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Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales

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[1] Ice-cored permafrost landscapes are highly sensitive to disturbance and have the potential to undergo dramatic geomorphic transformations in response to climate change. The acceleration of thermokarst activity in the lower Mackenzie and Peel River watersheds of northwestern Canada has led to the development of large permafrost thaw slumps and caused major impacts to fluvial systems. Individual "mega slumps" have thawed up to 10^6 $m^3$of ice-rich permafrost. The widespread development of these large thaw slumps (up to 40 ha area with headwalls of up to 25 m height) and associated debris flows drive distinct patterns of stream sediment and solute flux that are evident across a range of watershed scales. Suspended sediment and solute concentrations in impacted streams were several orders of magnitude greater than in unaffected streams. In summer, slump impacted streams displayed diurnal fluctuations in water levels and solute and sediment flux driven entirely by ground-ice thaw. Turbidity in these streams varied diurnally by up to an order of magnitude and followed the patterns of net radiation and ground-ice ablation in mega slumps. These diurnal patterns were discernible at the 10^3 km^2 catchment scale, and regional disturbance inventories indicate that hundreds of watersheds are already influenced by slumping. The broad scale impacts of accelerated slumping are indicated by a significant increase in solute concentrations in the Peel River (70,000 km^2). These observations illustrate the nature and magnitude of hydrogeomorphic changes that can be expected as glaciogenic landscapes underlain by massive ice adjust to a rapidly changing climate.

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1. Introduction

[2] Thawing permafrost (lake drainage, development of channel networks, and thaw slumping) [*Rowland et al.*, 2010] has the potential to significantly alter the geomorphology of fluvial and lacustrine environments across the circumpolar Arctic. Near-surface thawing can increase the concentrations of major ions in small lakes and streams [*Kokelj et al.*, 2009a; *Keller et al.*, 2010], and suspended sediment and solute concentrations in runoff over thermokarst-affected areas can be orders of magnitude greater than from the adjacent landscape [*Kokelj and Lewkowicz*, 1999; *Bowden et al.*, 2008; *Lamoureux and Lafrenière*, 2009]. Thus, even if disturbance is localized, there is potential for downstream aquatic impacts. It has been speculated that permafrost thaw has the potential to drive increases in nutrient, ionic, and DOC fluxes in circumpolar rivers [*Frey and McClelland*, 2009]. However, these inferences are based largely on the contrasts in geochemical conditions between nonpermafrost and permafrost-affected watersheds [*MacLean et al.*, 1999; *Frey et al.*, 2007], and the detection of anomalous trends in small permafrost dominated catchments [*Hobbie et al.*, 1999]. To date, there are few studies that have demonstrated the hydrological, fluvial, and geochemical impacts of thermokarst beyond the slope or small catchment scale. To our knowledge, there are no studies that have examined the impacts of intensive thaw slump activity on streams and rivers. Consequently, it is unknown how fluvial systems and stream ecosystems in periglacial environments will be

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Figure 1. Massive ground ice exposed in the headwall of a mega slump, Peel Plateau, Northwest Territories, Canada. The headwall of the slump is approximately 25 m high.

impacted as disturbance regimes intensify or how these impacts will manifest across a range of landscape types and watershed scales.

[3] Retrogressive thaw slumps are one of the most dynamic geomorphic processes influencing permafrost environments (Figure 1) [*French*, 1974; *Burn and Friele*, 1989; *Leibman*, 1995; *Romanenko*, 1998; *Lantuit and Pollard*, 2008; *Lantz and Kokelj*, 2008]. The abundance and size of thaw slumps is typically greatest in ice-cored landscapes which can be underlain by massive ice up to tens of meters in thickness (Figures 1 and 2) [*French*, 1974; *Lantuit and Pollard*, 2008]. Ice-cored terrain is widespread within large moraine belts, hummocky till, and glaciofluvial deposits in the North American western Arctic [*Mackay*, 1971; *St-Onge and McMartin*, 1999; *Dyke and Savelle*, 2000; *Lacelle et al.*, 2004; *Murton et al.*, 2005], the Mackenzie Valley [*Fulton*, 1995], and Siberia [*Astakhov et al.*, 1996; *Alexanderson et al.*, 2002]. In these landscapes, tabular ice bodies consist predominantly of buried glacier [e.g., *Lorrain and Demeur*, 1985; *French and Harry*, 1990; *Astakhov et al.*, 1996; *Murton et al.*, 2005] and massive segregated ice [e.g., *Mackay*, 1971; *Mackay and Dallimore*, 1992; *Lacelle et al.*, 2004].

[4] Thaw slumps initiate by a variety of mechanisms that expose ground ice including mechanical erosion by fluvial processes or wave action [*Lantuit et al.*, 2012], thermally driven subsidence along lakeshores [*Kokelj et al.*, 2009b], or mass wasting triggered by extreme thaw or precipitation [*Lacelle et al.*, 2010]. Slump growth is driven by summer ground-ice ablation and progressive backwasting of the ice-rich headwalls [*Lewkowicz*, 1987] (Figure 1). Thawed materials accumulate as a mud slurry on the slump floor and may be transported downslope by debris flows (Figure 2 and Supplementary Video 1). A slump can enlarge for decades until the exposed ground ice is covered by the accumulation of thawed sediments causing the disturbance to stabilize [*Burn and Friele*, 1989]. Some of the largest thaw slumps ever observed have developed along the valley sides and open slopes of fluvially incised glaciogenic landscapes in northwestern Canada (Figure 2). The mass wasting associated with the growth of these "mega slumps" throughout the Peel Plateau and eastern foothills of the Mackenzie Mountains (Figure 3) [*Ecosystem Classification Group*, 2010; *Lacelle et al.*, 2010] is making immense quantities of previously frozen, highly weatherable sediments available for leaching and transport to hundreds of streams and rivers.

[5] An increase in the intensity of thaw slump activity has the potential to dramatically alter arctic fluvial systems. The nival streamflow regime characterizes water, sediment, and solute flux through arctic and subarctic fluvial systems and is driven primarily by snowmelt- and rainfall-induced runoff [*McCann et al.*, 1972; *Carey and Woo*, 2001]. Normally, ephemeral runoff through a shallow organic active layer limits sediment and solute transport from the landscape to periglacial streams [*Lewkowicz and Kokelj*, 2002]. In the summer of 2010, several streams with watersheds ranging from 10^2 to 10^3 km^2 on the Peel Plateau of northwestern Canada were studied to test the hypotheses that (1) intensive thaw slump activity can significantly increase stream sediment and solute concentrations across a range of watershed scales and (2) diurnal ground-ice thaw influences the patterns of water, sediment, and solute flux in streams impacted by mega slumps. The sedimentological and geochemical effects of thaw slumps on streams were assessed over various spatial scales, and the regional-scale distribution and activity of slumping was explored using historical airphotos and satellite images. Long-term water quality data from the Peel River, which drains an area of approximately 70,000 km^2, were examined for evidence of broad-scale impacts of permafrost degradation.

