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# Climatic Controls on Streamflow and Suspended Sediment Transport in Three Large Middle Arctic Catchments, Boothia Peninsula, Nunavut, Canada

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## Abstract

Streamflow, suspended sediment transport, and meteorological variables were measured during two field seasons in order to determine the climatic controls on daily discharge and suspended sediment load for three large middle arctic catchments. Substantive suspended sediment transfer only occurred during the short-lived nival peak, and the duration of the peak appears to be broadly scaled with interannual catchment snow water equivalence (SWE). Thermal energy was critical in generating streamflow and suspended sediment transfer, but only until watershed snowpack had been exhausted. Thus, total annual suspended sediment load in this environment is ultimately a function of total discharge through SWE rather than melt energy. Specific sediment yields were some of the lowest recorded in the arctic, ranging between 0.2 and 1.9 t km$^{-2}$·a$^{-1}$. This study demonstrates the sensitivity middle arctic watersheds to both winter snowpack and spring thermal conditions and provides a basis for understanding the hydrological impact of future climate changes.

## Introduction

Annual transfers of water and sediment from nival arctic watersheds have been linked to either atmospheric energy input (Hardy, 1996) or snowpack (Church, 1988; Braun et al., 2000), while also being limited by the supply of sediment within the catchment (Cogley, 1975; Lewkowicz and Wolfe, 1994; Braun et al., 2000). Discharge magnitude has been shown to be of primary importance in these fluvial systems, whereby the bulk of the annual sediment load was transferred during the brief snowmelt flood. Summer rainfall can also have significant effects on sediment transfer (Cogley and McCann, 1976; Lamoureux, 2000), potentially accessing sediment sources protected from the snowmelt flood. However, large rainfall events are relatively rare in arctic environments.

The dominance of snow and permafrost in arctic environments also has a profound impact on the timing of sediment delivery. Channel ice and snow can substantially reduce bed scour during the initial flow period (Forbes, 1975). Higher water temperatures later in the season may facilitate greater sediment erosion and transport through thermal effects along the thawed channel bed perimeter (Miles, 1976). In larger basins, a lengthy delay between initial and peak flow may allow bed/bank thaw (and in turn increase sediment availability) prior to peak discharge, while the reverse may be true in smaller basins where snow and ice remain in the channel through the flood peak (Clark et al., 1988). As a result, large rivers can become exhausted of sediment before the flood peak, while small rivers experience delays in suspended sediment transport.

Comparatively little is known about large scale hydrological processes across the arctic as past research has focused predominantly on small watersheds and primary processes in the low and high arctic, while investigations in middle arctic regions have been limited (Vörösmarty et al., 2001). This paper reports the first such study from the Canadian middle arctic. Streamflow, suspended sediment transport, and meteorological variables were measured during two seasons in order to determine the hydroclimatic variables that influence daily discharge and suspended sediment load for three large catchments (Fig. 1). Establishing the climatic controls on watershed outputs of water and sediment is critical to understanding the sensitivity of arctic environments to climate change, and in turn, making inferences of past and future hydrological conditions.

## Study Area

The study area consists of the watersheds of the Lord Lindsay and its main East and West tributaries above Sanagak Lake, located on the central Boothia Peninsula, Nunavut (Fig. 1). The basins lie within the middle arctic zone, a region that includes the southern archipelago islands and northernmost sections of mainland Canada. Sanagak Lake is located at 191 m above sea level (a.s.l.) and headwaters in the Lord Lindsay and East Tributary watersheds reach altitudes above 550 m a.s.l., while the West Tributary watershed is entirely below 400 m a.s.l. The rivers flow through the lower Boothia plateau which is underlain by Precambrian gneiss and granite and Paleozoic carbonates (Dyke, 1984). The entire region was glaciated, and numerous glaciofluvial deposits, ice-contact deposits, and subglacial landforms characterize the landscape. The southern part of the Lord Lindsay and East Tributary watersheds and most of the West Tributary watershed are covered by thick glacial till that masks the bedrock structure, while the north and eastern headwater regions are characterized by bedrock outcrops with a patchy till veneer. Periglacial processes including frost heave and shatter have modified both crystalline and carbonate bedrock, resulting in extensive felsenmeer and block fields.

The landscape consists of extensive broad plains and plateaus with gently rolling topography dissected with both expansive low-profile valleys and isolated, deeply incised meltwater channels. The drainage pattern of the Lord Lindsay headwaters follow a deranged pattern (e.g., Lewkowicz and Wolfe, 1994), with numerous small lakes and ponds, while the central and lower portions of the basins are largely dendritic, with well-defined channels and a sinuous to meandering morphology. The channel beds contain well-sorted gravel and are locally bouldery at rock outcrops.

Lowland sites exhibit almost complete vegetation cover dominated by *Eriphorum angustifolium*, *Carex aquatils*, and moss, while highland plateaus are more sparsely vegetated, with *Dryas integrifolia* predominant (Laidler, 2002). Drier sites such as bedrock and gravel interfluves are mostly barren. The entire watershed falls within the zone of continuous permafrost, restricting subsurface flow to an active layer found to be a maximum of 1 m at the end of July 2001.

The region experiences long, cold, dry winters and short, cool summers with mean daily temperatures of –35°C and +10°C in January



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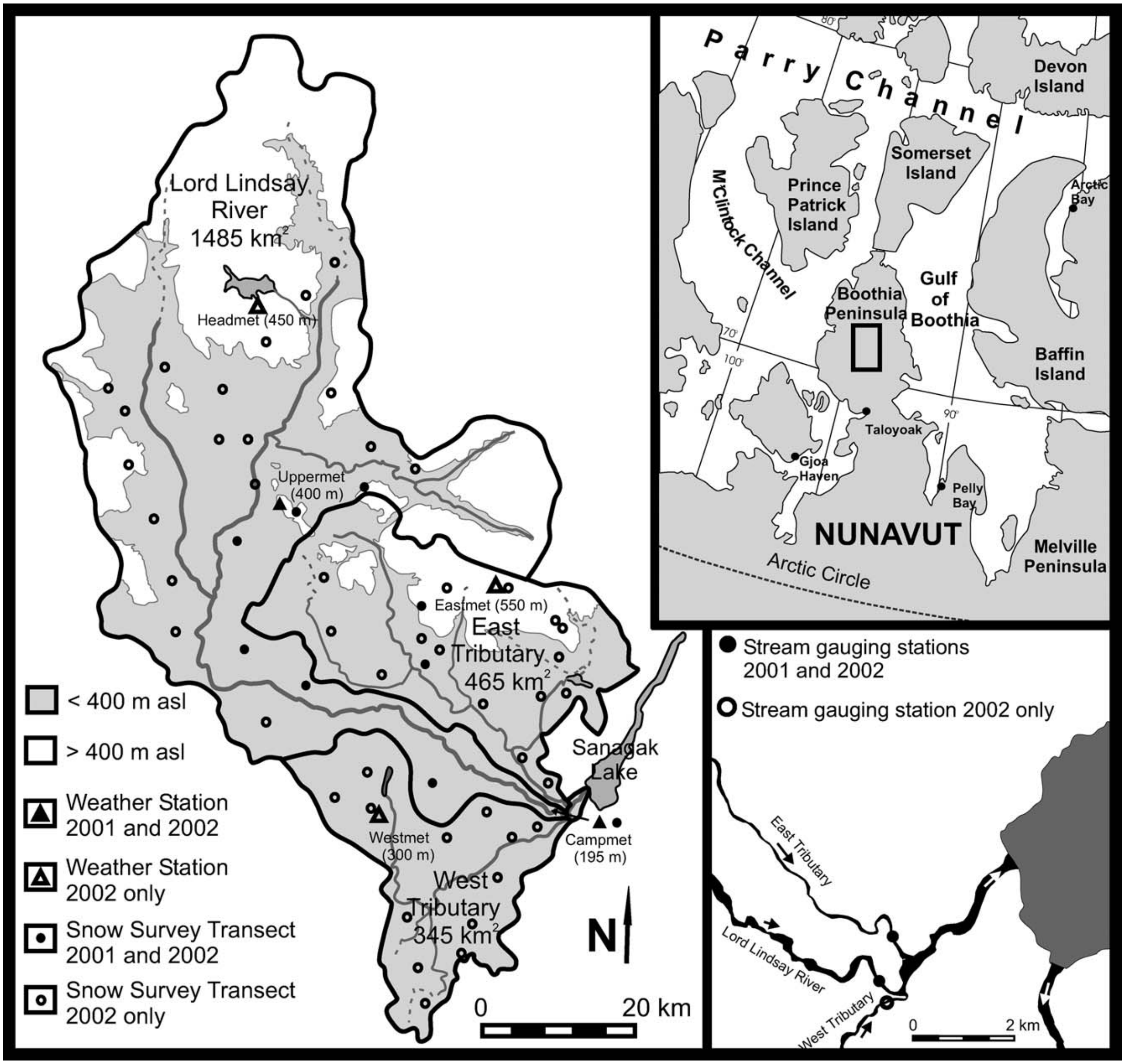



