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Streamflow and Suspended Sediment Transfer to Lake Sophia, Cornwallis Island, Nunavut, Canada

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Abstract

To ascertain the climatic controls on sediment transport to Lake Sophia, Cornwallis Island, Nunavut, Canada, we made detailed hydrological and meteorological measurements in the Sophia River watershed through the 1994 melt season. Streamflow and suspended sediment transport are limited, on an annual time scale, by the supply of snow and sediment in the watershed. Suspended sediment yield from the watershed was only 0.46 t km^{-2}, which is lower than any previously published yield for a stream in the High Arctic. Snowmelt runoff accounted for 88% of the annual suspended sediment load, whereas 6 and 9% were transported in response to a slushflow event and summer rainfall, respectively. These measurements provide no direct evidence that modern-day sediment delivery to Lake Sophia is related to fluctuations in air temperature, which has implications for the paleoenvironmental signal preserved in Lake Sophia's laminated sediments. We suggest that on-site sediment transport studies are necessary to establish the relationships among geology, geography, climate, and hydrology unique to each watershed-lake system and need to be an integral part of any calibration attempt. Additional years of data are needed however to define the interannual variability of streamflow and sediment transport in response to climate.

Introduction

Annually laminated (varved) lake sediments can provide unique, high-resolution records of past environmental change for many different parts of the world (e.g., Leonard, 1985; Itkonen and Salonen, 1994; Bradley et al., 1996; Zolitschka, 1998). To ascertain the paleoclimatic signal represented by interannual thickness variations in a clastic sedimentary record, the modern climate signal represented by land-to-lake sediment transfer must first be understood. In the absence of long hydrological data series, the calibration technique typically applied to lake sediments invokes simple statistical associations between laminae variability (e.g., annual thickness) through time and the nearest available climatic data (e.g., Leonard, 1985; Desloges, 1993; Hardy et al., 1996; Wohlfarth et al., 1998). Without a clear understanding of the processes controlling sediment supply, transport, and deposition in a watershed (Fig. 1), this empirical approach may result in spurious associations (cf. Perkins and Sims, 1983; Stihler et al., 1992). Episodic processes or events indirectly related to climatic variability such as slushflows or upstream releases of ponded meltwater may introduce a nonlinear component to the recorded climate signal. On longer time scales, climatic and geologic change will have profound impacts on the supply and availability of both water and sediment in a watershed (Woo and McCann, 1994), and indirectly on streamflow and sediment transport.

At Lake Sophia, Cornwallis Island (Fig. 2), we hypothesized that modern-day sediment transfer to the lake is controlled by summer climate. If contemporary climatic variability can be linked through snowmelt and streamflow to suspended sediment transport, then the correct conceptual model relating paleoclimate to laminae thickness may be developed, independent from the sediment core and instrumental climate data. The objectives of this study were therefore (1) to quantitatively investigate the short-term relationships and linkages between summer weather, streamflow, and suspended sediment transport through on-site hydrologic process studies and, based upon these relationships, (2) to qualitatively assess the interannual and long-term variability of sediment transport in response to climate variability, and hence the paleoclimatic significance of annual sediment thickness variations in Lake Sophia. This site is part of a north-south transect through the Canadian High Arctic where we have attempted to calibrate laminated lacustrine sediment records (Hardy et al., 1996; Braun, 1997) using this process-based approach.

Watershed Geography

CORNWALLIS ISLAND

Cornwallis Island is a small, low-relief island at the southern edge of Canada's Queen Elizabeth Islands (Fig. 2). The regional physiography of this central arctic lowland area is dominated by flat, low-lying terrain with little vertical relief, extensive plateau surfaces, and incised river channels. Cornwallis Island consists mainly of rolling plateau-like uplands between 100 and 300 m a.s.l. and a large featureless plateau in the southeast of the island (Edlund, 1991). Steep coastal cliffs fringe the island's east coast, which is indented by several fiord-like bays (Carter et al., 1987). Most of Cornwallis Island is underlain by Ordovician to Devonian limestones and dolomites (Edlund, 1991), which are common within the central Queen Elizabeth Islands (Cogley, 1975). There is evidence of local glaciation during the Late Wisconsinan, but past glacial activity had only minor and localized effects on the modern physiography of the island and the region (Edlund, 1991). More than 75% of Cornwallis Island is covered by bedrock or weathered bedrock debris, whereas spatially-extensive accumulations of fine surficial ma-

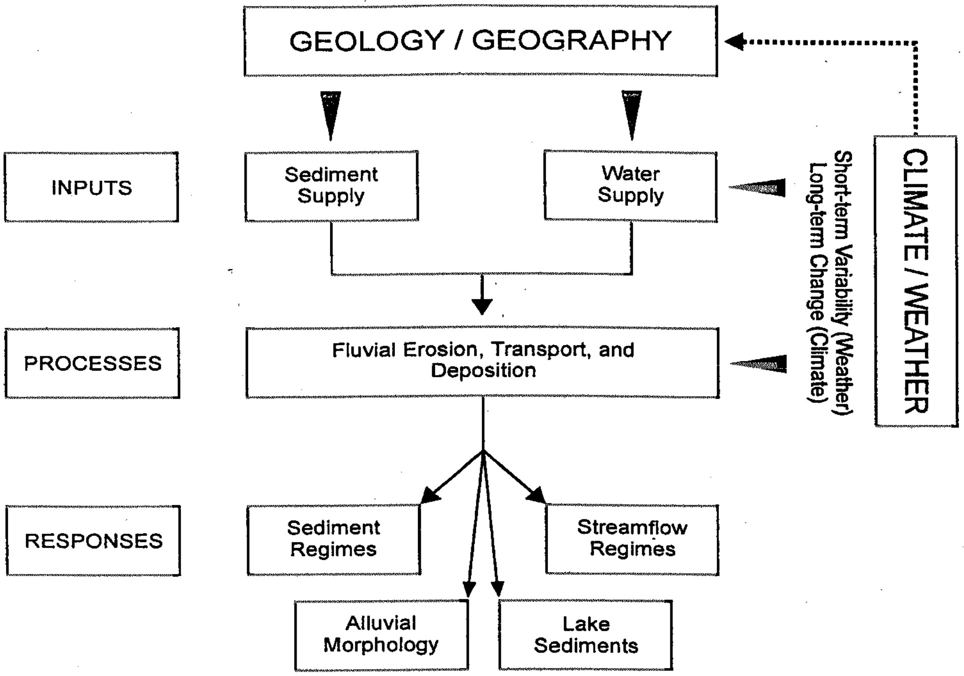

FIGURE 1. Schematic diagram of the linkages between the fluvial system and external forcing (after Woo and McCann, 1994).