2. Study Area

[6] The fluvial impacts of mega-slump development were investigated in a 1100 km^2 watershed (Stony Creek (SC)) characteristic of the many gravel bed streams that incise the Peel Plateau (24,000 km^2) and the extensive ice-rich moraine landscapes which flank the eastern slopes of the Mackenzie Mountains (Figure 3) [*Fulton*, 1995; *Ecosystem Classification Group*, 2010]. These deposits are within the maximum westward limit of the Laurentide Ice Sheet [*Dyke et al.*, 2002] and have been ice-free since about 12,000 B.P. [*Zazula et al.*, 2009]. In the Peel Plateau, up to 60 m of glacial, glacio-fluvial, and glacio-lacustrine sediments hosting ice-rich permafrost overlie the Lower Cretaceous marine shale and siltstone bedrock [*Norris*, 1984]. The area drains to the Peel River, which contributes significant discharge and sediment loads to the Mackenzie Delta, the world's second largest Arctic delta [*Carson et al.*, 1998]. Elevations in the study watershed range from about 1000 m in the mountains to less than 10 m above sea level (Figure 3). Open forest-tundra woodlands in the valley bottoms transition to tall shrub and dwarf shrub tundra at higher elevations. Maximum active-layer thicknesses are typically less than a meter. Ice-rich permafrost and steeply incised valleys permit the active layer detachment slides and retrogressive thaw slumps common throughout this region (Figures 2 and 3) [*Ecosystem Classification Group*, 2010; *Lacelle et al.*, 2010].

[7] The regional climate is continental, with long cold winters and short cool summers. Mean annual and summer

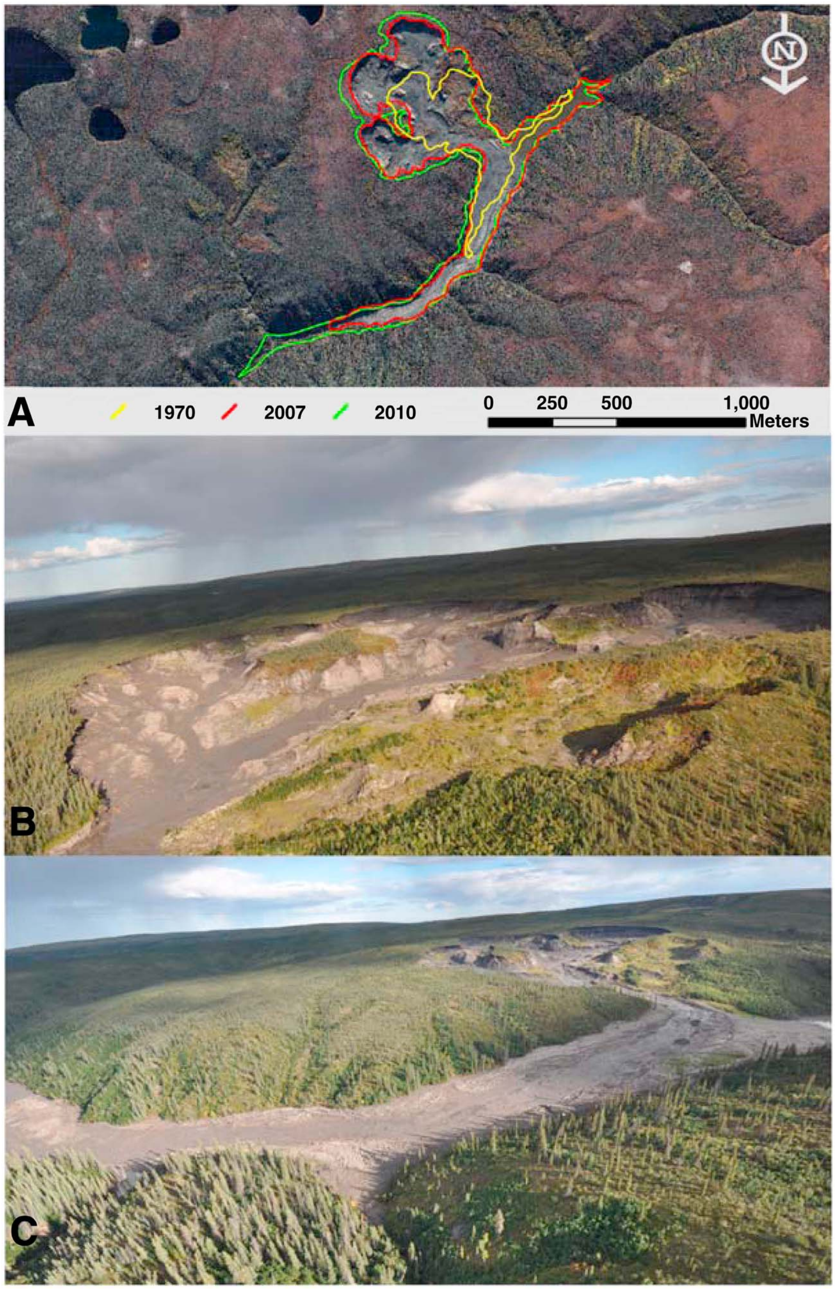

Figure 2. Vertical and oblique images showing one of several large mega slumps in the Stony Creek watershed, Peel Plateau, Northwest Territories, Canada (67 15′20.60″N, 135 14′03.05″). Mega slumps are distinguished from smaller slope-side thaw slumps because they are greater than 5 ha in area, possess headwalls greater than 4 m high, have retreated beyond the upper break in valley slope, and are characterized by debris flows that descend from the slump scar zone down to the valley bottom. (a) Quickbird satellite image (September 2008) showing the mega slump, debris flow, and valley infill. The colored lines indicate the size of the disturbance in 1970 (yellow), 2009 (red), and 2010 (green, ~39 ha). (b) Oblique aerial photograph taken in the summer of 2010 showing the headwall and scar of the same slump. The diameter of the active scar is about 800 m. In 2010, the headwall of exposed ground ice approached 30 m in height and approximately 900 m of the exposure length was active. (c) Oblique air photograph showing the 1.5 km debris flow and valley infill associated with the development of this mega slump.

air temperatures at Fort McPherson (1986–2007) are −6.2°C and 13.3°C, respectively [*Environment Canada*, 2010]. Mean annual air temperatures have increased at a rate of 0.77°C per decade since the 1970s [*Burn and Kokelj*, 2009], making the western Canadian Arctic one of the most rapidly warming regions on the planet [*Serreze et al.*, 2000]. Total annual precipitation at Fort McPherson (1986–2007) averages 295 mm, with rainfall accounting for approximately