**FIGURE 1. Weather stations, stream gauge sites, and snow survey transect locations in the Lord Lindsay River and tributary watersheds, Boothia Peninsula, Nunavut. Inset map indicates location of study area in the Canadian Arctic.**

and July, respectively (Maxwell, 1981). Streamflow is restricted to June through September, when mean monthly temperatures are near or above 0°C. Similar to other arctic environments, most precipitation falls as snow, and the ensuing nival melt is generally the dominant hydrological event. Mean annual snowfall at Taloyoak (formerly Spence Bay, 1953–2002), ~75 km south of the study site (Fig. 1), is 81 cm (Dyke, 1984), with the bulk of snowfall during the relatively warm fall months. Snow experiences significant redistribution during the winter by dominantly northwest winds (Maxwell, 1981). Rainfall usually occurs as trace or low intensity events, while high intensity events (>25 mm $d^{-1}$) are rare.

## Methods

The goal of the field program was to estimate daily water and sediment outputs in response to daily atmospheric conditions. A more detailed discussion of the methods used can be found in Forbes (2003).

### *HYDROMETEOROLOGY*

Snow surveys were conducted in May/June 2001 and 2002 using the terrain index method (Yang and Woo, 1999). Each snow survey transect consisted of 10 snow depth measures at 10-m intervals, with one measure of snow density and SWE at the mid-point. Some rolling hill, gullied terrain and slope aspect units were sampled at 5-m intervals as the 100-m-long standard transect exceeded the length of the feature or the 10-m interval was too coarse to capture variability along the unit. SWE measures were extrapolated along the transect length, averaged at each site, and finally compared by terrain unit and spatially by altitude and specific catchment.

Meteorological conditions in 2001 were recorded at two stations located at 195 and 400 m a.s.l., and in 2002 at five stations ranging between 195 and 550 m a.s.l. (Fig. 1). The additional stations in 2002 were used to improve estimates of lapse rate and rainfall variability across the watersheds. Weather stations recorded temperature at 1.5 m above the ground with an Onset Hobo temperature logger (0.2°C resolution) at 10-min intervals. Precipitation was recorded with a Davis industrial tipping bucket rain gauge (0.2 mm resolution) logged with an Onset event logger. In 2002, the primary weather station (Campmet) was equipped with a Davis solar radiometer (±4%), industrial model anemometer, and tipping bucket rain gauge logged with a Unidata Prologger at 10-min intervals. Air temperature and humidity at Campmet were recorded with an Onset Hobo Pro logger at 1.5 m elevation at the same time intervals.

Discharge measurements were conducted using the velocity-area method, whereby velocity and channel depth measurements were obtained from Zodiac boats using a cableway, and stage was recorded at 10-min intervals with a stilling well equipped with a calibrated Sensym SCX differential pressure transducer vented to the atmosphere and logged with an Onset Hobo logger. Hydrographs were developed for each river using stage-discharge rating curves (Forbes, 2003). Water temperature was measured by suspending an Onset water temperature sensor (0.2°C resolution) and Hobo logger from the cableway in the thalweg.

### *WATER SAMPLING*

Water samples for suspended sediment concentration (SSC) were obtained daily in the Lord Lindsay River and East Tributary in 2001 ($n = 70$) and twice daily in all three rivers in 2002 ($n = 121$) during the snowmelt and storm flow periods, and once every 2 to 3 days during recession and baseflow periods. Additional samples were taken during peak flow to determine diurnal variability. Each sample was vacuum filtered for suspended sediment through pre-weighed 0.45 μm cellulose nitrate or polycarbonate filters. The filter papers were stored, dried and weighed in the laboratory.

Attempts to obtain continuous turbidity records from the rivers were not successful due to low SSC and equipment failures. Hourly SSC records were established for all rivers using discharge-SSC rating curves. Daily SSQ records were then compiled by cumulatively summing the hourly SSC data.

### *HYDROMETEOROLOGICAL ANALYSIS*

Hydrological and meteorological relationships were assessed using regression analysis in order to determine the climatic controls on water and sediment outputs. The input variables considered were mean daily incoming short-wave radiation from the Campmet station (Fig. 1) and mean daily air temperature from all available meteorological stations. However, air temperatures from Uppermet were used exclusively for several reasons: (1) data was available from both seasons, thus allowing for interseasonal comparisons; (2) the station elevation (400 m a.s.l.) was representative of the largest proportion of the overall watersheds; and (3) observed relationships between air temperature and hydrological output variables showed only minor variability between stations (Forbes, 2003). The dependent variables considered were total daily runoff and mean daily SSC for each respective river. SSC values were based on manual sample measurements, whereby only the afternoon suspended sediment sample was available in 2001 and a mean value of the morning and afternoon sample was taken in 2002.

Daily hydrological outputs were found to substantially lag daily thermal conditions. Woo (1976) attributed this phenomenon to the changing areal extent and location of basin snow cover relative to the stream gauging stations. In order to allow direct comparisons of hydrometeorological variables, it was necessary to establish a fixed "hydrological day" for each river that captured the daily water and sediment outputs in response to the events of the meteorological day (0000–2400h). The average time of daily peak flow during the snowmelt period was calculated for each river and served as the midpoint for the hydrological day. The hydrological day was also applied to suspended sediment data as SSC and discharge were found to be consistently in-phase (e.g., Braun et al., 2000). The mean time of peak flow occurred at 0140h and 0240h for the West and East Tributaries, respectively, and 0600h for the Lord Lindsay River.

It is important to point out that the application of a fixed hydrological day is an oversimplification of the physical processes that occur across a watershed (Hardy, 1996). However, generalizations made in this study are warranted by the fact that considerably greater error would be introduced to the analysis by not applying any form of hydrological lag time. Over- or under-estimation that may result from applying a fixed hydrological day through the season would occur during daily low flow, a relatively insensitive period of the hydrograph.

