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The Effect of River-Ice Break-Up on Suspended Sediment and Select Trace-Element Fluxes

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Ice break-up on northern rivers presents a unique research challenge because of its dynamic nature and complexity of physical, chemical and biological processes. Rapidly moving ice, ice jamming, flood levels, and enhanced flow velocities can produce significant sediment transport and trace-element fluxes. Systematic sampling for these parameters, however, is rarely conducted because of logistical difficulties. This paper discusses the magnitude and relative significance of sediment and trace-element fluxes during break-up of the Liard River in northern Canada. Historical data for the open-water and stable ice-covered periods are compared to that measured during the 1987 and 1993 break-up events. Analysis reveals that a break-up pulse occurs during this period that if not accounted, can lead to significant underestimation of suspended sediment and trace-element fluxes. More generally, any estimates of annual sediment or trace-elements for northern rivers that do not include data for the critical break-up period must be regarded as being conservative.

Introduction

Northern river ice break-up can often be a spectacular process capable of modifying the biological, geomorphological and hydrological regime. It also presents a unique scientific challenge because of its dynamic nature and complexity of physical, chemical and biological processes. Upon release of an ice jam, dramatic increases in downstream water levels and velocities are not uncommon. For example, levels often rise by 1.0 m/min or more and velocities can exceed 5 m/sec. These dynamic conditions combine to intensify flow turbulence, disrupt biotic communities and, through ice scour of bed and banks, yield significant quantities of suspended sediment for downstream transport (*e.g.* Gatto 1993; Prowse 1993; Scrimgeour *et al.* 1994; Sherstone 1981). This transport of material can produce a number of ecological impacts such as the modification of channel morphology and associated fisheries habitat (Bird 1990; Horowitz 1991; Newcombe and MacDonald 1991; Williams 1989).

Break-up may also have significant effects on the transport of trace elements. Within the aquatic systems, trace elements become distributed among sediment, water, and biota. The greatest concentration of many elements, however, is associated with bed and suspended sediments and there is a strong correlation between increasing trace-element concentration and decreasing particle size (Combest 1991; Horowitz 1991; Horowitz and Elrick 1988; Luoma 1989; Ongley *et al.* 1988; Warren and Zimmerman 1993). Moreover, because many environmental pollutants are adsorbed or complexed to particle surfaces, such suspended material can be a major source of pollutant transport in river systems (*e.g.* Bero and Gibbs 1990). Given that break-up is the first major flow event to follow a protracted period of low-flow and associated fine-particle deposition, it is likely to be a period in which large quantities of this fine material and associated trace-elements become resuspended.

In a review of periglacial-hydrologic processes, Clark (1988) discusses the complexities associated with water flow and sediment transport in cold regions. While much work has been done on gross annual budgets, little has been done on sediment transport in relation to the discharge hydrograph, primarily because of problems associated with high inter-annual and long-term variability among various hydrologic process. Chacho (1990; 1993), for example, found that the temporal relationship between discharge and suspended-solids production has not been examined in any detail for the dynamic hydrologic period of spring snowmelt. A similar situation exists for all periods of ice-affected flows (*e.g.* Beltaos 1993). Some theoretical work has focussed on the effects of an intact ice cover in driving sediment transporting capacity (Lau and Krishnappan 1985) and laboratory studies have been conducted on various ice scour/deposition processes (Sayre and Song 1979; Wuebben 1986, 1988), but field studies are rare. Measurements of sediment transport have been obtained for the case of an intact winter cover on the Tanana River in central Alaska (Lawson *et al.* 1986), during the snowmelt period at Hot Weather Creek, Northwest Territories (Lewkowicz and Wolfe 1994) and for the active break-up period on the Liard River, Northwest Territories, Canada (Milburn and Prowse 1994; Prowse 1993).

Based on Liard measurements, Prowse (1993) suggests that current records of suspended sediment for ice-covered rivers likely underpredict values for the spring break-up period. Milburn and Prowse (1994) indicate that break-up activity is probably also responsible for unique values and temporal trends in a number of water-quality parameters, some of which are directly linked to the suspended sediment regime. For example, immediately prior to break-up, water quality conditions were characterized by a near-neutral pH, high degree of oxygen saturation, high clarity, and low ionic activity. As break-up commenced, the first noticeable change was reduced clarity as suspended sediment and a number of trace-metals, particularly those that tend to adsorb to sediment particles, increased by more than an order-of-magnitude over the whole break-up period. These unique data sets are further analyzed in this paper to characterize trends and quantify the significance of suspended sediment and select trace-element fluxes during river-ice break-up.