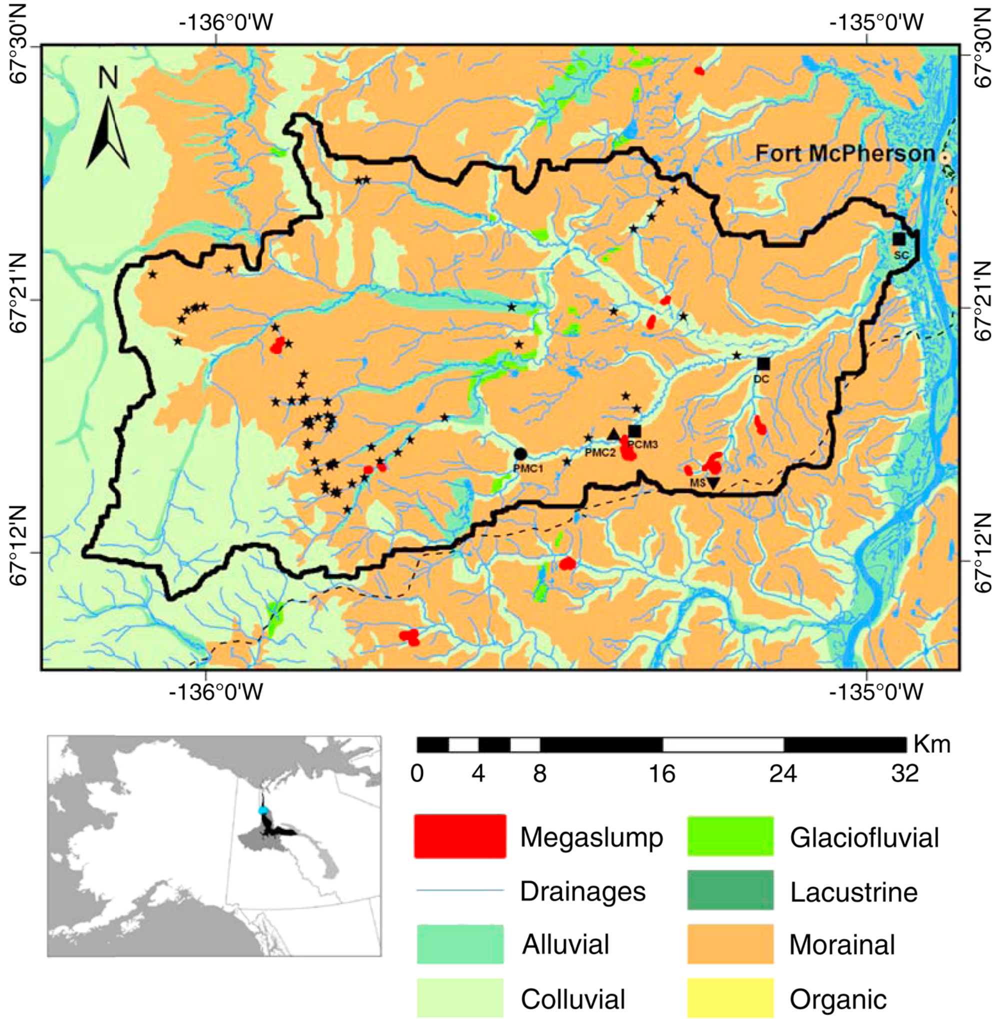

Figure 3. Distribution and size of mega slumps indicated by red (features greater than 5 ha) and small or stable thaw slumps (★) in the Stony Creek area, Peel Plateau. Map shows the boundary of the Stony Creek watershed (solid line), rivers and streams, surficial geology, and the Dempster highway (dashed line). Stream monitoring sites are also indicated: PMC1 (●) unimpacted stream; PMC2 (▲) stream impacted by a few small slumps; and PMC3, DC, SC (■) streams impacted by mega slumps. The meteorological station (▼) is abbreviated (MS). The inset map shows the Stony Creek watershed (light blue), the extent of the Peel Plateau (black), the Peel River watershed (dark grey), and the southward extension of similar ice-rich moraine deposits (light grey). Thaw slumps impact hundreds of streams and rivers throughout this region.

half (148 mm) [*Environment Canada*, 2010]. Convective storms occur in summer, and maximum annual rainfall values can approach 250 mm. Three of the five wettest summers on record extending back to the 1920s have occurred in the past decade.

3. Methods

[8] To investigate the influence of mega-slump development on streams and rivers, we mapped the distribution of thaw slumps in the Stony Creek watershed of the Peel Plateau, compared the sediment and solute flux of impacted and unimpacted streams, and examined multidecadal trends in geochemistry of the Peel River. The mapping and field sampling programs were initiated in the summer of 2010.

3.1. Thaw Slump Characteristics and Spatial Distribution

[9] To map the current distribution and size of active slumps, we used 2008, 2009, and 2010 Quickbird images (1.3 m resolution), 2007 SPOT images (10 m resolution), and aerial reconnaissance. Slumps were hand digitized on screen using ArcGIS 10.0. Active slumps larger than 5 ha, and with debris flows extending from the slump floor to the valley bottom, were classified as "mega slumps." Inactive thaw slumps or those smaller than 5 ha were classified as "stable or active thaw slumps" (Figure 3). To track the recent expansion of mega slumps, we estimated their extent using historical air photos (1970; 1972: 1:70,000) and compared these results with contemporary satellite images.

Table 1. Catchment and Stream Characteristics in the Study Area, Stony Creek Watershed, Peel Plateau[a]

Watershed ID	Catchment Area (km^2)	Impact Status	Impacted Area (ha)	Mean Specific Conductivity (µs/cm)	Mean Turbidity (NTU)	Diurnal Variation
Poor Man's Creek 1 (PMC1)	69	UI	N/A	99.0 (26.0)	[b]	0, 0[b]
Poor Man's Creek 2 (PMC2)	107	SS	5.7	105 (36.0)	52.1 (94.2)	0, 0, 0
Poor Man's Creek 3 (PMC3)	113	MS	43.0	178 (61.0)	585 (349)	1, 1, 2
Dempster Creek (DC)	61	MS	50.0	332 (156)	[b]	2, 2[b]
Stony Creek (SC)	1023	MS	159.1	240 (38.0)	[c]	1, 1, 2

[a]The disturbance status and dominant disturbance type is indicated for each catchment monitored. UI, unimpacted; SS, stable slumps; MS, mega slumps. Mean specific conductivity and turbidity were calculated based on time series data from 11 June to 11 July 2010, which represents the period of intact record for all streams. Standard deviation is reported in brackets. The nature of variations in water levels, conductivity, and turbidity, respectively, is indicated in the right column, where 0 indicates no evidence of diurnal variation, 1 indicates evidence of a weak diurnal pattern, and 2 indicates well-defined diurnal variation.

[b]Turbidity was not measured.

[c]Turbidity showed diurnal variation but record only complete for 10–15 July.