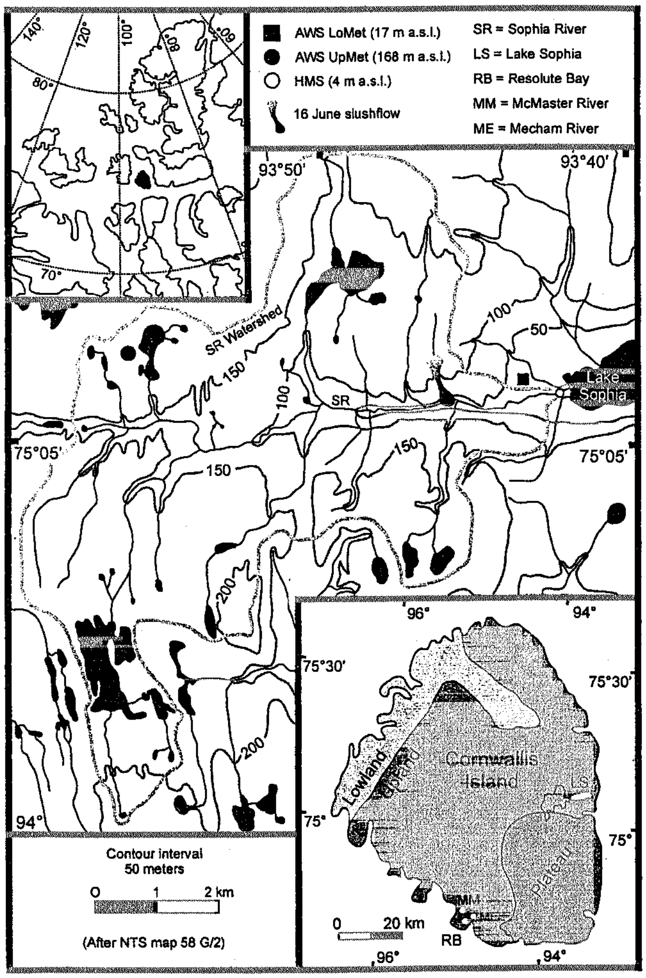

FIGURE 2. Map of the Sophia River watershed (drawn from NTS map 58 G/2). Inset maps show the location of Cornwallis Island in the Canadian Arctic Archipelago, and the physiography of Cornwallis Island (after Edlund, 1991).

terials are rare (Edlund, 1991). These coarse, calcareous surficial materials impede soil development and about 80% of the island is unvegetated today (Edlund, 1992).

LAKE SOPHIA AND THE SOPHIA RIVER WATERSHED

Lake Sophia (4 m a.s.l.) is located at about 75°06′N and 93°40′W (Fig. 2), 60 km northeast of Resolute Bay, where there is a 50-yr-long climate record (Atmospheric Environment Service, 1984). The lake is deep, hypersaline and meromictic, and contains anoxic bottom waters (Ouellet et al., 1987) with thinly laminated bottom sediments. The lake's major inlet is the snowmelt-fed "Sophia River" (unofficial name), with a watershed area of about 40 km^2 and an elevation range of 4 to 235 m a.s.l. (Fig. 2). More than 90% of the Sophia River watershed is above 100 m a.s.l. and forms an extensive plateau-like upland. This upper watershed represents the largest and most important source area for snowmelt runoff. In contrast, the watershed below 100 m a.s.l. consists of long, low-gradient talus and gelifluccted slopes. The drainage pattern in the upper watershed is deranged (Fig. 2), with numerous small lakes and ponds connected by shallow, ill-defined stream channels. In the lower watershed, well-developed drainage channels are deeply incised into the plateau surface. These channels typically fill with snow each winter and are important areas of snow storage, which influence channel development in the spring (Woo and Sauriol, 1980).

Sediment available for fluvial erosion and transport is extremely limited in the watershed. The barren plateau-uplands are covered by coarse, shattered, carbonate bedrock debris and are almost devoid of fine sediment. Bedrock outcrops are numerous, especially in the upper watershed and the incised stream channels. The gelifluction slopes in the lower watershed constitute the only significant sources for fine sediment, which are mobilized when summer rainfall events initiate slope wash. Marine, lacustrine, fluvial, or glacial sedimentary deposits are extremely rare (geographically limited), and not a significant source of sediment to the streams. Channel bed and bank erosion through thermoerosional niching, mudflows, active-layer detachment slides, and other point sources of sediment have been identified

TABLE 1

Mean monthly temperature and total precipitation for Resolute Bay (Atmospheric Environment Service, 1984) and Lake Sophia (this study)

	May	June	July	August	September
Temperature (°C)					
Resolute[a] (67 m a.s.l.)	−10.9	−0.6	4.1	2.4	−5.1
Resolute[b]	−7.0	1.0	4.1	2.0	−4.7
UpMet[b] (168 m a.s.l.)	*	−0.1	4.7	2.1	−5.4
LoMet[b] (17 m a.s.l.)	*	1.3	5.3	*	*
Precipitation (mm)					
Resolute[a] (67 m a.s.l.)	8.1	12.1	22.5	31.1	18
Resolute[b]	28.6	19.6	42.2	67.7	54.7
LoMet[b] (17 m a.s.l.)	*	15.8	26.5	*	*

[a] 1950–1981.

[b] 1994.

* data are incomplete.

as potentially significant sources of sediment to streams elsewhere in the Queen Elizabeth Islands (e.g., Lewkowicz and Wolfe, 1994), but there is no evidence for such processes along the Sophia River and its tributaries.

CLIMATE AND HYDROLOGY OF CORNWALLIS ISLAND

Cornwallis Island experiences a typical High Arctic climate, characterized by extreme seasonality, low temperatures, and low annual precipitation. Streamflow follows an arctic-nival regime (Church, 1974) where the bulk of the annual streamflow and sediment transport usually occurs within only 2 to 3 wk in June or early July during the annually recurring snowmelt flood. Runoff decreases once the snow cover has disappeared, and the baseflow period is only occasionally interrupted by streamflow responses to summer precipitation events. Exceptional summer rainfall events in the High Arctic infrequently generate dramatic hydrologic responses (e.g., Adams, 1966; Cogley and McCann, 1976). Mean monthly air temperatures at Resolute Bay are only positive during July and August (Table 1), with daily air temperatures on average below 0°C until 15 June and after 25 August (Maxwell, 1981). Rainfall occurs only during the summer months, usually as light showers, drizzle, or trace precipitation events, whereas heavy, high-intensity, rainfall events are rare. The bulk of the annual snowfall occurs from September to November while there still is sufficient moisture supply from the Arctic Ocean and interisland channels. The snow cover is redistributed by wind during the winter and large snowdrifts are deposited in topographic depressions, valleys, and stream channels, whereas hilltops, plateaus, and slopes are left with only thin snow cover after the winter. This uneven snow distribution favors the formation of snow dams across the incised stream channels of the island (Woo and Sauriol, 1980; Xia and Woo, 1992). Each spring during break-up, meltwater may form large ponds behind these temporary barriers, and often drain catastrophically when the snow disintegrates under the force of the impounded meltwater. Snow dams first delay streamflow responses to snowmelt (Kane et al., 1992), but their eventual collapse can greatly amplify streamflow and sediment transport for short periods of time.