Study Location and Sampling

The study was conducted on the Liard River just upstream of its confluence with the Mackenzie River at Fort Simpson, Northwest Territories, Canada (Fig. 1). The Liard River, which is unregulated and largely undeveloped, rises in Yukon and drains portions of that territory, British Columbia, Alberta, and the Northwest Territories. With a total drainage area of 277,000 km^2, the Liard River basin is one of the largest tributaries in the overall Mackenzie River Basin and the largest contributor of water and

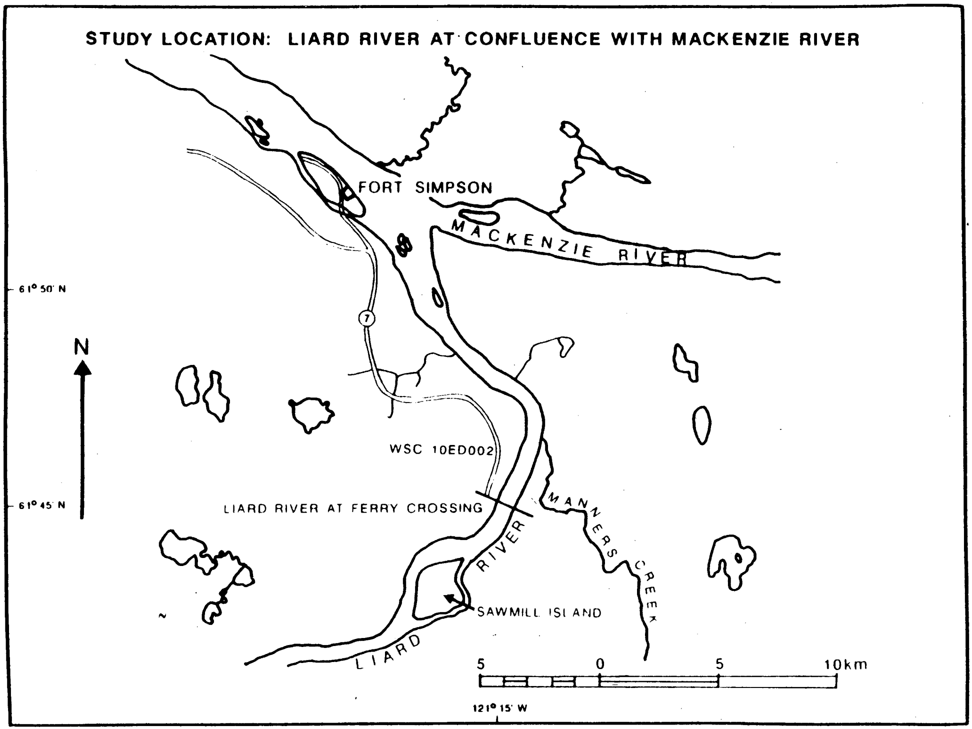

Fig. 1. Study Location, Fort Simpson, Northwest Territories.

sediment to the main stem of the Mackenzie River (MRBC 1981). The Liard River confluence is a site of recurrent and often spectacular ice jams, the release of which triggers the annual break-up on the Mackenzie River. Two factors explain the susceptibility of the Liard River mouth to ice jams: a) the influx of Liard River ice and water at a time when the Mackenzie River ice cover is usually intact and relatively strong; and b) a rapidly decreasing hydraulic gradient combined with increasing channel width that serve to dissipate the energy driving the Liard break-up front (Anderson 1982; Prowse 1986).