[10] To derive order of magnitude estimates of the amount of permafrost thawed during the development of a large mega slump, and the annual volume of sediments that contributed to the scar zone, we applied measurements of slump size (Figure 2) and conservative estimates of average ice contents from other studies conducted in the region [*Lacelle et al.*, 2010]. The approximation of volumetric permafrost thaw resulting from mega-slump development was estimated by multiplying the measured slump area (30 ha) by the average headwall height (10 m) of a large slump being monitored in the Stony Creek watershed (Figure 2). The annual amount of sediment contributed to the slump scar zone was estimated by multiplying an average rate of headwall retreat (5 m $year^{-1}$) estimated from observations of sequential remote sensing images, by total headwall length (1000 m) by the mean headwall height (10 m) (Figures 1 and 2). The nature of the ground-ice exposures, some over 1000 m in length, is highly variable due to differences in the nature and thickness of ground ice and overburden. We applied a conservative value of 50% volumetric ice content in our estimate [*Lacelle et al.*, 2010].

3.2. Hydrological Regime

[11] To examine the influence of mega slumps on fluvial regimes, we installed 5 YSI Data Sondes (600OMS, 6920VS) equipped with water level, specific conductivity, and turbidity sensors in impacted and unimpacted streams within the Stony Creek watershed (Figure 3 and Table 1). The accuracy of the water level sensor is ±0.003 m. The range of the conductivity sensor is 0–100,000 µs/cm and the accuracy is ±0.5%. The turbidity sensor has a range of 0–1000 nephelometric turbidity units (NTU) with an accuracy of ±2%. Three of the instruments were positioned along a stretch of Poor Man's Creek (local name) where the conditions graded from pristine (PMC1), impacted by few small active and stable thaw slumps (PMC2), to a site furthest downstream, impacted by a mega slump (PMC3). Loggers were also installed in a highly impacted stream (Dempster Creek (DC)) and at the base of the Stony Creek (SC) watershed at the outflow to the Peel River (Figure 3). All loggers were secured to weights placed on the stream-bed, and measurements were taken at hourly intervals from 15 June to 15 August 2010. The turbidity sensor in Stony Creek failed after 14 days.

[12] To complement the hydrological data, an automated meteorological station was established within the Stony Creek watershed, approximately 30 km southwest of Fort McPherson along the Dempster Highway. Air temperature, wind direction and speed, precipitation, incoming and net shortwave, longwave, and total radiation were recorded at 30 min intervals (Figure 3).

3.3. Geochemistry of Surface Runoff, Streams, and Rivers

[13] To quantify the influence of thaw slumps on stream geochemistry, water samples were collected from impacted and unimpacted streams and slump runoff in early June 2010. Spring melt in 2010 was rapid and characterized by hot, dry weather. Stream discharge and sediment levels at the time of sampling represent summer recession conditions. In mid-August, an additional water quality survey was focused on higher-order streams. During mid-August sampling, stream levels were also in recessional conditions as the preceding week had been rain free. At each sampling site, pH and conductivity were measured using a VWR symphony multiparameter meter. Water samples were field filtered through a 0.45 µm pore-diameter filter and collected in prerinsed 60 ml high-density polyethylene (HDPE) bottles. Due to the high sediment concentrations in slump runoff, samples were allowed to settle in 2 L HDPE bottles before filtering.

[14] The total suspended sediment (TSS) concentrations in the streams were determined following standard procedures [*Clesceri et al.*, 1998]. Cation concentrations were determined for acidified samples (pH 2) using a Varian Vista-Pro inductively coupled plasma–atomic emission spectrometer. Anion concentrations were determined using unacidified samples and a Dionex Chromatograph. Analytical reproducibility of the geochemical analysis was 5%, and the charge error balance was <5%.

[15] To assess if permafrost degradation and runoff through previously frozen tills has influenced stream geochemistry, we compared the concentrations of major ions in undisturbed streams with slump runoff and mega-slump impacted stream water. We also investigated the relation between Cl, a constituent that was relatively unimpacted

by permafrost thaw, and SO_4, a dominant ion released during thaw and weathering of tills [*Kokelj et al.*, 2005]. Geochemical ratios have been used extensively to trace water sources and hydrological flow paths [*Land and Ohlander*, 2000; *Quinton and Pomeroy*, 2006], including the assessment of surface water interactions with thawing permafrost [*Keller et al.*, 2010].

[16] To test for statistical differences in suspended sediment concentrations and specific conductivities of impacted and unimpacted streams, the Mann-Whitney *W* test was used to compare medians. To evaluate differences in the concentrations of major ions (Ca, K, Mg, Na, Cl, SO_4, SO_4/Cl) in slump runoff, mega-slump impacted streams, and undisturbed streams, we used a one-way analysis of variance (ANOVA) test [*R Development Core Team*, 2006]. To discriminate differences among the means, we used Tukey's test for multiple comparisons. Data were logarithmically transformed to meet the assumption of normality [*Aitchison*, 1986].

[17] To assess if thaw slumping has impacted geochemistry of the Peel River, we examined the 1960–2012 Peel River water quality and discharge data set recorded at the Water Survey of Canada gauging station 10MC002 situated about 15 km upstream of Fort McPherson and the Stony Creek watershed [*Environment Canada*, 2012a, 2012b]. This geochemistry data set consists of surface water grab samples that have been obtained from the Peel River up to several times a year since 1960 and analyzed for dissolved chemical constituents including major ions and metals. Geochemical and discharge trends were investigated for the summer period (July–September) when runoff from thaw slumps would be most likely to influence the Peel River.

[18] To examine changes in water chemistry in the Peel River from 1960 to 2012, we regressed the SO_4/Cl ratios against the Julian date of sampling. Statistical analyses were performed on the ratios of log-transformed SO_4 and Cl values [*Aitchison*, 1986]. To test this time series for serial autocorrelation, we calculated the Durbin-Watson statistic of this model (dwtest[lmtest]) and used the ACF function in the R base package. These tests revealed significant autocorrelation at lags between 2 days and 1 year. Consequently, we report the results of the least squares regression but also use a nonparametric technique (Mann-Kendall test) robust to missing values and serial dependence to assess the significance of this trend [*Hirsch et al.*, 1982; *Environment Canada*, 2011].