**TABLE 1**

**Snow survey results in 2002 divided by terrain index units. Average snow water equivalence (SWE) for the dominant broad plain terrain feature (59–74% watershed cover) was found to be most representative of the total index SWE for the watersheds.**

| Terrain unit >watershed | Transects ($n$) | Average SWE (mm) | Watershed cover (%) | Index SWE (mm) |
|---|---|---|---|---|
| Broad Plain | 22 | 76.5 | 70 | 53.6 |
| >West Tributary | 6 | 94 | 74 | 69.6 |
| >East Tributary | 4 | 55.9 | 59 | 33.0 |
| >Lord Lindsay | 12 | 74.6 | 73 | 54.5 |
| Bouldery | 12 | 44 | 10 | 4.4 |
| >West Tributary | 1 | 39.1 | 3 | 1.2 |
| >East Tributary | 5 | 30 | 16 | 4.8 |
| >Lord Lindsay | 6 | 56.6 | 10 | 5.7 |
| Rolling Hill | 8 | 80.7 | 7 | 5.6 |
| >West Tributary | 2 | 94.5 | 11 | 10.4 |
| >East Tributary | 4 | 68.9 | 9 | 6.2 |
| >Lord Lindsay | 2 | 90.5 | 6 | 5.4 |
| Highland Plateau | 6 | 54 | 6 | 3.2 |
| >West Tributary | 2 | 62.9 | 7 | 4.4 |
| >East Tributary | 1 | 30.2 | 7 | 2.1 |
| >Lord Lindsay | 3 | 56.1 | 6 | 3.4 |
| Gullied and Incised | 5 | 215.2 | 6 | 10.8 |
| >West Tributary | 1 | 215.2* | 5 | 10.8 |
| >East Tributary | 2 | 215.2* | 9 | 19.4 |
| >Lord Lindsay | 2 | 215.2* | 5 | 10.8 |
| North Slope^ | 2 | 58.5 | | |
| East Slope^ | 2 | 8.1 | | |
| South Slope^ | 2 | 12.3 | | |
| West Slope^ | 2 | 48.2 | | |
| Total SWE | 61 | 71.6 (SD = 61.1) | 100 | 77.6 |
| >West Tributary | | 87.2 (SD = 44.5) | 100 | 96.3 |
| >East Tributary | | 55.4 (SD = 93.9) | 100 | 65.6 |
| >Lord Lindsay | | 66.5 (SD = 31.3) | 100 | 79.7 |

* The morphology of gullied and incised terrain were not comparable between catchments and therefore the average SWE for the terrain unit was applied to each.

^ Slope aspect transects were conducted across single sites in each of the Lord Lindsay River and East Tributary catchments; however, were not included in estimates of total SWE.

## Results

### *HYDROMETEOROLOGICAL CONDITIONS IN 2001 AND 2002*

Both field seasons were substantially different due to a number of factors. The winter SWE that preceded the 2002 streamflow season was 78 mm, or, approximately half that of the 132 mm in 2001 (Table 1). Consistent with other arctic studies (e.g., Kane et al., 1991; Woo and Young, 1997; Yang and Woo, 1999), gullies, hollows, and channels collected approximately three times more snow than the broad plain terrain unit that dominates the watershed (Table 1). A more representative terrain index snow survey from 2002 confirmed the findings of Yang and Woo (1999), showing that at large scales, the dominant terrain feature showed the least variability and was most representative of the mean SWE for the watershed (Table 1). Elevation did not appear to have significant effect on SWE (Forbes, 2003). Based on this snow distribution it was possible to use the more limited snow survey data from 2001 (Fig. 1), which was estimated exclusively from transects conducted across broad plain terrain units.

The 2001 season had two major rainfall events, with 29 mm recorded during the largest at the Uppermet station on 12–13 July (Fig. 2a). The 2002 season was characterized by numerous trace rain and wet snow events and an 8-mm rainfall on 7–8 July. Soil moisture surveys and field observations noted the watershed to be highly saturated well into the snowmelt recession period of both seasons, followed by a rapid drying and expansion of the active layer, and brief return to saturated conditions after the major rainfall events. The saturated layer was observed to drop to 80 cm depth by the late summer in 2001. Estimated evapotranspiration rates, based on gravimetric measures from a network of soil samples, were 0.8 and 0.6 mm $d^{-1}$ in 2001 and 2002, respectively (Forbes, 2003).

Air temperature and incoming solar radiation followed strong diurnal variation through the season (Forbes, 2003). A vertical lapse rate was observed across the watershed, varying both intra- and interannually, and is evident in the comparison of air temperature records between Campmet and Uppermet stations (Fig. 2a). In 2001, an average lapse rate of 1.5°C/100 m was calculated from first flow (10 June) until the end of the snowmelt recession period (8 July), and lowered to 0.3°C/100 m in the last two weeks of study season. In 2002 the average lapse rate was 1.0°C/100 m and remained relatively stable until the end of the snowmelt recession period (1 July). During the final week of observations, the lapse rate was 0.7°C/100 m. The steady decline of the lapse rate through the snowmelt period and into the summer was likely due to waning snow cover and suggests that snowmelt followed an altitudinal retreat.

Daily mean air temperatures from both Campmet and Uppermet were highly correlated with the nearest weather station located at Taloyoak ($r^2 = 0.93$, $n = 122$, $p < 0.01$; and $r^2 = 0.92$, $n = 99$, $p < 0.01$, respectively). The timing of precipitation events between the stations was also similar, although the amounts were not as well correlated ($r^2 = 0.64$, $n = 34$, $p < 0.01$; and, $r^2 = 0.56$, $n = 34$, $p < 0.01$, respectively). This is a well-documented problem in arctic regions where meteorological records from coastal stations tend to underestimate precipitation relative to interior sites (Woo et al., 1999). Nonetheless, it can be concluded that the watersheds broadly experienced the same weather patterns as Taloyoak on a synoptic scale.

The diurnal pattern of the discharge hydrographs through the spring melt periods suggests that runoff was governed by the atmospheric energy available for snowmelt. Daily discharge amplitude dampened with the exhaustion of the snowpack. River water temperature also followed a diurnal pattern through the snowmelt period with opposite amplitude to discharge. The coldest waters coincided with highest discharge during peak snowmelt (Forbes, 2003). The cycle was dampened during the 2001 peak flow period, most notably for the Lord Lindsay River, indicating an almost complete snowmelt flush.

Subtle climatic differences between years produced pronounced differences in the hydrographs. Specific flow periods have been delineated with regards to the state of the snowpack and discharge response (Fig. 2b). Variable early season temperatures in 2001 caused an initial melt peak (1) to be interrupted by an inter-flood low-flow period (2). Subsequent warming resulted in the rapid rise (3) and recession (4) of the main snowmelt flood peak. Finally, a summer storm period (5) punctuated the baseflow period (6). The 2002 hydrograph was marked by a single prominent flood peak (1) in response to the spring snowmelt and followed by rapid recession (2) to baseflow (3). A week of modest early snowmelt flow preceded the main 2002 peak discharge (14–21 June) due to sustained cool temperatures (Fig. 2a). Maximum discharges were comparable between years: 400 and 360 $m^3$ $s^{-1}$ for the Lord Lindsay River, and 100 and 90 $m^3$ $s^{-1}$ for the East Tributary for 2001 and 2002, respectively.

### *SUSPENDED SEDIMENT TRANSPORT*

Suspended sediment concentration (SSC) was found to increase both linearly and non-linearly with discharge throughout the streamflow season (Fig. 3). Although sampling resolution prevented a more detailed analysis, it was evident that high flows were accompanied by variable, but relatively high SSC (10–30 mg $L^{-1}$), whereas subsequent low flows were characterized by low SSC (<2 mg $L^{-1}$). Results from 2002 indicate that SSC was generally higher for the morning (peak flow) compared to the afternoon (daily low flow), but during low to moderate flow periods the difference was minimal (~1 mg $L^{-1}$).

High suspended sediment transfer only occurred during the short-lived nival peak, suggesting that a threshold discharge was required in order to generate significant sediment transport. As previously mentioned, peak flow rates were comparable between seasons but, due to greater SWE, were sustained for approximately four days in 2001 compared to only one day in 2002. As a result, seasonal sediment yields were almost four times greater in 2001 than 2002 (Fig. 2c). Greater than 80% of total seasonal runoff and 93% of total annual suspended sediment transport occurred during the snowmelt periods, with approximately half the annual sediment being transferred during the maximum flow periods alone. The dominance of the snowmelt period for suspended sediment transport is consistent with other arctic studies (e.g., Woo et al., 1996; McNamara et al., 1998) and emphasizes the importance of the annually recurring snowmelt flood to suspended sediment transport (Braun et al., 2000). Nonetheless, the specific sediment yields recorded are some of the lowest reported from the Arctic, ranging between 0.2 and 1.9 t $km^{-2} \cdot a^{-1}$ (Fig. 2c).