Details of the field instrumentation for studies at this site are described in Prowse (1993) and Milburn and Prowse (1994). While the latter study employed standard depth-integrating suspended-sediment and water quality samplers, the earlier study used field-improvised samplers, but these are believed to have introduced minimal sampling error. In addition to the suspended sediment collected in 1993, 20 major cations and trace elements were also analyzed for water samples, although only aluminum, calcium, copper, magnesium, manganese, strontium, and zinc reported consistently above detection limits. From a biological perspective, the results for copper and zinc are of greatest significance because both of these trace metals become readily bioavailable under reduced pH conditions and can have toxic effects on aquatic biota. Because of their biological significance and their strong positive relationships with suspended sediment, copper and zinc are the focus of the trace-element analysis in this report.

Data Review and Analysis

Break-up Observations

The nature of break-up strongly influences the timing and magnitude of sediment transport during break-up (Milburn and Prowse 1994). Break-up types are described by Gray and Prowse (1993) by the interchangeable terms *premature, mechanical* or *dynamic*; and *overmature* or *thermal*. Regardless of type, the severity of break-up is governed by a number of factors including cover thickness, ice strength, river geometry, flow velocity, timing and magnitude of upstream runoff, and pre-break-up heat input to the ice cover (*e.g.* Beltaos 1990; Gray and Prowse 1993). A distinguishing characteristic of a dynamic break-up is an ice cover that has experienced minimal pre-break-up thinning and remains mechanically competent. Break-up is forced by rapid springmelt in headwaters that produce a break-up floodwave with sufficient energy to fracture the highly competent ice. High stages relative to actual discharge result from subsequent ice jamming. Prowse (1986) reports that this study site experienced a number of dynamic break-ups during the period from 1978-1984.

By contrast, a thermal event is characterized by ice that has thinned extensively and is weakened from large thermal inputs prior to break-up. Open water leads, free-floating ice covers, and low spring runoff are also conditions typical of a thermal

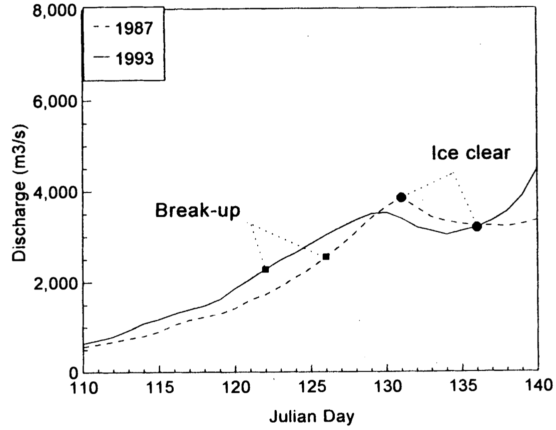

Fig. 2.
Discharge Hydrographs for Break-up Period, 1987 and 1993.

break-up. Although both the 1987 and 1993 break-ups, on which this study is based, were considered to fall into the general category of thermal break-ups, the earlier event contained more periods of vigorous break-up activity, including the formation of a relatively large ice jam. Discharge hydrographs for the break-up period for 1987 and 1993 are shown in Fig. 2.

Suspended Sediment Regime

The Water Survey of Canada (WSC) has periodically measured suspended sediment concentrations at the Liard River site (Station 10ED002: Latitude 61° 44′ 50″; Longitude 121° 13′ 25″) since 1972. Most measurements are obtained during open-water periods and from intensive collection programs. Data are then interpolated between the periodic samples over the entire open-water period forming a suspended-sediment concentration curve. This curve is then used to calculate daily sediment loads. Under-ice, winter loads are not reported. The method is especially prone to large errors if the sampling frequency is low and some measurements are anomalous or inaccurate (*e.g.* Carson 1988a). Reported loads are also suspect if the length of time between sampling is long and peak-flow events are missed (Walling 1977). Notably, in the Liard River case, this approach is also used commonly to extrapolate well out of the open-water period. In a majority of years, predictions of daily sediment load have been made as far back as April 25, or just before break-up, a period when sediment transport under ice is poorly understood (Beltaos 1993).

An alternate method to that of the basic suspended-sediment concentration curves described above is to produce a rating curve between all suspended-sediment data and discharge (*e.g.* Carson 1988b; Lopes and Ffolliott 1993; Walling 1977). The following rating curve for station 10ED002 for the period 1972-1986 was developed by Carson (1988b) using WSC data for the months late April to October, or the open-water period

$$C = 8.69\times10^{-5}\,Q^{1.805} \quad (n=371) \qquad (1)$$

where C is the concentration of suspended sediment in milligrams per litre (mg/L) and Q is discharge in cubic metres per second (m^3/sec).