Methodology

HYDROLOGY

A hydrologic monitoring station (HMS) was operated from 11 June to 23 August 1994 (74 d), 300 m upstream of Lake Sophia (Fig. 2). An array of sensors recorded stage, water temperature, electrical conductivity, and optical turbidity of the Sophia River streamwater every 10 s, using a Campbell Scientific CR10 datalogger. Ten-minute averages of the readings ($n = 60$) were automatically calculated and stored on a solid-state storage module. We measured stage using two nonvented Geokon, Inc. model 4580 vibrating-wire pressure transducers, and discharge using a Swoffer Model 2100 current meter. Discharge was then calculated using the velocity-area method and nonlinear curve fitting techniques were employed to establish a rating curve for the measurement cross-section.

We collected Sophia River streamwater samples ($n = 489$, 248 sampling times) 3 to 8 times/day at the stream gauging cross-section to determine suspended sediment concentration (SSC). Sampling frequency depended on the visually observed rate of change in SSC. Samples were typically collected using a US DH-48 suspended sediment hand sampler and depth-integration of three measurement verticals. Hand-dipped samples of one vertical ($n = 122$) were collected after 17 July, when runoff was very low and SSC practically nil (cf. Fig. 3G, 3I). Sampling locations of the verticals laterally in the channel cross-section were determined using the equal-discharge-increment (EDI) method (Edwards and Glysson, 1988). The samples were vacuum-filtered in the field through pre-weighed and individually-numbered 0.47 μm Whatman Type WCN filters and reweighed in the lab after drying for 60 min at 105°C. We calculated mean SSC for each sampling time as the average of all sampled verticals. To ascertain the source areas for suspended sediment, we conducted a comprehensive surficial mapping program in the Sophia River and Lake Sophia watersheds.

We developed an hourly SSC record (Fig. 3I) based on a combination of linear interpolation, field observations, and some basic assumptions regarding the relationship between streamflow and suspended sediment transport. Linear interpolation alone, while computationally convenient, cannot adequately represent the dynamics of fluvial sediment transport. Accordingly, we supplemented the SSC data set ($n = 248$) with values based on discharge ($n = 56$), since field observations indicated that discharge and SSC co-varied on a daily basis without a time lag. We then used linear interpolation to construct the hourly SSC time series. The total calculated suspended sediment load was 18.3 t (0.46 t km^{-2} yr^{-1}), which is the lowest suspended sediment yield of any stream so far monitored in the Canadian High Arctic (cf. compilations by Lewkowicz and Wolfe, 1994; Hardy, 1995). Streamflow began just prior to the field season and continued thereafter, but there was no evidence in the stream channel, nor on the lake ice, that any sediment transport occurred prior to 11 June 1994.

METEOROLOGY

We established two automated weather stations (AWS) in the Sophia River watershed in mid-May 1994 (Fig. 2). One, named "LoMet" AWS (75°05.55′N, 93°41.69′W, 17 m a.s.l.), was located close to the lake, whereas another ("UpMet") (75°05.96′N, 93°54.78′W, 168 m a.s.l.) was located in the upper watershed. Measurements at both AWS included wind speed/direction, air temperature, vapor pressure and radiative fluxes. In addition, barometric pressure and precipitation were recorded at LoMet. UpMet was winterized on 15 August and operated with a reduced array of sensors through the 1994/95 winter. The objectives of the meteorological data collection program were to (1) characterize the weather and climate at Lake Sophia over one complete annual cycle and (2) to ascertain if the climatic record