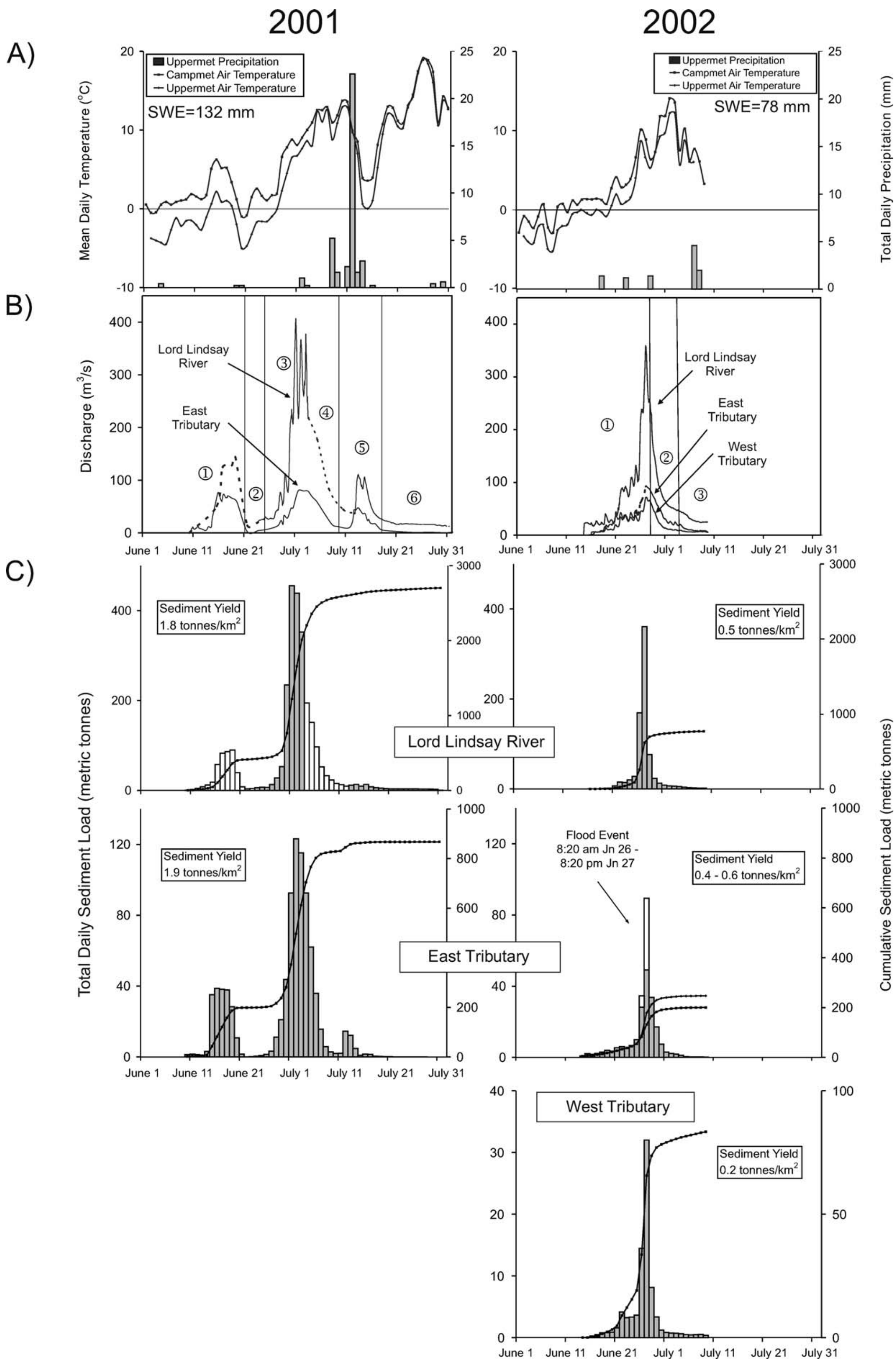
### *SUSPENDED SEDIMENT-DISCHARGE HYSTERESIS*

Suspended sediment-discharge hysteresis was evident both intra- and inter-seasonally with varying intensity in each watershed. Relationships between hydrological variables were analyzed at different times of the season and diurnally when possible (Fig. 4).

### *EARLY MELT AND RECESSION: MODERATE FLOW*

Broadly, periods of moderate flow in 2001 were characterized by higher SSC than similar discharge in 2002 (Fig. 4). Although larger rivers do not typically experience the effects of snow damming that both hinder flow and entrain sediment on smaller streams (e.g., Woo and Sauriol, 1983), snow- and ice-lined channels can act to buffer against fluvial erosion and thaw (Forbes, 1975; Scott, 1978; Woo and McCann, 1994). Deep channel snowpack was a common feature in the watersheds during both seasons of study. However, higher SSC at moderate flow rates in 2001 appears to suggest that rivers were better able to counter snow and channel ice effects and access greater sediment sources. This may be attributed to both the nature of the river breakup and time required to reach peak flow in each year.

Soon after initial flow in 2001, ice began to choke river channels, having either emerged from channel bottoms or calved from banks. Ice jamming (Prowse, 1991) followed and led to brief periods of hydrological back-up. Through the higher flow of the initial peak (15–19 June), ice became mobile and floes were observed to scour channel banks, beds, and other ice slabs (Mackay and Mackay, 1977). When stage dropped, substantial erosion marks were observed along channel banks. By comparison, the ice breakup in 2002 was less pronounced, ice floes were



2001
2002
A)
B)
C)
Uppermet Precipitation
Campmet Air Temperature
Uppermet Air Temperature
SWE=132 mm
SWE=78 mm
Mean Daily Temperature (°C)
Total Daily Precipitation (mm)
Discharge (m3/s)
Lord Lindsay River
East Tributary
West Tributary
Sediment Yield 1.8 tonnes/km2
Sediment Yield 0.5 tonnes/km2
Sediment Yield 1.9 tonnes/km2
Sediment Yield 0.4 - 0.6 tonnes/km2
Sediment Yield 0.2 tonnes/km2
Flood Event 8:20 am Jn 26 - 8:20 pm Jn 27
Total Daily Sediment Load (metric tonnes)
Cumulative Sediment Load (metric tonnes)
June 1
June 11
June 21
July 1
July 11
July 21
July 31