The advantage of this approach is that it amalgamates all data and allows extrapolation based on discharge, not simply time. Carson's Eq. (1) is based on an array of data points over the period April to October with the majority of data points for measurements taken from June to September. Only six of the 371 data points are for April measurements. Accordingly, it does not treat spring ice-affected flows separately. While this approach improves markedly on the concentration curve approach, it treats all streamflow events equally. For example, suspended sediment transport on a rising limb during spring peak flow is treated the same as low-flow, pre-freeze-up conditions. This assumes that sediment supply is unlimited, which is not necessarily the case of the Liard River (Grey 1981). Furthermore, it does not consider potential hysteresis effects, and because it is generated for open-water data only, it has unknown validity for ice-covered conditions.

Therefore, to improve on this approach, rating curves can be developed for specific portions of events such as rising versus falling limbs. Lopes and Ffolliott (1993), for example, in an analysis of over 700 data pairs for suspended sediment and discharge show distinct differences in rating curves for four types of streamflow events. Tomasson (1991) similarly reports the development of rating curves based on stream types, and temporal and suspended sediment characteristics. WSC suspended sediment-discharge data, which exclude the observed break-up data from 1987 and 1993, were analyzed for the period April 1 to June 30, which represents late winter, pre-break-up to the open-water period (Fig. 3). The following modified sediment rating curve for the spring period of generally rising flow that brackets the break-up period was produced

$$C = 3.18\times10^{-3}\ Q^{1.399} \qquad (2)$$

$$(r^2 = 0.751\ , \quad p \leq 0.05\ , \quad n = 149)$$

Calculating a logarithmic rating curve for river sediment loads can lead to underestimation of lower values but by correcting for this bias according to Ferguson (1986), the following modified rating curve for the period April 1 to June 30 was produced

$$C \equiv 3.55\times10^{-3}\ Q^{1.399} \qquad (3)$$

An examination of this modified rating curve shows a large clustering of data points at discharges above 4,000 m^3/sec with a wide scattering of fewer points at lower discharges typically experienced during late winter recession and break-up. The variance from the line of best fit for this expression is attributed to low-flow residuals, which is consistent with Carson (1988b). This variance can be explained in part by infrequent, systematic sampling during periods of low flow before and during break-up, and sampling bias from sampling near the detection limit during low-flow conditions.

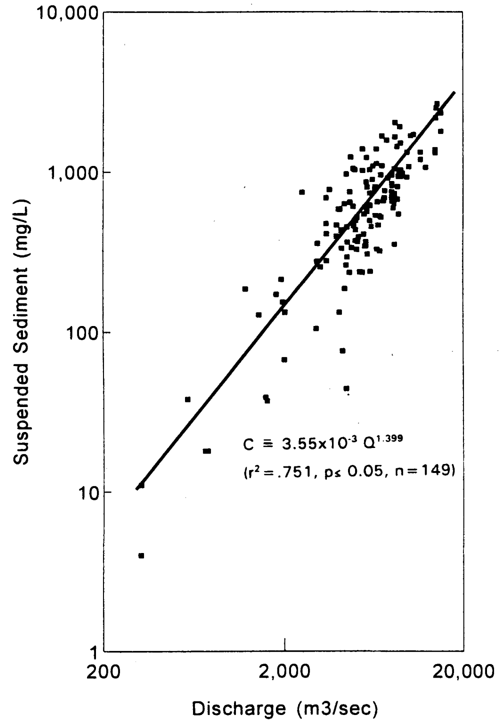

Fig. 3. Modified Suspended Sediment Rating Curve.

Comparisons of suspended sediment concentrations using the two rating curves and observed data for study years 1987 and 1993 are shown in Figs. 4a and 4b. Observed data for the period prior to 1987 break-up fall within the two predicted concentration curves; however, at break-up, the maximum measured concentration of 1,067 mg/L on Julian Day 126 (May 6) is significantly higher than that predicted by either Carson's (125 mg/L) or the modified rating curve (206 mg/L). Observed data for 1993 follow Carson's rating curve more closely, but again at break-up, measured concentrations are higher than predicted. The maximum measured suspended sediment concentration was 331 mg/L on Julian Day 126 (May 3) compared to 119 mg/L and 198 mg/L predicted by Carson's and the modified rating curve respectively. The reduced scale of maximum measured suspended sediment concentrations in 1993 is attributed to the more thermal nature of the 1993 break-up.