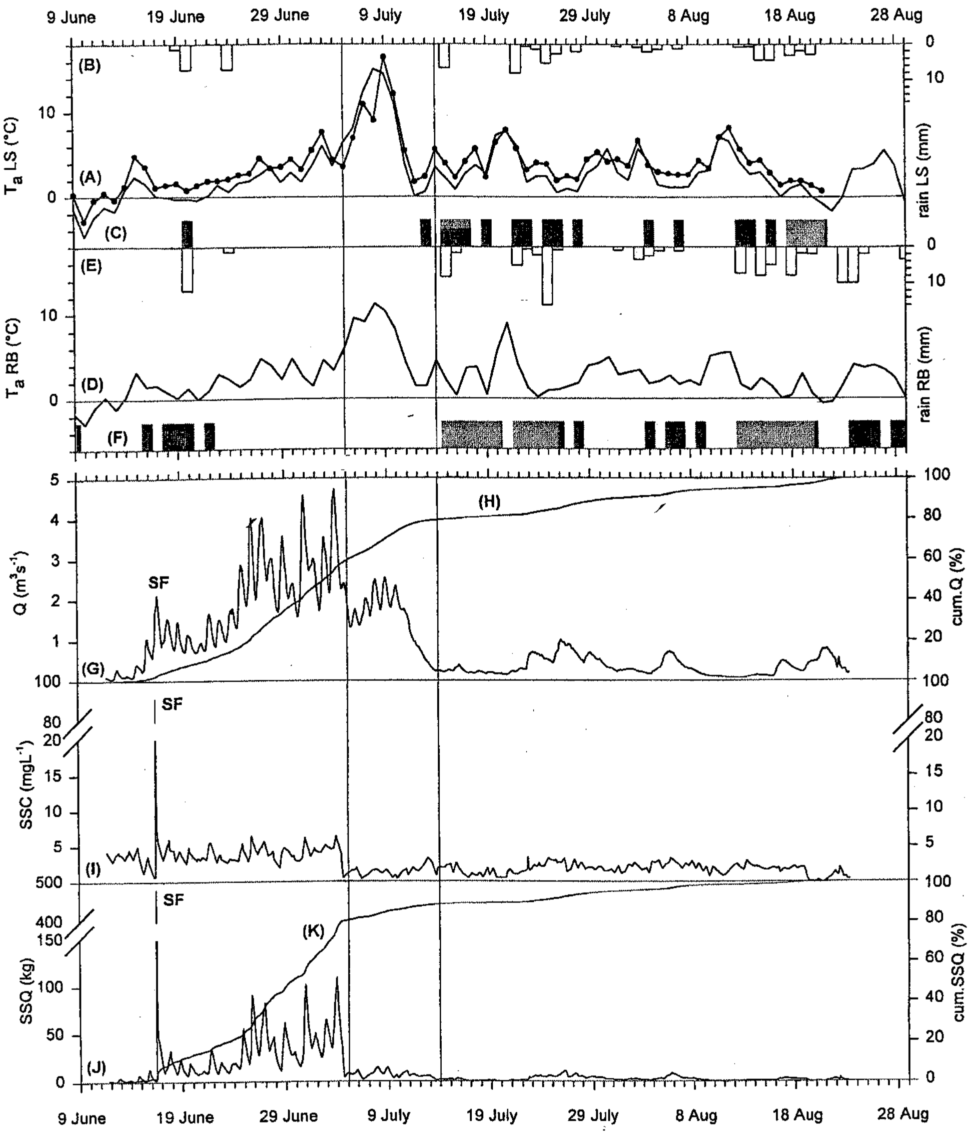

FIGURE 3. Summer weather, streamflow, and suspended sediment transport, Sophia River, 1994. A: Daily mean air temperature (T_a) at LoMet (circles) and UpMet (solid); B: Total daily rainfall at LoMet; C: Fog days at LoMet; D: Daily mean air temperature (T_a) at Resolute Bay; E: Total daily rainfall at Resolute Bay; F: Fog days at Resolute Bay; G: Hourly discharge (Q), Sophia River; H: Cumulative % total measured runoff, Sophia River; I: Hourly suspended sediment concentration (SSC), Sophia River; J: Hourly suspended sediment load (SSQ), Sophia River; K: Cumulative % total measured suspended sediment transport, Sophia River. Subperiods are delineated by vertical lines: main snowmelt: 11 June–4 July; late snowmelt: 5–13 July; baseflow; 14 July–23 August. SF marks the 16 June slushflow event. RB: Resolute Bay; LS: Lake Sophia.

from Resolute Bay is representative of past climatic variability at Lake Sophia. In this study, air temperature is used as an integrated proxy for the atmospheric energy available for snowmelt (Threlfall, 1986; Lang and Braun, 1990). A more sophisticated, physically based approach to model snowmelt would involve solving the energy-balance equation of the snowpack, but the required data are difficult to measure automatically and accurately in remote and harsh environments such as the Arctic. In addition, distributing the energy-balance from one point represented by the AWS over the entire watershed poses many complex and not adequately solved problems. A simple model was also needed in order to tie the 1-yr data set into the 50-yr instrumental record from Resolute Bay.

Results

SUMMER CLIMATE AT LAKE SOPHIA AND RESOLUTE BAY IN 1994

Meteorological records from LoMet, UpMet, and Resolute Bay (Fig. 3A, 3D) demonstrate that air temperature at all three sites followed a similar temporal pattern in 1994 (r = 0.92 Resolute Bay/LoMet; r = 0.94 Resolute Bay/UpMet). Temperatures were equally well correlated (r = 0.97) between LoMet and UpMet, with the lower-elevation site being warmer on average than the upland site (Δh = 151 m) by 1.1°C (n = 99 d). Temperature inversions occurred 5–8 July, when air temperatures at UpMet exceeded those recorded at LoMet by as much as 6°C.

This unusual 4-d period was further characterized by high atmospheric pressure, light winds, and clear skies. In contrast, fog was a common summer weather phenomenon on Cornwallis Island (Fig. 3C, 3F), and generally coincided with periods of summer precipitation (Fig. 3B, 3E). Air temperature variability during the latter half of the summer was mainly a function of reduced radiation receipts during fog and precipitation periods. The precipitation records from LoMet and Resolute Bay also display similar temporal patterns; however, the amount of precipitation at Lake Sophia was consistently lower than the amount recorded at Resolute Bay during the same event (Table 1). This difference may be due to the geographic location of the two sites (Fig. 2), and/or methodological differences (e.g., instrumentation). Most of the precipitation and fog periods occurred after mid-July, when sea ice break-up in the interisland channels and the Arctic Ocean led to increased availability of local moisture sources. All precipitation events recorded at LoMet were of low magnitude and intensity, and fell as drizzle, light showers, or trace events. Atmospheric pressure (not shown) was extremely well correlated ($r = 0.98$) between Resolute Bay and LoMet, indicating that both sides of the island experienced the same weather on a synoptic scale. These strong similarities were not unexpected, given the homogenous surface conditions on Cornwallis Island, the lack of significant topographic barriers, and the short horizontal and vertical distance between the two sites. This comparison of selected aspects of the 1994 summer climate at Resolute Bay and Lake Sophia suggests that the Resolute Bay instrumental record is reasonably representative of past climatic variability at Lake Sophia.

RELATIONSHIPS BETWEEN SUMMER CLIMATE, STREAMFLOW, AND SUSPENDED SEDIMENT TRANSPORT, SOPHIA RIVER, 1994

Summer Climate and Streamflow

Streamflow was dominated by snowmelt runoff in 1994 (Fig. 3G), but its temporal variability on a seasonal timescale did not consistently follow the patterns of air temperature (Fig. 3A). Large diurnal discharge cycles from 11 June–13 July suggest that runoff was indeed governed by the atmospheric energy available for snowmelt. This daily pattern weakened and eventually almost disappeared when the source areas for runoff gradually changed from spatially extensive snow cover to discrete, late-lying snow banks and the active layer. Runoff was sustained at intermediate levels for 9 d (5–13 July) following annual peak flow on 3 July. The watershed snow reservoir was exhausted around 11 July, resulting in streamflow recession to baseflow. Discharge remained low and without clearly measurable diurnal cyclicity for the duration of the summer, despite comparatively high air temperatures, and its temporal variability was solely a function of several rapid and prolonged streamflow responses to summer precipitation events (Fig. 3B). The coarse and well-drained surficial sediments in the watershed allowed quick routing of the rainwater input to the Sophia River and its tributaries, whereas the large land surface storage capacity of the upper watershed with its numerous lakes and ponds dampened and prolonged each rainfall runoff pulse.