4. Results and Discussion

4.1. Mega Thaw Slumps

[19] Thaw slump activity across the western Arctic of North America has recently intensified [*Lantuit and Pollard*, 2008; *Lantz and Kokelj*, 2008; *Lacelle et al.*, 2010]. The mega thaw slumps we have documented in the Stony Creek watershed (Figures 1 and 2) are among the largest reported, although numerous features of similar magnitude impact fluvial systems across the Peel Plateau and watersheds draining the eastern foothills of the Mackenzie Mountains (Figure 3) [*Ecosystem Classification Group*, 2010]. These large, active retrogressive thaw slumps are distinguished from smaller slope-side thaw slumps because they are greater than 5 ha in area, possess headwalls greater than 4 m height, and/or have retreated beyond the upper break in valley slope (Figures 1 and 2). They are also characterized by debris flows that descend from the slump scar zone down to the valley bottom, thereby physically coupling the slope and fluvial systems (Figure 2c). In the study catchment, we identified more than 60 active or recently active thaw slumps (Figure 3) and we classified 9 of these as mega slumps (Figure 2). These features have near-vertical headwalls up to 30 m high, exposing massive ice overlain by 2–5 m of till, and a slump floor with a slope of less than 5^o (Figure 1). The debris flows may be characterized by steeper gradients (Figure 2b) [*Lacelle et al.*, 2010]. The average area of active mega slumps (scar and debris flow) was 13.2 ± 5.7 ha, whereas the remaining slumps in the study area were typically smaller than 2 ha. The largest mega slumps were up to 40 ha. Our first-order estimates suggest that mass wasting associated with the development of a large mega slump can release up to $10^4\ m^3\ year^{-1}$ of sediment from thawing terrain. We also observed debris flows associated with the development of large thaw slumps that have extended onto floodplains or infilled stream valleys. These debris flows provide evidence that a significant portion of thawed sediments are being transported downslope (Figure 2). Between 2007 and 2010, the debris flow associated with one mega slump grew by approximately 500 m down valley (Figure 2a). Field observations suggest that this mass wasting occurred relatively rapidly during the extremely wet summer of 2010. Although rainfall patterns can vary locally, total precipitation in the Stony Creek catchment from 6 June to 18 August was 245 mm. This exceeded the maximum total summer precipitation measured at Fort McPherson for the entire instrumental record (1920–2010) [*Environment Canada*, 2010]. These debris flows have altered streamflow, and in some cases, debris dams have created small lakes which may drain periodically. Valleys with ancient infill comparable to that shown in Figure 2c were not evident in the examination of air photographs and aerial reconnaissance from the region. The disturbance status of the monitored stream catchments is summarized in Table 1.

4.2. Mega-Slump Development Drives Patterns of Stream Water, Solute, and Sediment Flux

[20] Meltwater derived from ground-ice ablation in large retrogressive thaw slumps can drive the sediment and solute flux in the adjoining streams. This runoff also has a discernible, second-order influence on the water levels of impacted streams. The influence on stream water flux was most evident in Dempster Creek (DC) which drains an area of about 60 km^2 and contains three mega slumps (Figure 3). Several convective storm events were associated with rapid increases in all stream water levels (Figures 4a and 4e), but diurnal variations were clearly apparent in Dempster Creek during recessional periods (Figure 4ai). Figure 4ai shows that diurnal water level variations in the mega-slump impacted stream lagged net radiation by several hours. Subtle diurnal patterns in stream water levels were also discernible in the larger impacted streams during warm dry periods (Table 1). No diurnal patterns were observed in unimpacted stream or in those affected by a few small thaw slumps (Figure 4a, ai, and Table 1).

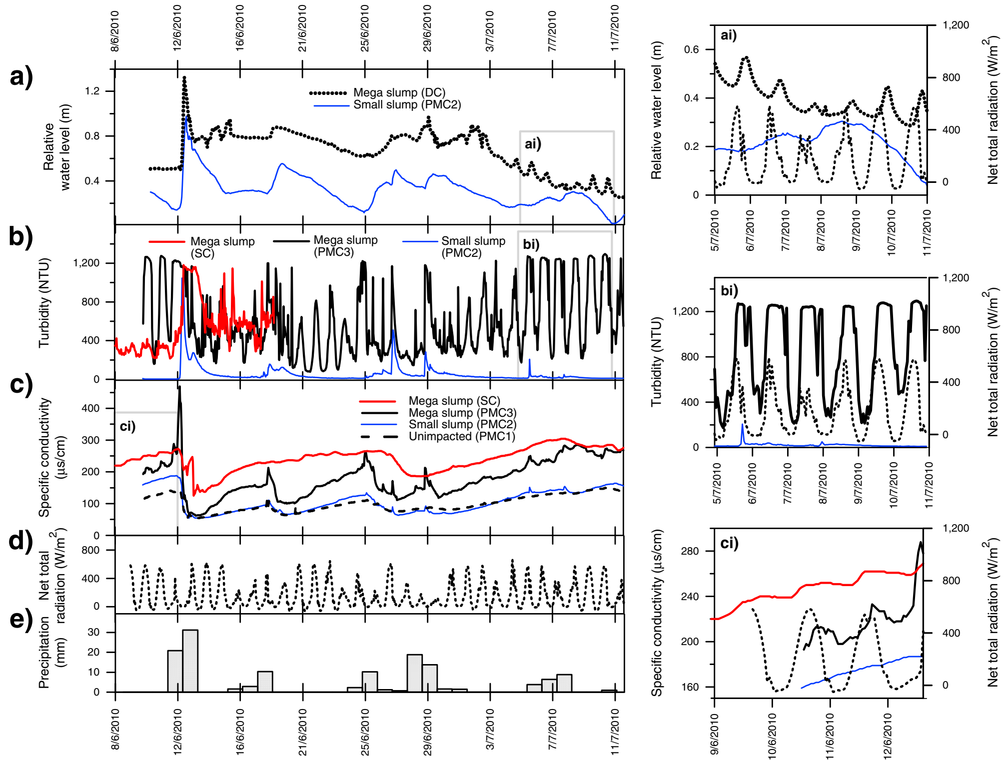

Figure 4. Stream conditions in unimpacted, small-slump and mega-slump impacted watersheds, and net solar radiation, and precipitation, 8 June to 11 July 2010. (a) Stream water levels. (b) Turbidity. (c) Specific conductivity. (d) Net shortwave radiation. (e) Total daily precipitation. ai, bi, and ci show detailed data for stream water levels, turbidity, and specific conductivity, respectively. Net total radiation is indicated by the thin dotted lines. Figures 1a and 1ai show stream water levels for a 61 km^2 watershed (DC) intensively impacted by three mega slumps and a 107 km^2 catchment containing only a few small slumps (PMC2). Figures 1b and 1bi show levels and patterns of variation in stream water turbidity between mega-slump impacted catchments (SC, 1023 km^2; PMC3, 113 km^2) and a largely unimpacted catchment containing only a few small slumps (PMC2, 107 km^2). Note that turbidity at PMC2 is virtually identical to PMC1 which is upstream and entirely uninfluenced by slumping. Figures 1c and 1ci show specific conductivity of slump impacted and unimpacted streams.

[21] Mega-slump activity had a significant influence on the magnitude and timing of fine-sediment transport in streams. The suspended sediment contribution from slump runoff and erosion of debris flows raised stream turbidity and total suspended sediment (TSS) concentrations by 1–3 orders of magnitude over levels measured in streams unaffected by mega slumps (Figures 4b and 5a and Table 1). In unimpacted streams, turbidity was generally low, though abrupt spikes up to 1000 NTU were observed during rainfall-induced runoff events (Figure 4b). Suspended sediment transport in streams impacted by mega slumps also responded to rainfall events, but turbidity often remained elevated into the flow recession period. During recession and low water periods, turbidity in mega-slump impacted streams displayed diurnal oscillations that lagged several hours behind the daily increases in net solar radiation (Figure 4b, bi). Turbidity in a mega-slump impacted stream (PMC3) ranged from about 200 NTU between 02:00 and 12:00 hours to peak levels of up to1200 NTU (exceeding the instrument maximum) 2–3 h after maximum daily solar radiation (Figure 4b, bi). Similar but subdued diurnal variations in turbidity were observed in Stony Creek at the outflow to the Peel River during the several clear days that preceded sensor failure (Figure 4b). Diurnal variation in stream turbidity was not observed in undisturbed streams or in those influenced by only a few small slumps and landslides (Figure 4b).