For both study years, the modified rating curve overestimates suspended sediment concentrations derived using Carson's curve. The reason for this overestimation is that the modified rating curve is heavily biased towards near-peak discharge, whereas Carson's open-water rating curve includes a large number of samples collected during the falling limb and mid- to late summer low-flow periods. The measured suspended sediment concentration curves for both years illustrate the influence of break-up conditions and the development of an under-ice sediment plume, or the build-up of suspended sediment concentrations into a previously clear water col-

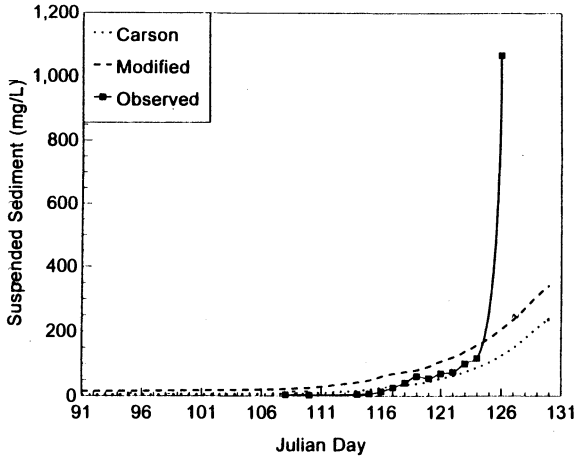

Fig. 4a. Comparison of Suspended Sediment Rating Curves and Observed Data, 1987.

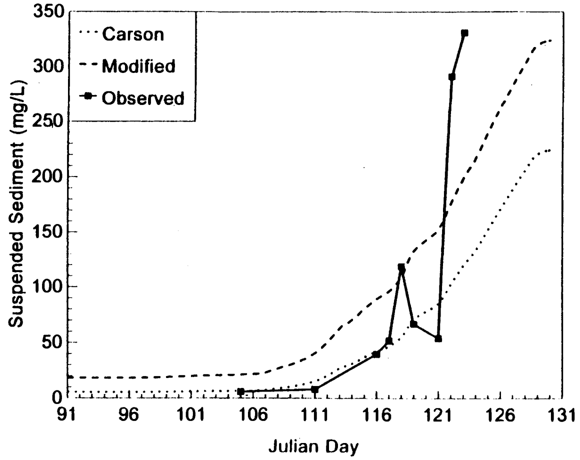

Fig. 4b. Comparison of Suspended Sediment Rating Curves and Observed Data, 1993.

umn. Concentrations of suspended sediment in 1987 remained below 10 mg/L in the two-week period before break-up. With a gradual increase in daily discharge of 200 m^3/sec, concentrations rose sharply from 6 to over 100 mg/L, although break-up had not occurred. A similar trend was experienced in 1993 with concentrations remaining below 10 mg/L until a week before break-up then rising to over 100 mg/L before break-up occurred. Again, daily discharge increased gradually by approximately 200 m^3/sec during the under-ice period. The source of sediment for this under-ice plume is upstream where break-up had already commenced. Because the discharge under ice cover is considerably less than at break-up or post break-up, this rise in concentration would be completely overlooked if a rating curve is used. Prowse (1993), for example, shows that suspended sediment concentrations are significantly greater during break-up than for equivalent discharge in other times of the year. The recession of suspended sediment concentrations can not be determined at this time; however, it is speculated that a sharp recession will occur after ice has moved from the river. Because the studies were part of other break-up studies, it was not logistically feasible to extend the sampling program in each of these two years to the post break-up period.

These results that represent two different break-up events illustrate that the rating curve method to determine suspended sediment concentrations at break-up may be an improvement over the extrapolation method used by WSC, but it can not accurately account for the dynamics of river ice break-up. Both rating curves significantly underestimate suspended sediment concentrations at break-up because the effects of intense ice scouring of beds and banks, bank slumping and bottom ice release are not considered in either rating curve. While the modified rating curve may be an improvement over Carson's, its usefulness is limited to near-peak flow discharges at break-up.

