers. Comm. Water Survey of Canada, Environment Canada, Fort Simpson, Northwest Territories.
- Wuebben, J.L., 1986. A Laboratory study of flow in an ice-covered sand bed channel. *In Proceedings of the IAHR Ice Symposium*, Iowa City, 3-14.

Wuebben, J.L., 1988. A preliminary study of scour under an ice jam. *In* Proceedings, 5th Workshop on Hydraulics of River/Ice Jams, Winnipeg, Canada, 177-189.