[22] Throughout the summer, specific conductivity in streams influenced by mega slumps was significantly greater than in unimpacted streams and in those affected by small thaw slumps (Figures 4c and 5b and Table 1). Specific conductivities in an undisturbed headwater stream (PMC1) were very similar to the conditions measured further downstream, below a few small thaw slumps (PMC2). In contrast, stream water specific conductivity was dramatically greater at site PMC3, which is located just downstream and below the confluence of runoff from a large mega slump (Figures 3 and 4c and Table 1). During base flow periods, streams impacted by mega slumps also displayed subtle diurnal variations in conductivity (Figure 4c, ci), matching the higher amplitude oscillations in turbidity described above. Streams impacted by a few small thaw slumps and those with unimpacted catchments did not display diurnal variations in specific conductivity (Figure 4ci and Table 1). At the mega-slump impacted stream (PMC3), specific conductivity spiked during the onset of

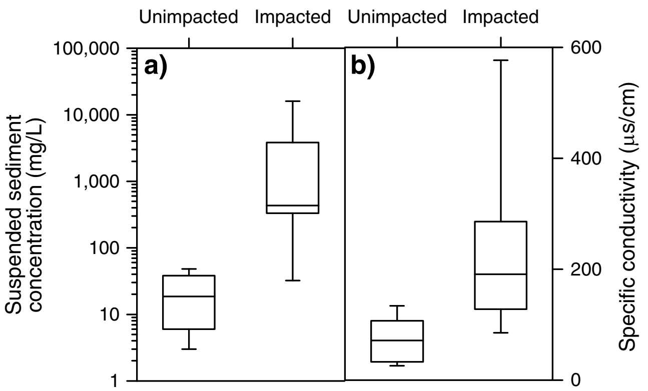

Figure 5. Box and whisker plots of (a) total suspended sediment concentrations and (b) specific conductivity from unimpacted ($n = 12$) and slump impacted ($n = 22$) streams on the Peel Plateau, August 2010. Between-group medians (Mann-Whitney W test) are significantly different for stream water suspended sediment concentrations ($W = 128.5$; $p < 0.0001$) and specific conductivity ($W = 119.0$; $p < 0.0001$).

rainfall (Figure 4c). Rainfall-induced spikes in specific conductivity were followed by abrupt decreases in impacted and unimpacted stream water conductivity with increasing discharge (Figures 4a and 4c).

4.3. Impacts of Mega Slumps on Surface Water Geochemistry

[23] Mega-slump development can release immense volumes of previously frozen ice-rich tills that thaw and accumulate in the scar zone or enter the floodplain via debris flows (Figure 2). In the lower Mackenzie Valley, soluble SO_4 levels in permafrost are up to two orders of magnitude greater than in the overlying active layer or at the top of permafrost [*Kokelj and Burn*, 2005]. The dissolution of gypsum or the oxidation of pyrite [*Drever*, 2002] provides two potential sources of sulphate from the thawing tills. Subsequent leaching can significantly elevate SO_4 and base-cation concentrations in slump runoff (Table 4) [*Kokelj et al.*, 2005] and in mega-slump impacted streams (Figure 6 and Table 2). The relative proportion of major ions, with the exception of Cl, was similar among the slump runoff, impacted, and unimpacted streams (Table 2), reflecting the general homogeneity in the composition of the till deposits that blanket much of the study basin.

[24] To evaluate the impact of slumping on surface waters, we investigated the relationship between SO_4, a dominant ion released during thaw and weathering of tills [*Kokelj et al.*, 2005], and Cl, an ion that showed only minor increase with permafrost degradation (Table 2). Impacted streams show a clear mixing signal of slump runoff and unimpacted stream water end-member values (Figure 6a). Sulphate concentrations and SO_4/Cl ratios in slump runoff are more than tenfold greater than those found in surface waters derived from undisturbed terrain (Table 2 and Figures 6a and 6b). Variation in the relative contribution of slump runoff to streams accounts for the overlap in the geochemical characteristics of impacted and unimpacted stream water (Figure 6b). Taken together, these data show that the SO_4/Cl ratio can serve as a geochemical indicator of the influence of thaw slump development on stream water for tills comprising the Peel Plateau, and likely other glaciogenic deposits in northwestern Canada [*Kokelj et al.*, 2005].

4.4. Peel River Geochemical Trends

[25] Intensive slumping throughout the Peel Plateau suggests that thaw slump impacts on periglacial streams are already widespread (Figure 3) [*Lacelle et al.*, 2010]. To assess if development of mega slumps has impacted the geochemistry of the Peel River, we examined temporal trends in the summer season SO_4/Cl ratio for Peel River from 1960 to 2012 [*Environment Canada*, 2012a]. Figure 7 shows that the summer SO_4/Cl ratios in the Peel River have more than doubled in the last 40 years. Large temporal autocorrelation in this data set suggests that the parameter estimates associated with a least squares model are biased, but a nonparametric test for trend (Mann-Kendall) confirms that there is significant monotonic increase in the SO_4/Cl ratio over the period of record ($\tau = 0.57$, $p < 0.001$). To examine the potential influence of discharge on the Peel River geochemical trends, we examined the correlation

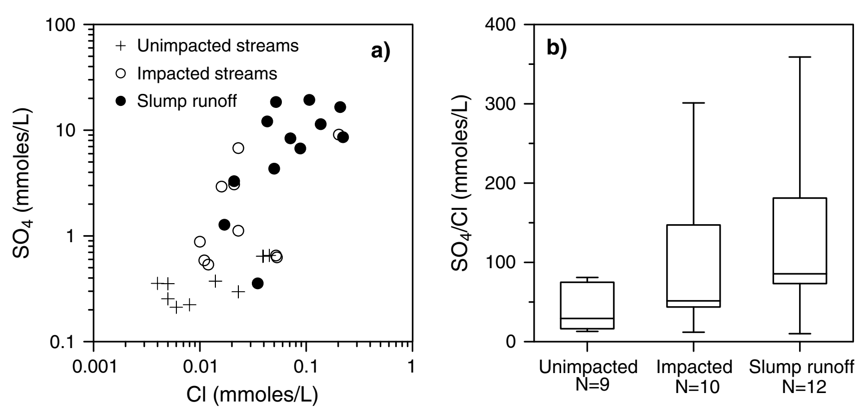

Figure 6. (a) Scatter plot showing Cl versus SO_4 for mega-slump runoff and impacted and unimpacted streams. (b) Box and whisker plot of SO_4/Cl values for unimpacted and mega-slump impacted streams and mega-slump runoff, June 2010. There are significant differences among the three sample groups ($F_{2,\ 28} = 13.25$; $p < 0.0001$). The mean SO_4/Cl ratio for slump runoff is significantly different from unimpacted and impacted stream water.