Trace-Element Chemistry

Water chemistry samples are also collected regularly throughout the year by WSC for station 10ED002, usually at one-month intervals during open water, but not at break-up. This sampling does not necessarily coincide with a suspended sediment sampling program, thus it is difficult to derive direct suspended sediment-trace element relationships. Ordinary least squares regression was performed on reported data for total copper and total zinc, and discharge yielding a poor correlation in both instances: $r^2=0.46$ for total copper and discharge, and $r^2=0.46$ for total zinc and discharge ($p\leq0.05$; $n=64$). One probable reason for this poor relationship is that many samples were collected during low-flow, under-ice conditions, a period of low sediment transport, and any measured concentrations of copper and zinc will be dissolved in the aqueous phase.

Analysis of suspended sediment and select trace elements for samples collected during the 1993 break-up study show that strong relationships exist between concentrations of total aluminum ($r^2=.96$), copper ($r^2=.83$), iron ($r^2=.93$) and zinc ($r^2=.90$), and suspended sediment (all at $p\leq0.05$). The relationships between total copper and total zinc and suspended sediment are shown below and in Fig. 5

$$C_{\mathrm{Cu}} \equiv 7.99\times10^{-4} + 3.4\times10^{-5}\, SS \quad (n=20) \text{ and} \tag{4}$$

$$C_{\mathrm{Zn}} \equiv 1.02\times10^{-4} + 1.2\times10^{-4}\, SS \quad (n=20) \tag{5}$$

where C_x is the total concentration of trace element x in mg/L and SS is the measured concentration of suspended sediment in mg/L.

Because a relationship exists between concentrations of trace elements and suspended sediments, and suspended sediments and discharge, it should be possible to relate trace element concentrations and discharge. Any increase in discharge should

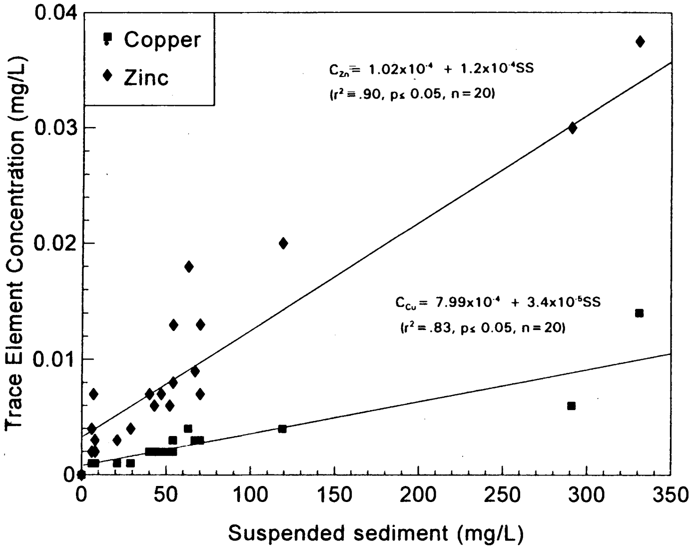

Fig. 5. Relationship between Total Copper and Total Zinc, and Suspended Sediment.

produce a corresponding increase in concentrations of select trace elements. At break-up, however, both Carson's and the modified rating curve underpredict suspended sediment concentrations at break-up, thus the trace element-suspended sediment relationships Eqs. (4)-(5) will also underpredict trace element fluxes. Results from 1993 show that gradual increases in discharge do not produce corresponding increases in trace element concentrations as break-up occurs (Fig. 6). In the case of total copper, concentrations hovered near the detection limit during the latter stage