A scatter plot of discharge against air temperature at UpMet (Fig. 4A) highlights the inconsistency of the temporal relationship between the variables. Values are grouped into three distinct clusters, corresponding to sequential subperiods, delineated by changes in watershed snow supply. Cluster I represents the main snowmelt period (11 June–4 July), when snowmelt was still unlimited by snow supply and streamflow responded very sensitively to air temperature variability. Once snowmelt commenced in early June, the thin and spatially extensive watershed snow cover ablated rapidly and relatively synchronously. Snowmelt was accelerated by turbulent heat transfer from the gradually increasing snow-free areas (Woo, 1983). Following peak runoff (cluster II, late snowmelt, 5–13 July), discharge still followed fluctuations in air temperature, albeit less sensitively than during the main snowmelt period. This late-snowmelt period received the highest receipts of atmospheric energy (cf. Fig. 3A), but lower discharge suggests snowmelt was limited by snow supply. Finally, cluster III represents the baseflow period (14 July–23 August), when the watershed was essentially snow free, and runoff variability was a function of summer precipitation events and the associated rainfall runoff. The weak inverse relationship between air temperature and discharge during this period is a result of reduced air temperatures during the precipitation and coinciding fog periods. This temporal inconsistency, caused by watershed snow supply depletion and rainfall runoff, precludes consistent and robust statistical relationships between measures of summer climatic variability (e.g., air temperature) and streamflow. Streamflow variability in 1994, on an annual time scale, was not a simple function of summer climate, but instead fundamentally limited by the amount of snow available for melt in the watershed, and additionally influenced by summer precipitation events.

Streamflow and Suspended Sediment Transport

The suspended sediment concentration (SSC) of Sophia River (Fig. 3I) remained extremely low over the entire 1994 monitoring period (mean = 2.4 mg L^{-1}, $n = 1743$ hourly values). Visually perceptible amounts of sediment were transported for less than 6 h, following a slushflow event on 16 June (cf. Fig. 2); otherwise, the streamwater remained clear even during the highest levels of snowmelt and rainfall runoff. A noticeable shift in SSC occurred on 4 July (mean SSC before shift = 4 mg L^{-1} [$n = 547$]; after shift = 1.7 mg L^{-1} [$n = 1196$]), indicating complete sediment supply exhaustion following annual peak runoff (cf. Fig. 3G). Diurnal hysteresis in the discharge and SSC relationship suggests sediment supply variability also on a daily time scale (Fig. 5). Summer rainfall events (Fig. 3B) and the associated rainfall runoff had no visible, and only a barely measurable, effect on SSC, suggesting that rainfall intensity and magnitude in 1994 were insufficient to deliver significant sediment to the stream.

The relationship between streamflow and SSC was not consistent, when considering the 1994 monitoring period as a whole (Fig. 5). Hourly SSC values ($n = 1725$, estimated minimum measurement uncertainty = 1.7–2.6 mg L^{-1}), excluding those directly influenced by the 16 June slushflow ($n = 18$), ranged from 0 to *only* 6.5 mg L^{-1}. Therefore, much of the apparent SSC variability represents noise, caused by natural variability and/or subtle inconsistencies in suspended sediment sample acquisition and processing procedures. A discharge–SSC scatter plot (Fig. 5) illustrates three distinct clusters, with a similar pattern to the air temperature–discharge relationship (cf. Fig. 4A). The association was strongest during the period of highest snowmelt runoff (23 June–4 July), when discharge and SSC reached their highest levels of 1994, thereby reducing the noise in proportion to the signal component in the SSC record. However, the overall temporal inconsistency due to insufficient sediment supply precludes the quantification of a robust relationship between streamflow and suspended sediment transport (Gurnell, 1987; Lawson, 1993).

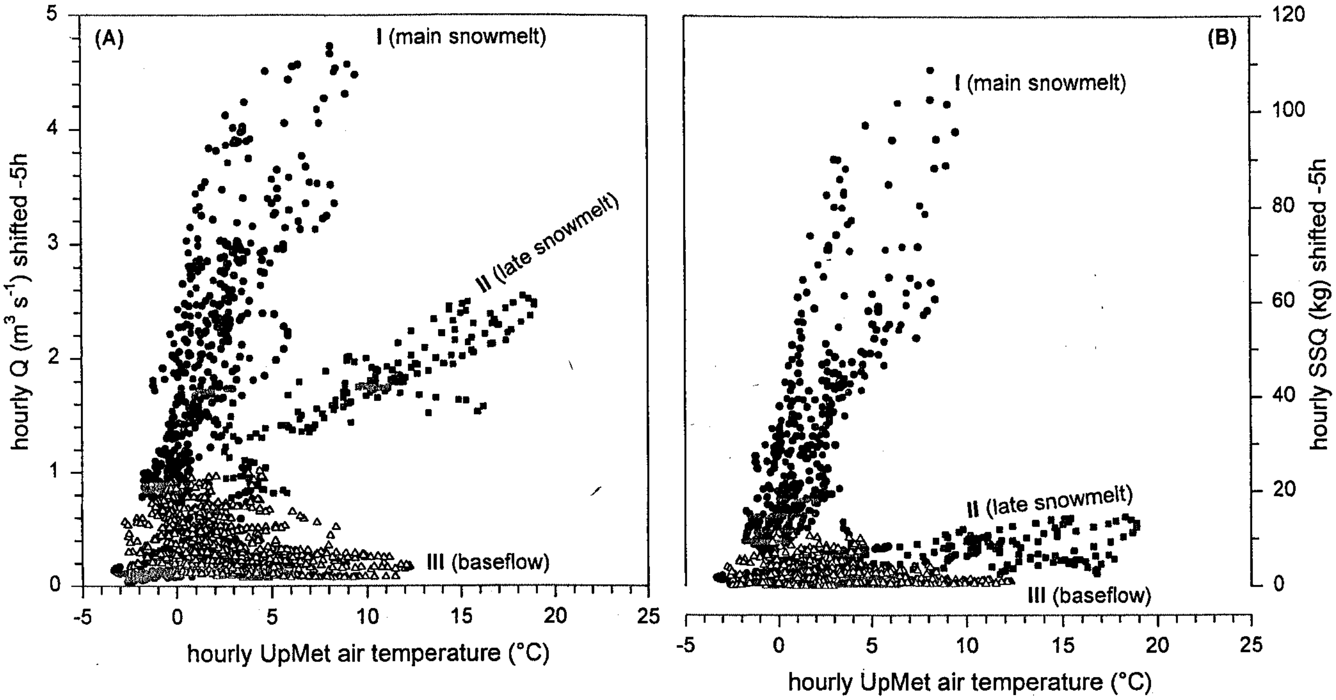

*FIGURE 4. Relationships between air temperature, streamflow (Q), and suspended sediment load (SSQ), Sophia River, 1994. Hourly Q (Fig. 4A) and hourly SSQ (Fig. 4B) are plotted against mean hourly air temperature at UpMet using a 5-h offset with respect to air temperature (best-match position of time series) to account for meltwater routing delays. For SSQ, values directly affected by the 16 June slushflow event (*n *= 18) are excluded. Subperiods: main snowmelt: 11 June–4 July (circle); late snowmelt: 5–13 July (square); baseflow: 14 July–23 August (triangle).*