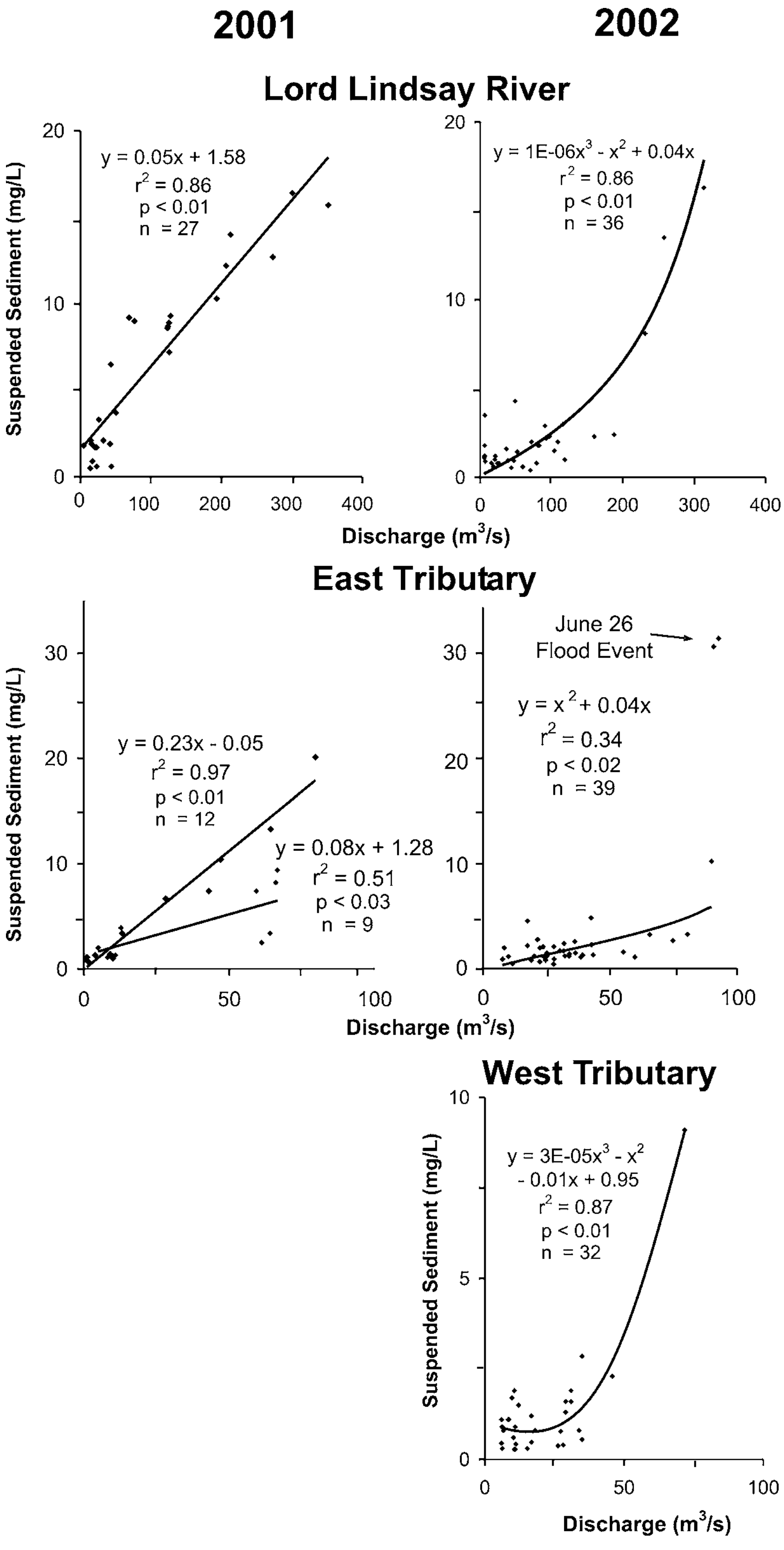



**FIGURE 3.** Suspended sediment–discharge rating curves for the Lord Lindsay River and tributaries. The line with lower slope for the East Tributary in 2001 represents the initial melt peak period, and line of increased slope represents the rest of the season.

←

**FIGURE 2.** (A) Meteorological, (B) hydrological, and (C) suspended sediment load records for the study rivers. Broken lines indicate periods when stilling wells were out of operation due to ice jams, and discharge was estimated using manual stage and discharge measurements. Hollow bars for the Lord Lindsay River (2001) represent periods with manual stage measurements. Hollow bars for the East Tributary (2002) indicate the highly turbid samples from 26–27 July estimated by linear interpolation (see text).

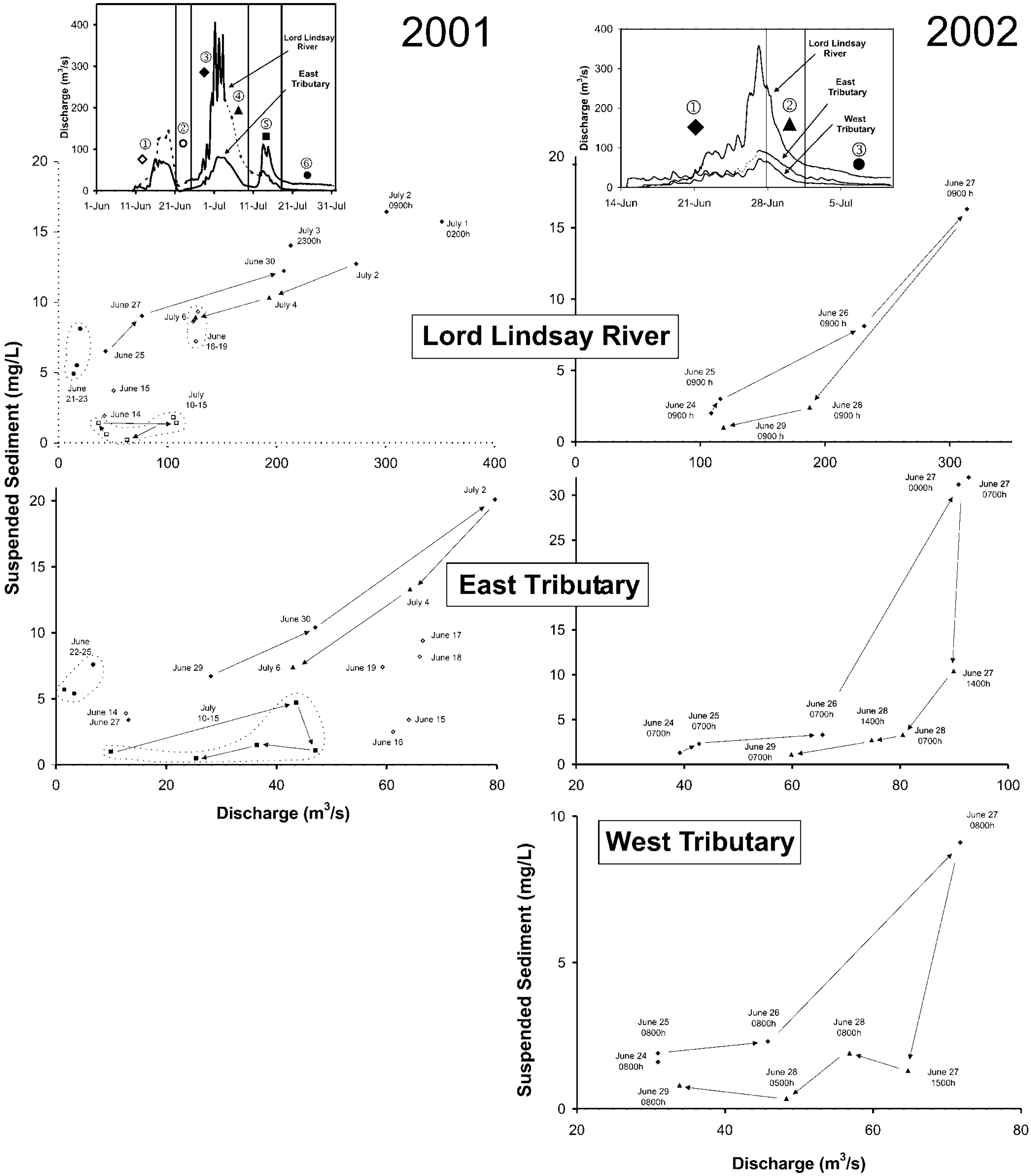



**FIGURE 4. Suspended sediment–discharge hysteresis plots for the Lord Lindsay River and tributaries. Symbols in plots correspond to periods indicated in the inset hydrographs. In 2001, limited hysteresis was evident in the East Tributary, whereby suspended sediment concentration (SSC) was higher during the peak flow period compared to similar discharge during the initial melt peak. Sediment exhaustion was also evident in both rivers following the 29-mm rainfall event. In 2002, prominent hysteresis in the West Tributary following peak flow was likely due to hydrological back-up that resulted in overestimated discharge between 27 and 29 June.**

greatly reduced, and those that emerged from channel bottoms and banks generally remained in place. As previously mentioned, the first week of discharge in 2002 was marked by cooler temperatures and reduced flows that limited ice mobility. Thus, much of the 2002 channel ice was allowed to gradually decay before stage substantially rose.