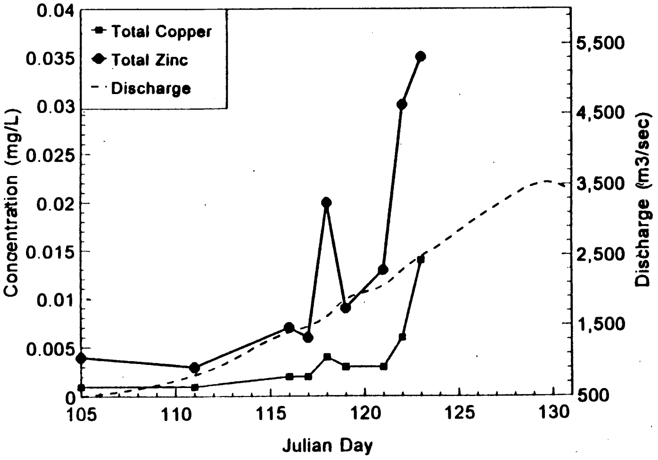

Fig. 6. Total Copper and Total Zinc, and Discharge, 1993.

of winter recession and rose gradually after Julian Day 111 (April 21) from 0.001 mg/L to 0.003 mg/L on Julian Day 121 (May 1). At break-up; however, a small increase in mean daily discharge (200 m^3/sec) resulted in total copper concentrations of 0.006 mg/L on Julian Day 122 (May 2) and 0.014 mg/L on Julian Day 123 (May 3).

A similar trend is shown for total zinc concentrations. Concentrations rose gradually from the influence of the under-ice sediment plume from 0.0040 mg/L on Julian Day 105 (April 15) to 0.0130 mg/L just before break-up on Julian Day 121 (May 1). As break-up occurred, concentrations rose dramatically to 0.0300 mg/L on Julian Day 122 (May 2) and 0.0350 mg/L on Julian Day 123 (May 3), an almost three-fold increase in concentration over a three-day period.

The influence of river-ice break-up processes on suspended sediment-trace element fluxes is shown in Fig. 6 as the sharp rise in concentrations on Julian Day 121. Milburn and Prowse (1994), in their description of the 1993 break-up, attribute these rapid episodic increases in concentrations to shunting, or short-term, large scale movement of ice, that enhances turbulence and scouring.

Discussion

Results of the data analysis for predicted and measured suspended sediment concentrations reveal that measured values are significantly higher than those predicted using a rating curve. The reason for this difference is the turbulent flow, scouring process and higher stream velocities that occur during break-up, although discharge is low compared to peak flow that occurs almost two months later. Consequently, a dynamic break-up with its associated jamming and release will produce higher suspended sediment fluxes than a thermal break-up.

The significance of suspended sediment fluxes before and during break-up is further illustrated in Fig. 7 that compares 1987 sediment loads reported by WSC based on extrapolation and those calculated from measured 1987 data. During the period of late winter recession and under-ice plume, the WSC curve overpredicts loads. At break-up, however, the curve for calculated loads rises significantly over the WSC reported loads. For example, the WSC extrapolated load for Julian Day 126 (May 6) is 163,300 tonnes/day compared to a calculated load of 235,032 tonnes/day, or a difference of over 70,000 tonnes/day. Daily loadings of over 200,000 kg/day are not reported until Julian Day 148 (May 28), 20 days after break-up. Although this example is based on one extreme data point (1067 mg/L), a more mechanical break-up would produce even greater sediment loads. The variance in the WSC-reported and measured loads is caused by inherent inaccuracies in interpolation of suspended sediment concentrations from only a few data points. Based on reported WSC data, the two data points that set the suspended sediment curve during the break-up period are November 3, 1986 (20 mg/L) and June 5, 1987 (1720 mg/L).

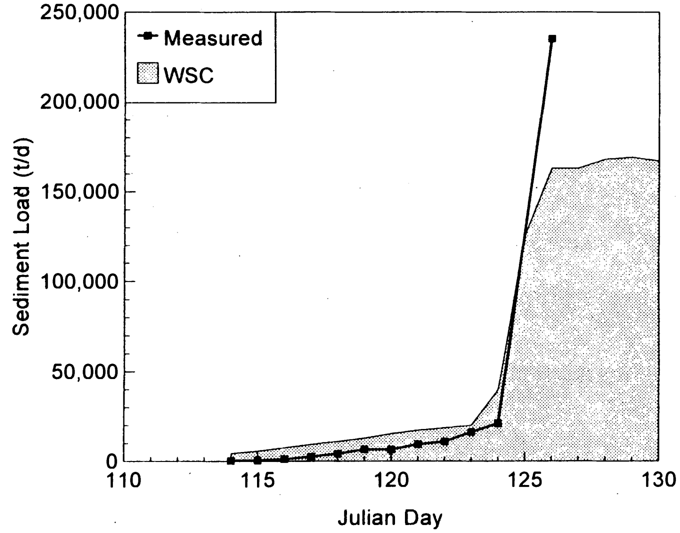

Fig. 7. Comparison of Suspended Sediment Loads based on WSC Calculations and 1987 Measurements.