Table 2. Geochemical Concentrations in Surface Water Samples from the Stony Creek Watershed, June 2010[a]

Sample Type	Ca	K	Mg	Na	Cl	SO_4
	(mmol/L)					
Unimpacted streams ($n=9$)	0.61 (0.47)	0.02 (0.01)	0.35 (0.23)[1]	0.15 (0.06)	0.02 (0.02)[1]	0.38 (0.16)
Impacted streams ($n=10$)	1.97 (1.83)	0.07 (0.07)	0.91 (0.79)[1]	0.79 (0.80)	0.04 (0.06)[1,2]	2.63 (3.01)
Slump runoff ($n=12$)	5.93 (4.22)	0.21 (0.11)	2.71 (1.72)	2.20 (1.42)	0.09 (0.07)[2]	9.26 (6.51)
ANOVA results	$F_{(2,28)}=14.8$; $p<0.0001$	$F_{(2,28)}=30.3$; $p<0.0001$	$F_{(2,28)}=15.5$; $p<0.0001$	$F_{(2,28)}=19.5$; $p<0.0001$	$F_{(2,28)}=10.2$; $p<0.001$	$F_{(2,28)}=21.8$; $p<0.0001$

[a]The table shows the mean and standard deviation of major ions for impacted streams, unimpacted streams, and slump runoff and the results of the analysis of variance contrasting sample groups. For each ion, sample groups that have the same subscript were not significantly different.

between available discharge data (daily mean) and solute concentrations. The Spearman's rank correlation revealed no significant relationship between these two parameters ($S=33628.89$, $p=0.395$). We also examined temporal trends using the available summer discharge data following the same statistical methods applied to the geochemistry data. The Mann-Kendall test ($\tau=0.054$, $p=0.265$) revealed no significant temporal trend in the Peel River discharge data.

[26] The increasing solute concentrations in the Peel River can be attributed to the acceleration of geomorphic activity rather than to temporal variation in summer discharge or the regional deepening of the active layer. Long-term monitoring of thaw depths shows significant year-to-year variability and small increases at only some sites in the region [*Smith et al.*, 2009]. Increasing active-layer thickness would thaw only the top of permafrost [*Shur et al.*, 2005], which is characterized by ionic concentrations similar to those at the base of the active layer [*Kokelj and Burn*, 2005; *Kokelj et al.*, 2002]. Base cation concentrations typically increase by an order of magnitude at depths of 1–2 m below the base of the contemporary permafrost table [*Kokelj and Burn*, 2005]. At present, these ion-rich materials are thawed only by extreme geomorphic activity such as thaw slump development [*Kokelj et al.*, 2005]. Furthermore, extreme active layer thaw should only influence the geochemistry of late summer runoff, but the Peel River geochemical trend is composed of samples collected through July to the end of September. Atmospheric deposition of SO_4 with precipitation in the far northwest of Canada is generally low and well below the values measured in the impacted streams and in the Peel River [*Environment Canada*, 2012c]. Atmospheric deposition was not considered to be a major driver of the Peel River solute load.

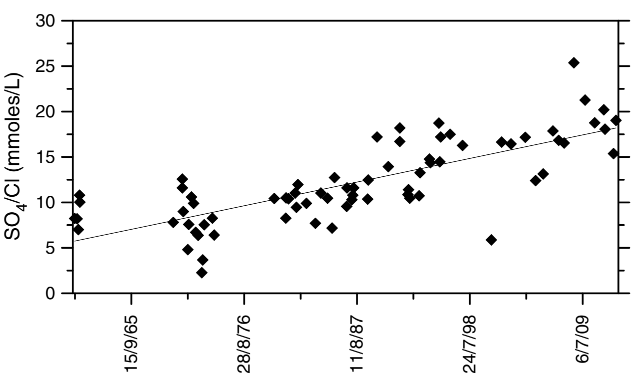

Figure 7. The SO_4/Cl molar ratios of water samples collected from the Peel River above Fort McPherson (July–September, 1960–2012). Line shows the least squares linear regression, $r^2=0.3316$; $F_{1,\ 71}=35.23$; $p<0.0001$. The Peel River watershed is approximately 70,000 km^2 in area, and the lower portion is characterized by glaciogenic deposits of the Peel Plateau.

4.5. Sensitivity of Fluvial Systems in Ice-Rich Glaciogenic Landscapes

[27] Glaciogenic landscapes underlain by massive ice occur throughout the circumpolar North. These environments have the potential to undergo major geomorphic changes as a result of climate warming and accelerated thermokarst activity (Figure 2). Here we show that fluvial regimes across a range of watershed scales are being significantly altered by the thawing of massive ice in mega slumps (Figures 1, 2, and 4). During the summer, ablation of massive ground ice drives diurnal pulses of water, and suspended sediment and solute loads, causing large increases in turbidity, specific conductivity, and geochemical concentrations in impacted streams. Thaw slumping is of sufficient intensity and magnitude that diurnal variations in these parameters are now being expressed in streams draining medium-sized watersheds (10^3 km^2) (Figure 4).

[28] The development of mega slumps changes the nature of the geomorphic coupling between slopes and streams. Runoff derived from thawing ground ice can drive the patterns of slope sediment and solute fluxes. Diurnal fluxes measured in impacted streams are strengthened during warm dry periods in summer when the contrast with undisturbed stream systems becomes most pronounced (Figure 4). Immense debris flows associated with mega-slump growth transfer materials from slopes to valley bottoms and floodplains, where fine-grained sediments are entrained by the stream (Figures 2 and 4). Long-term geomorphic impacts can be expected because these large slumps remain active for decades, while new slumps continue to initiate [*Lacelle et al.*, 2010]. Surface disturbance and an increase in slope sediment availability, leaching of slump soils by surface runoff, and delivery of debris to the floodplain by mass wasting will influence stream sediment loads and ionic concentrations for centuries. These longer-term increases to stream sediment supply can also shift the geomorphic systems from fluvial incision to a phase of floodplain aggradation (Figure 2).