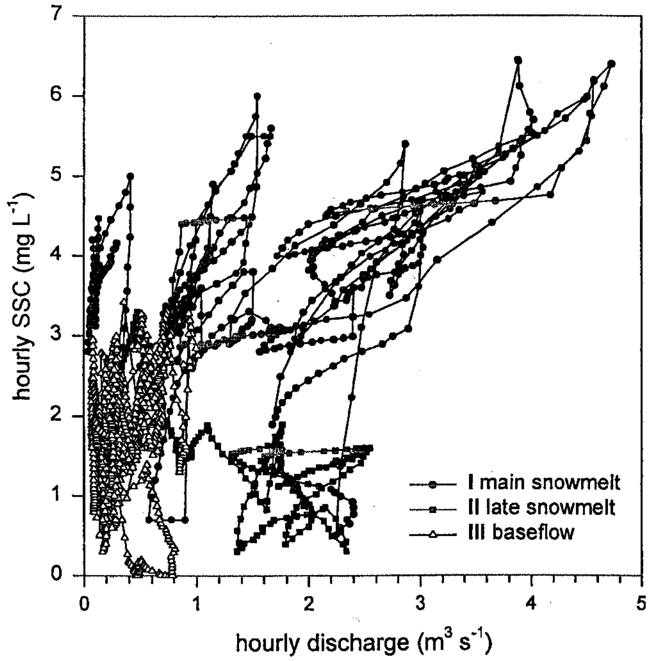

*FIGURE 5. Relationship between discharge (Q) and suspended sediment concentration (SSC), Sophia River, 1994. Shown are hourly values (*n *= 1725) of Q and SSC; hourly values directly affected by the 16 June slushflow event (*n *= 18) are excluded. Subperiods: main snowmelt: 11 June–4 July (circle); late snowmelt: 5–13 July (square); baseflow: 14 July–23 August (triangle).*

Summer Climate and Suspended Sediment Transport

The time series of suspended sediment load (SSQ) (Fig. 3J) reflects fluctuations in both discharge and SSC and provides the best single estimate of sediment delivery to lakes dominated by allochtonous influx (Hardy, 1996). The temporal pattern of SSQ closely resembled that of discharge (cf. Fig. 3G), as fluctuations were mainly caused by streamflow variability. SSQ responded even less sensitively to air temperature variability (Fig. 4B) during the late snowmelt period and the baseflow period than streamflow alone (Fig. 4A), because SSQ was not only affected by snow supply exhaustion, but also by the abrupt drop in SSC on 4 July. This combination of two limiting factors (snow and sediment) also amplified the nonlinearity of suspended sediment transport through time compared to runoff (Fig. 6). If streamflow and suspended sediment transport were directly and consistently linked to variations in snowmelt, one could expect a nearly linear increase of cumulative runoff and suspended sediment transport in response to a cumulative measure of atmospheric energy input to the watershed (Hardy, 1996). During the main snowmelt period, only 15% of the total cumulative degree-days above 0°C (ΣMDD) recorded at the UpMet generated 60% of the total measured runoff, but 80% of the total measured SSQ (Fig. 6). This ratio changed drastically during the late snowmelt period, when another 30% ΣMDD at UpMet resulted in merely an additional 20% of the total measured runoff and only another 8% of the total measured SSQ. The step-wise increases in cumulative runoff and SSQ during the baseflow period were due to rainfall runoff (Fig. 3B, 3G). The combined snowmelt period (main + late snowmelt; 11 June–13 July) accounted for 80 and 88% of the total measured runoff and suspended sediment transport respectively in 1994, whereas only 20 and 12% occurred as a result of baseflow and rainfall runoff. These values emphasize the

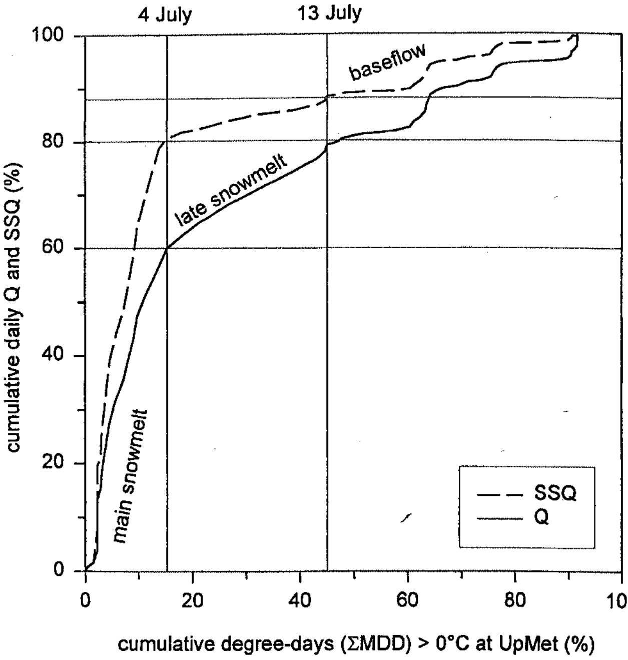

FIGURE 6. Cumulative fluxes of streamflow (Q) and suspended sediment load (SSQ), plotted as a function of cumulative degree-days above 0°C (ΣMDD) at UpMet (all in % of their 1994 measured totals). Subperiods: main snowmelt: 11 June–4 July; late snowmelt: 5–13 July; baseflow: 14 July–23 August.

overwhelming importance of the annually recurring snowmelt flood on streamflow and suspended sediment transport.

In summary, coherent relationships existed between atmospheric energy input, streamflow, and suspended sediment transport in 1994, but only while sufficient snow and sediment sources were available in the watershed to provide the necessary link between climatologic input (e.g., air temperature) and hydrologic output. Beginning in early July, snow and sediment supply exhaustion, combined with rainfall runoff, decoupled the systems and led to abrupt, nonlinear relationships between streamflow and sediment transport variability, independent of air temperature. In terms of the interannual variability of sediment transfer to Lake Sophia, and its possible impact on the paleoclimatic information archived in the lake, it is necessary to ascertain how representative this 1-yr data set is on a longer temporal and larger spatial scale. While 1 yr of measurements precludes precise quantitative predictions of the direct and indirect effects of past or future climatic change on sediment delivery and deposition, a qualitative extrapolation of the collected data to longer temporal and larger spatial scales is instructive (Woo and McCann, 1994).