Trace-element fluxes, which are directly related to sediment fluxes, will also be significantly higher at break-up than predicted by using either an extrapolation or suspended sediment-discharge rating curve approach. It has already been shown that rating curves underpredict suspended sediment concentrations at break-up and they would also underpredict trace element concentrations. Trace element loads are calculated for the break-up period but direct comparisons with WSC data can not be made because WSC does not report trace element loads.

Calculated loads for total copper and zinc and total zinc over the break-up period show a dramatic increase over a short period of time with a gradual rise in discharge. During the latter stage of the winter recession (Julian Day 105 to 111), copper and zinc loads rose from 43 to 68 kg/day, and 43 to 117 kg/day respectively with an increase in discharge of only 300 m^3/day. On Julian Day 116 (April 26) to Julian Day 119 (April 29), the period of under-ice plume effects, loads rose to 482 and 1060 kg/day for total copper and total zinc respectively. At break-up on Julian Day 122 (May 2), the trace element loads more than doubled to 1,181 kg/day for total copper and 2,285 kg/day for total zinc. Maximum calculated loads on the last day of sampling, Julian Day 123 (May 3) are 3,000 kg/day for total copper and 7,500 kg/day for total zinc.

These findings are particularly important because of suspected ecosystem effects from rapid onset of suspended sediment and trace-element fluxes. Copper and zinc, two trace metals that can become readily bioavailable under reduced pH conditions and can have toxic effects on aquatic biota, are examples. The higher than predicted concentrations of these elements, therefore, could have important environmental implications. As break-up occurs, significant, rapid increases in these trace elements that are associated with the suspended sediment pulse are observed. The fate of these sediments, their effects and ecosystem response can not be speculated; however, biological studies have not yet acknowledged the significance of this dynamic hydrological period.

Conclusions

It is shown that break-up has a significant effect on suspended sediment and trace-element fluxes that are overlooked using conventional predictive methods. A modified suspended-sediment rating curve was developed from WSC data available for the spring period that improves on results produced by a similar curve derived from WSC data for the entire open-water season or by a simple interpolation method. These predicted values, however, still significantly underpredicted suspended-sediment concentrations during the active break-up period. Enhanced erosion produced by high flow velocities and associated ice scour of bed and extensive bank areas serves to elevate the suspended-sediment concentrations during this period. To improve predictions during this period, even more temporally-specific rating curves would have to be developed. In addition to the peak break-up concentrations, more information is required about duration and magnitude of suspended sediment concentrations associated with the pre-break-up plume and the post-break-up falling limb. Notably, however, all of these are likely to vary depending on the severity of break-up. The extreme concentrations observed for the two years of study in this report may only be indicative of thermal break-up conditions. Even higher values could be possible during very dynamic break-up events. Additional research is required to evaluate the effect of dynamic break-ups.

Select trace-element fluxes, which are strongly associated with suspended sediment concentrations, were also shown to be greater than expected during break-up. In the case of total copper and total zinc, the increase in concentration can be as great as one order of magnitude over a short time period. For example, total copper rose from 0.001 mg/L to 0.014 mg/L in a period of 12 days. Total zinc similarly rose from 0.0017 mg/L to 0.035 mg/L in the same period. During this period, discharge increased gradually from 797 m^3/sec to 2,480 m^3/sec. Other trace elements that are strongly linked to suspended sediment would also show increased concentrations at break-up. Again, systematic, frequent sampling programs during break-up are required to more properly quantify the potential range and magnitude of these trace-element fluxes. Such programs should also be expanded to include examination of the relationships between particle-size distribution of suspended-sediment and trace-element/contaminant concentrations. More generally, the potential environmental significance of these previously-undocumented pulses also requires through examination.

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