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Fluvial Impact of Extensive Active Layer Detachments, Cape Bounty, Melville Island, Canada

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Abstract

Exceptional and persistent warm temperatures recorded during July 2007 at Cape Bounty, Melville Island, Canada (74°54′N, 109°35′W), resulted in rapid and deep active layer formation. The thickened active layer, together with up to 10.8 mm of rainfall in late July, resulted in widespread active layer detachments across the West watershed during 23–31 July. Mapping indicates that approximately 1.9% of the watershed was directly impacted by disturbances. By contrast, only two small detachments occurred in the adjacent East watershed.

The immediate fluvial impact of the detachments was primarily in the form of abrupt, short-lived rises in river turbidity, along with a more gradual increase in discharge and overall turbidity. Sediment transport pulses resulted from the hydrological connection of major detachment slides, most of which were upslope from the main channel. The largest detachment dammed the river over a length of 200 m, and resulted in an upstream pond and prolonged increased sediment transport. In total, the increased sediment transport during the last week of July amounted to an estimated 44.3 Mg, or 18% of the seasonal yield. While the detachments had an immediate and substantial impact on river conditions, erosion of unstable material is likely to have a sustained impact on watershed fluxes in future years.

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Introduction

Growing evidence for enhanced arctic warming (ACIA, 2005), indications of permafrost degradation (e.g., Jorgenson et al., 2006; Fortier et al. 2007; Isaksen et al., 2007), along with predictions of the widespread decline in permafrost extent in the next century (Lawrence and Slater, 2005) has focused research towards assessment and characterization of permafrost landscape sensitivity to disturbances associated with increased melt season active layer depth (Young, 2006; French, 2007). While permafrost disturbance has been widely documented in geomorphic studies (e.g., Kokelj and Lewkowicz, 1998, 1999; Fortier et al. 2007), comparatively little is known about the fluvial impact of major permafrost disruptions. Detailed observations indicate that nivation hollows and other intense, localized disruptions can substantially increase sediment erosion and lead to exceptionally high suspended sediment and solute loads from slopes (Kokelj and Lewkowicz, 1999). The increased erosion may continue for decades following initial disturbance as evidenced by both geomorphic (Kokelj and Lewkowicz, 1999) and downstream sedimentary records (Lamoureux, 2002). Declines in erosion of land surface materials, followed by establishment of vegetation, contribute to the ultimate stabilization of these disturbances (Lewkowicz, 1990).

An important class of permafrost disturbance features are mass movements of soil and surface sediment along the base of the active layer (French, 2007). These slides, referred to as active layer detachments (ALDs), occur when saturated overburden slides over the frozen substrate, and result in the downslope travel of material up to hundreds of meters over low slope angles (Lewkowicz, 2007). Saturation of the overburden can occur from ground ice melt during deep thaw, upslope drainage seeps from perennial snow banks, or rainfall contributions (Hodgson, 1977; French, 2007). ALD features vary substantially due to different soil, vegetation, and slope characteristics, but usually involve a combination of highly disturbed soil, sharp lateral shear zones or boundaries, and formation of extensive fracture and fold regions as soil moves (Harris and Lewkowicz, 1993; Lewkowicz, 2007). In some cases, downslope movement of soil material may result in the undisturbed displacement of soil and vegetation within the ALD. Downslope movement may reach rates up to 9 $m \cdot h^{-1}$, followed by reduction or cessation of movement (Lewkowicz, 2007). Hence, ALDs represent important permafrost landscape features with the potential to impact watershed processes, sediment and solute budgets, aquatic ecosystem responses, and may in some cases represent a geotechnical hazard.

While the morphology and primary processes involved in ALDs are reasonably well known (e.g., Harris and Lewkowicz, 1993; Lewkowicz, 1990, 2007), little is known about the impacts on the hydrological and fluvial environment that result from ALD occurrences. Given the potential for high sediment and solute erosion from permafrost disturbances (Kokelj and Lewkowicz, 1999), downstream impacts could be substantial. This paper reports initial results from paired watersheds located at the Cape Bounty Arctic Watershed Observatory (CBAWO) in the Canadian High Arctic, and evaluates the immediate hydrological and sediment transport impact of widespread ALD formation after an extended period of exceptional summer warmth and a large rainfall event. These results point to the importance of ALDs and permafrost disturbances in general to watershed-scale responses of sediment yield, and to our knowledge, represent the first documented case of these processes.