Discussion

SNOW SUPPLY LIMITATION IN THE HIGH ARCTIC: SPATIAL AND TEMPORAL CONSIDERATIONS

Streamflow data for the Mecham (Cogley, 1975) and McMaster Rivers (Woo, 1983) indicate that snow reservoir exhaustion is an annually recurring phenomenon on Cornwallis Island. In all 11 yr of measurement, peak annual runoff occurred several days to weeks *before* air temperature at Resolute Bay reached its summer maximum (Table 2). Snow-reservoir exhaustion is also suggested in published data from other arctic-nival watersheds, for example on southern and central Ellesmere Island (Woo, 1976; Lewkowicz and Wolfe, 1994), Devon Island (McCann and Cogley, 1972; Marsh and Woo, 1981), Bathurst Island (Wedel et al., 1977), and Melville Island (McLaren, 1981). The annual transfer of water and sediment in these arctic-nival systems does not appear to be primarily controlled by atmospheric energy input to the watershed during each melt season, but instead by the amount of snow accumulation during each previous winter (Church, 1988; Lawson, 1993), or by summer rainfall (Church, 1988). Winter snowfall at Resolute Bay (Fig. 7A) may provide an estimate for the interannual variability of streamflow on Cornwallis Island, in conjunction with the varying influence of summer rainfall events. In addition, suspended sediment transport is also affected by sediment supply limitations, depending on the supply situation unique to each watershed.

TABLE 2

Date of annual peak discharge (Q_{max}) of the Mecham, McMaster, and Sophia Rivers (Fig. 2) and annual maximum air temperature (T_{max}) at Resolute Bay. Dates for the Mecham and McMaster Rivers were estimated from plots in the literature.

Watershed (stream)	Year	Date Q_{max}	Date T_{max}	Lag (days)
Mecham River[a]	1970	8 July	10 Aug	33
Mecham River[a]	1971	28 June	22 July	24
Mecham River[a]	1972	17 July	8 Aug	22
Mecham River[a]	1973	24 June	5 Aug	42
Mecham River[a]	1974	14 July	10 Aug	27
McMaster River[b]	1976	19 July	29 July	10
McMaster River[b]	1977	6 July	20 July	14
McMaster River[b]	1978	9 July	31 July	22
McMaster River[b]	1979	15 July	24 July	9
McMaster River[b]	1980	24 June	4 Aug	41
McMaster River[b]	1981	25 June	10 July	15
Sophia River[c]	1994	3 July	8 July	5

[a] Cogley (1975).
[b] Woo (1983).
[c] This study.

SEDIMENT SUPPLY LIMITATION IN THE HIGH ARCTIC

Spatial Considerations

Two fluvial sediment transport studies have been previously conducted on Cornwallis Island, both in watersheds very similar to that of Sophia River in terms of their geology and geography. Cogley (1975) monitored sediment transport by the Mecham River (Fig. 2) in 1971 and discovered that "for most of the runoff season suspended sediment load is practically nil." Infrequent bursts of sediment-laden water during the snowmelt period were attributed to upstream snow dam collapses (Cogley, 1975). Woo and Sauriol (1981) reported similar low values and observations for the McMaster River (Fig. 2), with the authors stating that "no. . . correlation [with discharge] was apparent for the McMaster River [in 1977]." It appears that in both cases, SSC was primarily limited by sediment supply, whereas streamflow variability exerted only a secondary control.

Sediment supply is a function of the geologic and geographic characteristics of a given watershed. The geology (carbonate bedrock), glacial history, and geography (e.g., low relief, plateau-topography, incision of streams, sparseness of vegetation) of the Sophia River watershed are typical not only for Cornwallis Island, but for large regions of the central Canadian Arctic. Sus-

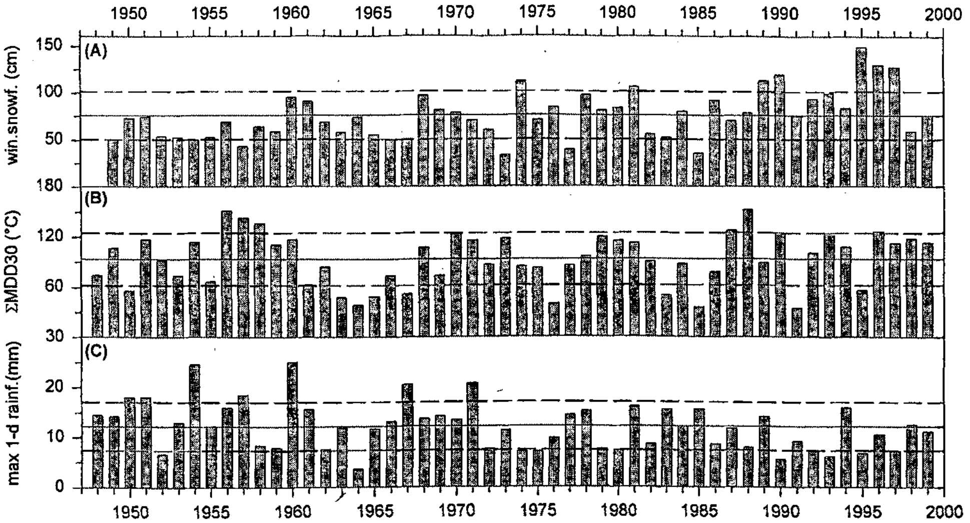

FIGURE 7. Interannual variability of selected climatic variables recorded at Resolute Bay. A: Total previous winter snowfall (cm, September–May); B: Cumulative degree-days >0°C (ΣMDD) for the first continuous 30-d period with mean daily air temperatures >0°C (°C); C: Maximum 1-d summer rainfall event (mm). Solid horizontal lines denote the long-term mean, dashed horizontal lines the one standard deviation envelope.

pended sediment transport in arctic-nival watersheds with similar geologic and geographic boundary conditions may also be supply-limited and thus of comparatively low annual magnitude.

Temporal Considerations

In 1994, the 16 June slushflow was the single most important sediment transport event (cf. Fig. 3J), resulting in 6% of the annual suspended sediment load. This slushflow was part of the spring channel break-up sequence in one of the tributaries to the Sophia River (Fig. 2) and occurred at an abrupt change in channel gradient, where the stream exits the upland-plateau and plunges steeply into the main Sophia River valley. The slushflow formed a temporary dam across the Sophia River stream channel, damming up the river for about 30 min. Following its collapse SSC increased abruptly by 2 orders of magnitude, yet dropped to pre-slushflow values within 3 h, while there was only a minor interruption in the diurnal cycle of runoff. The frequency, magnitude, and significance of such events in a longer-term context are impossible to quantify, given our observations alone, however slushflows are commonly associated with spring stream channel break-up (Woo and Sauriol, 1981) on Cornwallis Island. It is therefore probable that slushflows are annually recurring sediment transport events associated with snowmelt runoff initiation along the Sophia River and its tributaries each spring.