Peak discharge occurred after 22 days of river flow in 2001 and only 13 days in 2002, while the recession was delayed a further four days in 2001 as a result of sustained maximum flows. The extended delays may have allowed for extended channel bed and bank thaw (Clark et al., 1988) and subsequent increased sediment availability to

**TABLE 2**

**River Melting Degree Days (RMDD) for the Lord Lindsay River and tributaries. Channel banks and beds were exposed to substantially more melt energy input from river water leading up to the snowmelt flood peak in 2001.**

| | RMDD—prior to peak flow | # Days | RMDD—prior to first day of snowmelt recession | # Days |
|---|---|---|---|---|
| 2001 Lord Lindsay River | >52* | 22 | >75* | 25 |
| 2002 Lord Lindsay River | 11 | 11 | 17 | 12 |
| East Tributary | 19 | 12 | 24 | 13 |
| West Tributary | 10 | 12 | 16 | 13 |

*Early season data in 2001 (pre-June 18) was lost due to the destruction of the stilling well. Value given is a minimum estimate of RMDD.

the rivers. Miles (1976) noted the importance of thermal effects on the perimeter of the channel bed, explaining that high water temperatures can facilitate greater sediment erosion and transport. Various bank failures, including processes of subsidence and slumping, can occur along channel banks when materials of high ice content are subjected to melt by river water (Church and Miles, 1982). Some measure of this effect can be obtained from the cumulative thermal energy in the river. River water was measured to have exerted more than 52 “River Melting Degree Days” (RMDD) from initial flow to peak in 2001 compared to 11 RMDD in 2002 (Table 2).

Greater exposure to thermal energy inputs from river water that resulted in reduced channel snow may also help to explain the higher SSC in the East Tributary during the peak flow period of 2001 compared to similar discharge rates during the initial melt peak (Fig. 4). Although discharge rates and effects of river breakup appear to have been substantial enough to clear the majority of channel snowpack on the larger Lord Lindsay River, snow and ice-lined channels were observed to persist longer on the East Tributary. As a result, a different suspended sediment–discharge rating curve was apparent for the river during the early melt period (Fig. 3).

The inter-flood low-flow period in 2001 was marked by moderate sediment transport in both rivers (5–8 mg $L^{-1}$, $n = 6$) (Fig. 4). These SSC measurements were not applied to the rating curves as they were in poor agreement with later season baseflow where SSC remained consistently low (<2 mg $L^{-1}$, $n = 14$). The moderate levels of SSC during this period were perhaps a residual effect of the river ice breakup during the initial melt peak that mobilized suspended sediment and transported moderate sediment concentrations of between 7 and 9 mg $L^{-1}$ for four days, only to be abruptly terminated by cold temperatures. Furthermore, a severe wind storm accompanied the colder temperatures during the inter-flood low-flow period and contributed substantial eolian debris to the channels.

## *PEAK FLOW*

Maximum flow occurred in channels with reduced snowpack and resulted in consistent SSC-discharge relationships. During each season, suspended sediment load from the falling limb of the main melt peak showed minimal evidence for hysteresis in the Lord Lindsay River and East Tributary (Fig. 4). As an interesting comparison, the mean daily SSC in the Lord Lindsay River during peak discharge from both seasons were 14.6 and 14.9 mg $L^{-1}$, respectively.

Pronounced suspended sediment–discharge hysteresis was evident in the West Tributary immediately following peak flow, from the afternoon of 27 June to the morning of 29 June. However, it is important to note that hydrological backup was observed at the gauging station during this period due to peak flow on the main river, and as a result discharge was likely overestimated. Manual measurements indicated discharge to be less than half of stage-discharge rating curve estimates for this time. The narrow range of SSC values during this period prevented the use of a separate rating curve. Instead, linear interpolation from measured SSC values was used to provide a more accurate estimate of SSQ.

The 26 June 2002 flood peak caused exceptionally high SSC on the East Tributary (>30 mg $L^{-1}$, $n = 2$). The river water was observed to be unusually turbid for at least 12 hours. Due to the relatively extreme nature of these SSC samples, the values were not included in the SSC-discharge rating curve (Fig. 3). In order to estimate the significance of this event, linear interpolation was used from the point that these turbid conditions were first and last observed (26 June 2020h to 27 June 0820h) with the measured SSC values through this period. These estimates suggest that this event increased the annual East Tributary sediment yield by c. 35%. During this event, the river was observed to have overtopped its banks at the stream gauging station and various locations upstream, potentially mobilizing substantial amounts of floodplain sediment.

## *RAINFALL RESPONSE*

Lower intensity rainfall (<8 mm $d^{-1}$) produced both minimal discharge and suspended sediment response, confirming the observations of other arctic studies (e.g., Kriet et al., 1992; Braun et al., 2000). Discharge after the 29-mm rainfall event in 2001 increased substantially in both rivers (Fig. 2b), while SSC increased only slightly (~1–3 mg $L^{-1}$) (Fig. 4). Summer storms generally occur when materials are thawed and thus more readily eroded (Woo and McCann, 1994). Furthermore, rain events occur across the entire watershed and are potentially capable of accessing sediment sources otherwise protected from fluvial erosion (Braun et al., 2000; Lamoureux, 2000). The minimal sedimentological response across the watersheds suggests that erodable sediment was limited. Sediment exhaustion has been identified in many arctic nival catchments (Lewkowicz and Wolfe, 1994; Woo and McCann, 1994; Braun et al., 2000). The wide range in SSC values during the rainfall event period prevented the use of a separate rating curve. Linear interpolation was used with the measured values from 12 to 17 July to provide an estimate of total SSQ.

## *METEOROLOGICAL AND HYDROLOGICAL ASSOCIATIONS*

Significant linear correlations between daily mean air temperature and daily runoff, and mean SSC, were found through the main snowmelt periods of each streamflow season (Table 3). By contrast, cross correlation between mean daily incoming solar radiation and both discharge and SSC produced weak relationships ($r^2 < 0.27$). The strength of the temperature relationships deteriorated with the onset of recession as the snowpack was depleted. The strength of correlations was substantially weaker through the early melt of both seasons, likely due to limited fluvial erosion in snow- and ice-lined channels and low water temperatures. These results suggest that the potential for sediment erosion in many cases far exceeded the supply of materials (Woo and McCann, 1994), preventing strong relationships between hydrometeorological variables.

Cumulative watershed outputs of water and sediment showed a linear response to cumulative mean degree-days (MDD) until SWE was depleted (Fig. 5), suggesting that both were initially linked to variations in snowmelt (e.g., Hardy, 1996). It is interesting to note that the cumulative suspended sediment yield and degree-day plots for both seasons in the Lord Lindsay River showed maximum daily discharge peaks and subsequent sediment transfer peaks to have occurred after 18.4 MDD, despite other substantial meteorological differences. The

**TABLE 3**

**Relationships between daily runoff (Q), mean daily suspended sediment concentration (SSC), and mean daily air temperature (T) during specific flow periods (refer to Fig. 2b) for the Lord Lindsay River and tributaries, 2001–2002. Sample (n) corresponds to a single daily sample time in 2001 and an average of two daily sample times in 2002. Values shown in bold typeface are significant at the 95% level.**

| | Lord Lindsay River | | | | | | East Tributary | | | | | | West Tributary | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T vs Q | | | T vs SSC | | | T vs Q | | | T vs SSC | | | T vs Q | | | T vs SSC | | |
| Flow Perlod | $r^2$ | $p$ | $n$ | $r^2$ | $p$ | $n$ | $r^2$ | $p$ | $n$ | $r^2$ | $p$ | $n$ | $r^2$ | $p$ | $n$ | $r^2$ | $p$ | $n$ |
| 2001 | | | | | | | | | | | | | | | | | | |
| 1st Peak ① | 0.42 | 0.08 | 10 | **0.67** | **0.01** | **8** | **0.66** | **0.01** | **10** | 0.31 | 0.12 | 9 | | | | | | |
| Inter-flood low flow ② | 0.27 | 0.65 | 3 | **0.99** | **0.02** | **3** | 0.34 | 0.61 | 3 | N/A | N/A | 2 | | | | | | |
| 2nd PeakA ③ | **0.95** | **0.01** | **10** | **0.92** | **0.01** | **5** | **0.96** | **0.01** | **10** | 0.88 | 0.06 | 4 | | | | | | |
| Flood Recession ④ | 0.19 | 0.39 | 6 | 0.94 | 0.16 | 3 | 0.17 | 0.42 | 6 | N/A | N/A | 2 | | | | | | |
| Rain Event ⑤ | 0.01 | 0.82 | 5 | 0.56 | 0.25 | 4 | 0.13 | 0.66 | 5 | 0.90 | 0.20 | 3 | | | | | | |
| Baseflow ⑥ | 0.15 | 0.13 | 17 | 0.55 | 0.06 | 7 | **0.48** | **0.01** | **17** | 0.01 | 0.91 | 7 | | | | | | |
| 2002 | | | | | | | | | | | | | | | | | | |
| 1st Flow to Peak ① | **0.94** | **0.01** | **12** | **0.95** | **0.01** | **12** | **0.96** | **0.01** | **13** | **0.79** | **0.01** | **13** | **0.85** | **0.01** | **11** | **0.82** | **0.01** | **11** |
| Flood Recession ② | 0.46 | 0.21 | 5 | 0.20 | 0.19 | 5 | 0.72 | 0.07 | 5 | 0.27 | 0.37 | 5 | 0.58 | 0.14 | 5 | 0.10 | 0.60 | 5 |
| Baseflow ③ | 0.61 | 0.07 | 6 | 0.25 | 0.67 | 3 | **0.76** | **0.03** | **6** | 0.14 | **0.54** | 5 | **0.70** | **0.04** | **6** | 0.67 | 0.09 | 5 |