[29] Sediment and solute delivery to valley bottoms and streams due to development of mega slumps has geomorphic consequences that extend across a range of watershed scales. Infilling of stream valleys indicates large magnitude,

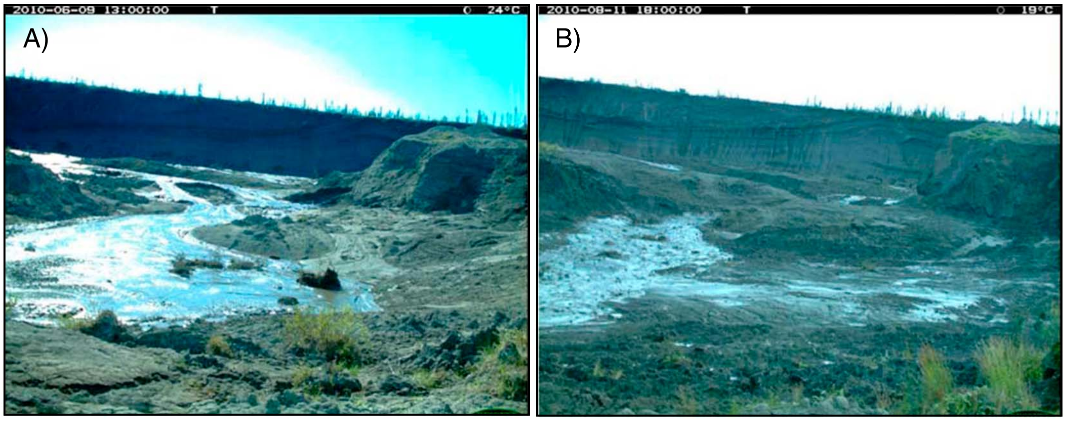

Figure 8. Scar zone and headwall of large mega slump on (a) 9 June 2010 and (b) 11 August 2010. This slump is also shown in Figures 1 and 2. Comparison of the photographs taken from a fixed position shows a lowering of the scar surface following extreme precipitation during summer 2010. Total summer precipitation measured at the Peel Plateau meteorological station exceeded the maximum total measured at Fort McPherson for the entire period of instrumented record. The evacuation of materials from the slump scar zone occurred in conjunction with the down valley extension of the debris flow shown in Figure 2.

local-scale impacts on fluvial geomorphology (Figure 2), whereas elevated stream sediment and solute concentrations can be clearly detected at the 10^3 km^2 watershed scale (Figures 4–6). Although ice-rich glaciogenic terrain underlies less than 30% of the Peel River basin, the acceleration in thaw slump activity has likely caused the significant increasing trend in the geochemical concentrations of this large river (Figure 7). These observations suggest that thermokarst degradation of ice-cored glaciogenic landscapes can have a disproportionately large influence on the ionic and sediment flux of major rivers.

[30] Based on our observations, we suggest that increasing intensity and amounts of summer precipitation will have a significant impact on accelerating geomorphic activity in ice-rich glaciogenic landscapes. With respect to the development of mega slumps, intense rainfall events promote the evacuation of materials that would otherwise accumulate in the scar zone and cover the ground-ice exposure, stabilizing the slump (Figure 8) [*Lewkowicz*, 1987; *Lacelle et al*., 2010]. Acceleration in the rate of sediment removal from the scar zone can increase the upslope growth potential of these disturbances by maintaining the height of the ground-ice exposure. Intense summer rains combined with slump meltwater runoff can also promote gullying of the scar zone [*Lantuit and Pollard*, 2008]. These processes can perpetuate slump growth and promote polycyclic behavior of the disturbance. Where slope and ground-ice conditions are favorable, intensification of summer precipitation regimes will likely increase the potential for smaller active thaw slumps to evolve into mega slumps.

[31] Our field observations and interpretations can be considered in the context of stratigraphic evidence from northern Alaskan rivers where periods of rapid floodplain alluviation have been correlated with climate warming and enhanced moisture regimes during the early Holocene climate optimum [*Mann et al*., 2010]. Widespread thermokarst activity and geomorphic change occurred during this time period throughout ice-rich glaciogenic landscapes, including the Peel Plateau [*Lacelle et al*., 2004] and in the more subdued, lake-rich environments underlain by massive ice to the east of the Mackenzie Delta [*Rampton*, 1988; *Burn*, 1997; *Murton*, 2001]. Sedimentary evidence of past acceleration of thermokarst activity highlights the geomorphic sensitivity of ice-cored glaciogenic environments to changing climate conditions.

[32] An acceleration of thaw slump activity and the geomorphic impacts on fluvial systems will have major implications for stream ecosystems. Freshwater invertebrate communities are particularly sensitive to stream sediment and water quality conditions [*Larsen and Ormerod*, 2009; *Wagenhoff et al*., 2011; *Benoy et al*., 2011], so we anticipate that intensive thaw slumping will negatively impact benthic communities. Numerous streams and rivers that drain ice-rich glaciogenic landscapes in the lower Peel and Mackenzie basin are fish bearing, and many of these slump impacted rivers host migratory populations of Dolly Varden (*Salvelinus malma*) [*McCart*, 1980]. The distribution of thermokarst disturbances relative to spawning, rearing, and overwintering habitat, the nature of water quality, and stream sediment characteristics during migration periods and the impacts of these conditions on fish physiology will be important factors in considering the emerging stressors on aquatic ecosystems and fisheries resources in a warming circumpolar north.

5. Conclusions

[33] The development of large retrogressive thaw slumps can dramatically increase stream sediment and solute fluxes across a range of watershed scales. In glaciogenic landscapes of northwestern Canada, immense thaw slumps, some exceeding 40 ha in area with debris flows up to 1.5 km in length, have made large volumes of previously frozen, highly weatherable fine-grained sediments available for leaching and transport to adjacent streams. Suspended sediment and solute concentrations in slump impacted streams were several orders of magnitude greater than in unimpacted streams. In summer, streams in watersheds with mega slumps displayed diurnal fluctuations in water levels,

and solute and sediment concentrations, which were driven by ground-ice thaw. All streams were characterized by abrupt rainfall-induced turbidity peaks. In slump influenced streams, elevated suspended sediment concentrations were sustained following peak flow, reflecting the abundant sediment supply in mega-slump impacted watersheds. The influence of thaw slumping on the patterns of stream sediment and solute flux was discernible at the 10^3 km^2 catchment scale. Regional disturbance inventories indicate that hundreds of watersheds are impacted by slumping in the Peel and lower Mackenzie River basins and throughout the western Arctic.

[34] The geochemistry of slump impacted and unimpacted surface waters indicates the SO_4/Cl ratio may be utilized to track the influence of thaw slumps on streams draining glaciogenic landscapes in northwestern Canada. A significant increase in summer season SO_4/Cl ratio for the Peel River between 1960 and 2012 suggests that an increase in thaw slump activity has influenced the geochemical flux of this large river.

[35] Our observations suggest that the stability of ice-rich glaciogenic landscapes can have significant influence on stream sediment and solute fluxes across a range of watershed scales. This landscape type constitutes a major source of sediments to the Peel and Mackenzie Rivers [*Carson et al.*, 1998], and to numerous other river systems across the circumpolar north. Thaw slump activity and the geomorphic and fluvial consequences that we describe can be expected to increase as glaciogenic landscapes underlain by massive ice adjust to rapid climate warming. Many northern stream ecosystems that have evolved under cold climate conditions will be under tremendous stress as fluvial systems adjust to increases in the intensity of thermokarst activity.

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