On an annual time scale, the total magnitudes of 1994 runoff and suspended sediment load were less related to short-term summer weather fluctuations than the seasonal snow accumulation during the previous winter. Total winter snowfall (Fig. 7A) during the 1993/94 winter at Resolute Bay (83.7 cm) was similar to its long-term mean (75.8 cm), indicating average snow supply and snowmelt volume. The resulting suspended sediment transport is additionally influenced by the rapidity of snowmelt each spring, given the often highly nonlinear relationship between discharge and SSC. Figure 7B shows the ΣMDD for the first continuous 30-d period with mean daily temperatures > 0°C at Resolute Bay, a parameter which provides a proxy for snowmelt intensity. With 107.4 ΣMDD, 1994 was above the long-term mean (93.2 ΣMDD), suggesting slightly enhanced snowmelt intensity. The Sophia River reached bankfull discharge and occasionally overtopped its banks during the snowmelt period, which is indicative of normal levels of snowmelt runoff (Church, 1988). Both winter snowfall and snowmelt intensity exhibit considerable inter-annual variability over the last 50 yr. Suspended sediment transport during years with a combination of reduced (e.g., 1985) or enhanced (e.g., 1990) snow supply and snowmelt intensity may be quite different from what was observed in 1994. However, there was no consistent relationship between Sophia River discharge and SSC (Fig. 5), which is in direct contrast to our earlier studies at Lake C2 (Hardy et al., 1996) and Lake Tuborg (Braun, 1997). In these fluvial systems, discharge magnitude was of primary importance, and the nonlinearity between discharge and SSC resulted in transfer of most of the annual sediment load during brief, high-discharge intervals. It is possible that suspended sediment transport to Lake Sophia remains relatively constant from year-to-year, despite different levels and intensities of snowmelt and runoff, simply due to insufficient sediment supply in the watershed.

Summer rainfall events can have considerable effects on sediment transport (e.g., Cogley and McCann, 1976), as they potentially affect the entire watershed and access sediment sources otherwise protected from fluvial erosion. In 1994, 9% of the annual suspended sediment load was transported in response to summer rainfall events. Given that the normal levels of snowmelt-controlled sediment transfer to Lake Sophia appear to be extremely low each year, a high-intensity summer rainfall event could possibly transport the bulk of the annual sediment load to the lake. No direct evidence is available to support this hypothesis, as rainfall intensities in 1994 were insufficient to have any significant effect on fluvial sediment transport. Indeed no rainfall-runoff event has yet been documented, from unglacierized basins in the Queen Elizabeth Islands, in which peak discharge exceeded that of the same year's snowmelt runoff (Hardy et al., 1996). Nonetheless, extreme rainfall events, such as recorded at Resolute Bay (Fig. 7C), may have the potential to mobilize large amounts of otherwise inaccessible sediment, particularly from the gelifluction slopes surrounding the stream and lake below 100 m a.s.l. (Fig. 2). The precipitation data for 1994 (Fig. 3B, 3E) indicates considerable spatial variability of rainfall magnitude and intensity between Resolute Bay and Lake Sophia, even over this comparatively small part of the High Arctic. The long-term precipitation data from Resolute Bay may therefore not resolve actual, site-specific rainfall amounts and intensities at Lake Sophia, making it difficult to assess the significance of summer rainfall on sediment transport and deposition.

Snow and sediment supply limitations complicate fore- or hindcasting of future or past fluvial sediment transport to Lake Sophia. On short time scales, over which the geologic and geographic boundary conditions governing sediment availability, mobilization, and transport remain constant (e.g., bedrock lithology, topography, permafrost, vegetation type/cover, and glacial/geomorphic history), contemporary variations in weather and climate regulate the intensities of the fluvial processes (Fig. 1). But, as the climate changes (both in the past and future), the availability of snow, ice, and sediment on the land surface will be indirectly affected as well, with varying response times (Woo and McCann, 1994) and empirical relationships quantified for modern-day conditions become invalid. Woo and McCann (1994) propose an initial increase in sediment transport by arctic-nival streams due to increased sediment supply and more frequent summer rainfall events in response to a possible future climate warming. Eventually, a milder climate would allow more extensive vegetation, thereby reducing erosion and sediment supply (Woo and McCann, 1994). These interactions between weather/climate and suspended sediment transport have important consequences for the climatic information recorded by Lake Sophia's sediments today and in the past. Based on the 1994 data, there is no evidence that modern-day weather and climate are directly linked to suspended sediment delivery and laminae deposition, because of limited water and sediment supply. Suspended sediment delivery to Lake Sophia today is relatively low, which increases the proportional significance of sediment input associated with runoff other than direct snowmelt (e.g., slushflows and summer rainfall). A changing climate will enhance or reduce these supply limitations, thereby modifying both the contemporary climate signal represented by suspended sediment transfer, as well as the climatic signal recorded as variations (e.g., annual thickness) in the laminae. Therefore, lamina thickness today, and its variability through time, cannot be explained exclusively by one simple climatic index (e.g., mean summer temperature, total winter snowfall, or maximum summer rainfall). The underlying control on suspended sediment transport and laminae deposition on longer time scales is indirectly climatic (and ultimately geologic), and modern-day process studies and instrumental records are unsuited to assess this directly. These long-term effects of climatic change will occur superimposed on the natural, year-to-year, variability of the hydrologic and climatic system and may be difficult to detect and separate in sedimentary records.

Conclusions

Streamflow and suspended sediment transport into Lake Sophia are limited by the supply of snow and sediment in its watershed; climatic variability only controls the intensities of runoff and suspended sediment transport during each years snowmelt period. After the snow reservoir is depleted, streamflow and suspended sediment transport become a function of summer rainfall. In the Lake Sophia basin, sediment transport and deposition is extremely low and possibly decoupled from streamflow and modern-day climate by the sparseness of transportable sediment. The direct influence of summer rainfall on suspended sediment transport cannot yet be quantitatively assessed. Laminae deposition in Lake Sophia today appears to be relatively insensitive to changes in summer temperature, and may reflect the amount of snowfall or snow storage each preceding winter, complicated by varying sediment input associated with high-intensity summer rainfall events and slushflows.

The Sophia River/Lake Sophia watershed-lake system is similar to other High Arctic nival systems in carbonate-dominated terrain, typical of much of the central Canadian Arctic Archipelago, which raises questions regarding the paleoclimatic significance of other lacustrine sedimentary records from this area. It is inappropriate to merely assume that lake sediments preserve a simple and consistent record of climatic variability (e.g., mean summer temperature), given the feedbacks between climate and sediment supply on various time scales. We suggest that it is necessary to establish the modern-day, site-specific relationships among geology, geography, climate, and hydrology for each system if one wants to more confidently reconstruct paleoclimate using lake sediments. Even a single year of data collection can dramatically improve our understanding of fluvial sediment delivery and its relationship to the sedimentary record, as we have shown for Lake Sophia, but additional years of data collection are necessary to fully quantify the inter-annual variability of the sediment delivery processes.

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