East Tributary experienced similar sediment transfer peaks in 2002 and the onset of high sediment transfer conditions in 2001 following the same number of MDD. However, the sustained peak flow period consisted of only between 10% and 15% of the MDD in both years, but resulted in approximately 50% of the sediment delivery. Hence, although melt energy was a direct control over snowmelt, cumulative discharge and suspended sediment yield were limited by SWE (Fig. 5). Comparison of cumulative sediment yield between 2001 (SWE = 132 mm) and 2002 (SWE = 78 mm) demonstrates this control is proportional, but two years of field data are insufficient to identify a quantitative relationship.

## Discussion

### *LIMITATIONS OF AIR TEMPERATURE FOR FORECASTING STREAMFLOW: SNOWPACK EXHAUSTION*

Thermal energy appears to be critical in generating streamflow and suspended sediment transfer in large middle arctic catchments, but only until the SWE begins to undergo substantial depletion. Once watershed snowmelt begins to wane, a decoupling occurs between the atmospheric energy input (e.g., air temperature) and hydrological output. Braun et al. (2000) also noted that coherent relationships between atmospheric and hydrological variables in the Sophia River watershed on Cornwallis Island weakened and eventually disappeared as a result of snowpack exhaustion. Although late-lying snowbanks and channel snowpack were both observed and measured with hydrochemical indicators to contribute approximately 15–50% of summer flow in the Lord Lindsay River and tributary watersheds (Forbes, 2003), lower summer discharge was not at levels to support high SSC. In this regard, the hydrological output during summer baseflow was not representative of melt energy input, and for all intensive purposes the watershed was exhausted of snowpack that could contribute appreciably to streamflow and sediment transfer.

There is good reason to believe that snowpack exhaustion is not unique to the two seasons of study. Snowpack exhaustion has been observed to be a recurring phenomenon in studies at the Meecham River (Cogley, 1975) and McMaster Rivers (Woo, 1983) on Cornwallis Island and Hot Weather Creek (Lewkowicz and Wolfe, 1994) on Ellesmere Island. For these nival-regime catchments, snow accumulation during each previous winter acts as the primary control on watershed streamflow and suspended sediment transport (Church, 1988). In our study, only peak flow discharge rates were capable of moving high SSC (>10 mg $L^{-1}$). Increased SWE in 2001 resulted in a prolonged period of maximum annual discharge and substantive sediment transfer. Thus, annual suspended sediment load in this environment was ultimately a function of total peak discharge through SWE rather that a function of melt energy.

In addition to Braun et al. (2000), the only other comparable investigation of climatic influences on hydrological outputs in arctic regions, not hindered by the presence of snow dams (e.g., Wedel et al., 1977; Woo, 1983), was conducted by Hardy (1996) at the Lake C2 catchment (21 $km^2$) on northern Ellesmere Island. Here, the magnitude of daily discharge was found to be limited by melt energy rather than the supply of snow and appears to argue against a SWE control. However, Hardy (1996) noted that the Lake C2 watershed had substantial areas of perennial snow. Although late-lying snow contributed to relatively minimal discharge and suspended sediment outputs within the catchments on the Boothia, it is possible that perennial snowbanks in high arctic catchments could contribute appreciably to watershed outputs. Marsh and Woo (1981) and Lewkowicz and Young (1990) also showed that the runoff regime in many areas of the High Arctic is dominated by late-lying snow. Snowpack persistence due to colder temperatures could explain why associations between watershed outputs and air temperature at Lake C2 remained strong through the summer streamflow season.

More generally, Sampson (2001) found strong correlations between total annual discharge and the magnitude of the nival peak in the Hayes River, a middle arctic watershed (18,100 $km^2$) ~300 km south of the Lord Lindsay River, during the 1970s ($r^2 = 0.79$) and 1980s ($r^2 = 0.84$). Associations between daily mean temperature and discharge were found to be much lower ($r^2 < 0.30$). These results further reinforce the importance of snowpack at increasing spatial scales.

The large watersheds in this study experienced long delays to both daily and seasonal peak flow as a result of substantial routing and muted topography. While a single day of warm weather may be capable of generating a rapid runoff response accompanied by relatively high sediment transport on a small stream, larger watersheds require greater hydrological inertia to produce substantial discharge. High rates of discharge and sediment transfer did not occur in our study rivers until the meltwater source areas became highly integrated (Bowling et al., 2003). Thus, the maintenance of peak flow rates at the large scale was a culmination of hydrometeorological processes. Although similar

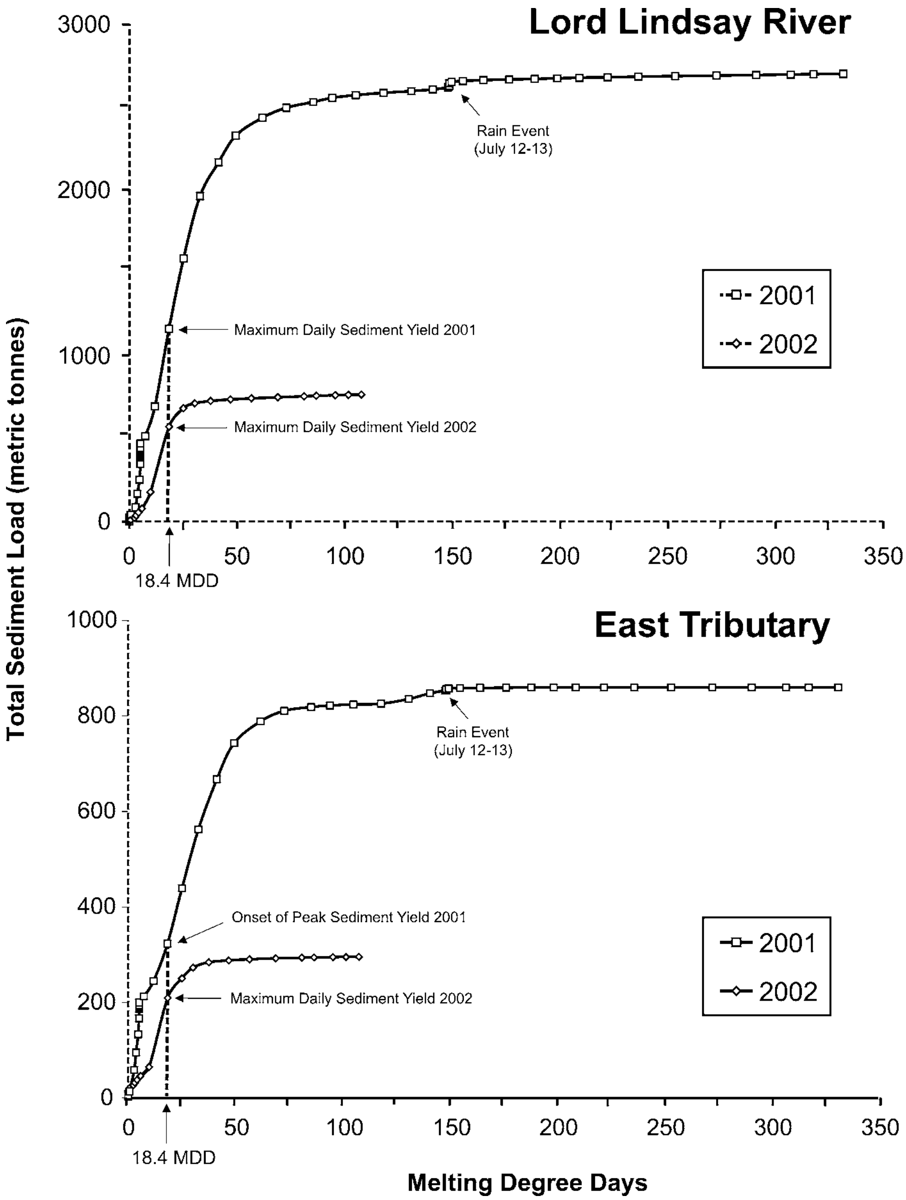



**FIGURE 5. Cumulative suspended sediment load in the Lord Lindsay River and East Tributary in response to cumulative melting degree days. Greater snow water equivalence (SWE) in 2001 allowed for an extended period of peak discharge and a substantial increase in sediment yield. Maximum daily sediment yields occurred in the Lord Lindsay River during both seasons after 18.4 melting degree days (MDD). The cumulative plot for the East Tributary in 2002 includes the exceptional 26 June flood event (see Fig. 3).**

amounts of melt energy (18.4 MDD) were required to reach peak discharge during both seasons, it was catchment SWE that appeared to control the duration of peak flow for all rivers, and hence, annual sediment yield.

### *RAINFALL-INDUCED SUSPENDED SEDIMENT TRANSPORT*

With the depletion of the snowpack, watershed outputs in nival regime arctic watersheds generally only respond to summer rainfall (e.g., Braun et al., 2000). Church (1988) suggested that large rain events in arctic environments have the potential to produce sediment yields larger than the nival peak. This has been supported by exceptionally high sediment loads following a major storm in a glacierized high arctic watershed (Cogley and McCann, 1976) and inferred from a sedimentary record (Lamoureux, 2000), but has yet to be quantified within a nival regime arctic catchment (e.g., Hodgson, 1977; Braun et al., 2000). The fact that a major rainfall event (>25 mm) in this study was unable to produce a substantial sedimentological response can be at least partly attributed to sediment source limitations. However, there is also reason to believe that differences in watershed vegetation cover, topography, and spatial scale may have reduced sediment erosion compared to other high arctic studies.

High arctic catchments are generally poorly vegetated and can subsequently exhibit greater response to rainfall (Woo and Young, 1997). Considerable sediment delivery can occur through wash on poorly vegetated slopes flows, gullying, and localized earth flows (Woo and McCann, 1994; Lamoureux, 2000). The Lord Lindsay River and tributaries have considerably higher vegetation cover (~80%; Laidler, 2002) than high arctic sites and are less susceptible to these forms of erosion. Thick vegetation cover in the subarctic has been shown to buffer the soil from erosion by both rain drops and running water, while the root system strengthens the soil against mass wasting (Woo and McCann, 1994). Furthermore, Lamoureux (2000) argued that localized mass wasting processes would be unlikely to contribute appreciably to sediment yield from a large catchment.

High rates of rain-induced sediment erosion have also been typically observed in smaller catchments (<100 $km^2$). Kriet et al. (1992) noted that larger rivers such as those on the north slope of Alaska, including the Kuparuk River (8100 $km^2$), have sufficient watershed area to buffer local summer storms. In the same manner, the Lord Lindsay

River and tributaries have not only large areas but limited relief (>350 m). The low-slope gradients attenuate surface flow and increase water ponding, which infiltrates or evaporates rather than contributing to runoff and sediment erosion (Bowling et al., 2003).

As a final point, rain-induced sediment erosion is generally dominated by the erosion of channel banks and remobilization of floodplain materials (Cogley and McCann, 1976; Woo and McCann, 1994), processes which require high river stage. In this study, high sediment yield only occurred when rivers were near bankfull. The rain event appears to have been substantial enough to satisfy the watershed storage capacity and generate runoff, but not to elevate stage to the level necessary to initiate channel bank erosion and access substantial amounts of floodplain materials.

### *IMPLICATIONS FOR CLIMATE CHANGE*

Climatic changes will inherently influence hydrological processes at varying response times (Woo and McCann, 1994). Studies like this one are of particular importance to understanding the sensitivity of arctic environments to future climate change as well as toward making inferences of past hydrological conditions.

Of particular concern is human-induced climate change, due to activities that have increased atmospheric content of carbon dioxide and other greenhouse gases. General circulation models (GCMs) offer the most plausible scenarios of future anthropogenic climate change (Woo and McCann, 1994), and although forecasts from the various GCMs are not in complete agreement, the consensus is that the arctic environment will be particularly sensitive and experience amplified warming (Watson et al., 1998; Houghton et al., 2001). Broad increases in precipitation have also been predicted at high latitudes (Vörösmarty, 2001), although forecasted changes to precipitation patterns and intensity are considerably more uncertain than temperature (Woo and McCann, 1994).

In the case of runoff in large middle arctic catchments, results from this study suggest that increased winter snowfall would be of greater influence over watershed outputs than increasing melt season temperatures. Higher winter SWE would extend the duration of the nival peak and period of high sediment transfer. Woo and McCann (1994) have also suggested that eventually, a warmer climate would support more extensive vegetation across the region. This may further reduce sediment erosion rates during rain events and provide a greater buffer against erosion during the snowmelt flood.

Past arctic climates have been interpreted from varved lake records through the link between river discharge, suspended sediment delivery, and sediment deposition (e.g., Hardy et al., 1996; Lamoureux, 1999). In the case of Sanagak Lake, located downstream from the rivers in this study (Fig. 1), the amount of sediment entering the lake each year is primarily the function of the duration of the nival peak, essentially a period of several days. By extension, sediment accumulation in the lake can be viewed as proportional to the cumulative sediment delivery in the river (Fig. 5). While it is possible that heavy rain events (>30 mm) would be capable of producing additional sub-annual laminae in some watersheds, results from this study suggest the sediment delivery response and resultant deposition in the lake would be minimal for a c. 25-mm event (Fig. 5). These results point to the necessity of understanding the specific catchment controls over sediment availability and transport in order to interpret sedimentary records as paleohydrological proxies.

Although more seasons of study would be necessary to quantify the relationship, the close association between meteorological variables in this study and the Taloyoak weather station warrants the comparison between the instrumental climate and sediment record in Sanagak Lake as a proxy for past discharge. In particular, SWE in this study was proportional to total winter snowfall at Taloyoak (164 and 103 cm, for 2001 and 2002, respectively). Therefore, the potential exists to extend the analysis of SWE variability during the past 50 years using the sedimentary record (e.g., Hardy et al., 1996).

## Conclusions

Thermal energy was critical in generating streamflow and suspended sediment transfer, but only until watershed snowpack was exhausted. Similar amounts of melt energy were required to reach maximum seasonal discharge, but it was snowpack that appeared to control the duration of peak flow rates, and hence substantive SSC. Greater SWE in 2001 prolonged maximum discharge and sediment transport. Thus, high annual suspended sediment load in this environment appears more closely related to peak discharge duration through SWE rather than a function of early season melt energy. With few exceptions, the watersheds responded similarly to snowmelt and rainfall events. Suspended sediment–discharge hysteresis was observed following the early snowmelt period and following a large rain event (>25 mm), demonstrating seasonal sediment supply limitations in the environment.

This study demonstrates the sensitivity of two scales of middle arctic watersheds to both winter SWE and spring thermal conditions with specific implications for climate change. Furthermore, this research provides a basis for interpreting lake sediments as proxies of past hydrological conditions, particularly nival discharge and SWE.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