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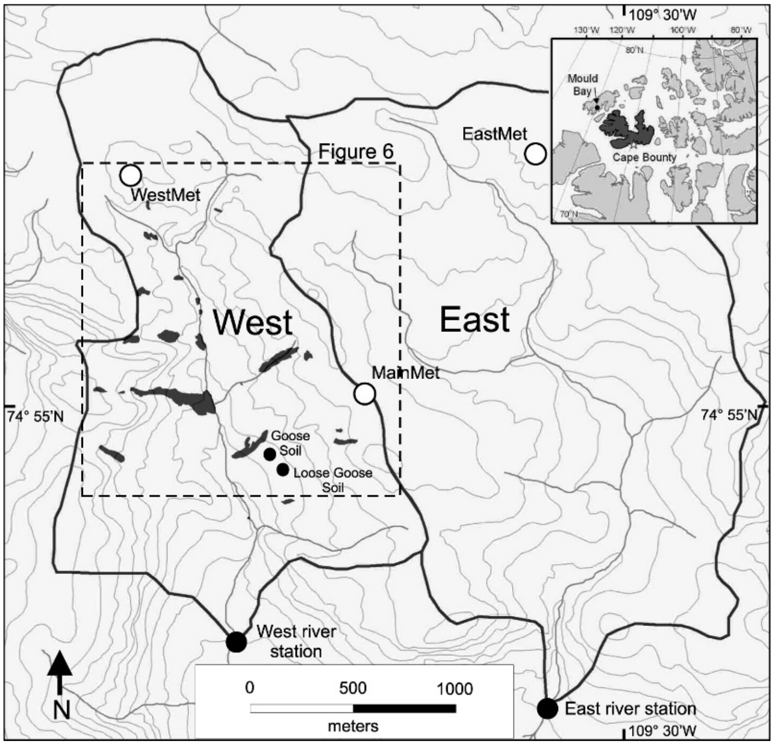

FIGURE 1. Study area at Cape Bounty, Melville Island (regional location in Canadian Arctic shown in inset). Watershed boundaries are shown by heavy black lines and locations of river gauging stations and MainMet are indicated. The extent of active layer detachments (ALDs) mapped in late July 2007 are shown in black. Outline of map in Figure 6 is indicated by dashed rectangle. Contour interval is 10 m (base map prepared from NTS 1:50 000 map 78F/15).

Study Area

The CBAWO is located on the south-central coast of Melville Island, Nunavut, Canada (74°54′N, 109°35′W; Fig. 1). This High Arctic location is characterized by incised, low elevation plateaux that rise 100–125 m above sea level (a.s.l.). Bedrock is composed of Devonian sandstone and siltstone of the Weatherall, Griper Bay, and Hecla Bay formations, overlain by late Quaternary glacial and marine sediments (Hodgson et al., 1984). With the exception of rock outcrops, slopes are generally gentle and slope drainage is characterized by shallow channels or diffuse flow in concavities, or sheet flow over saturated soils. Vegetation is highly heterogeneous, and broadly composed of sparse polar desert tundra communities (Walker et al., 2002). Locally wetter areas, in concavities downslope of late-lying snow banks, support extensive wet sedge communities and intermediate moisture sites contain similar species with reduced vegetation cover (D. M. Atkinson, personal communication, 2008).

The climate is cold throughout the year, with melting temperatures between June and August. Low precipitation, most of which falls as snow, is extensively redistributed by frequent winter winds and results in thick accumulations of snow in channels, lee slopes and concavities, and more variable cover on other surfaces. Hydrological activity is limited to the melt period that typically begins with snow melt in early to mid-June, initial runoff in mid-June, and a brief nival freshet that is usually over after the first week of July. Streams recede during summer due to the absence of groundwater baseflow in this continuous permafrost environment. Summer thaw depths typically extend to c. 50 cm depth and ground ice has been observed in eroded channel banks and small surface disturbances. Freezing temperatures return in August and end runoff.

Methods

A comprehensive watershed monitoring network was established at CBAWO in 2003. Systematic measurements of meteorological, hydrological, soil, and limnological variables were obtained at fixed stations, along with automated and manual sampling of water for sediment and hydrochemical components in paired watersheds (West [8.0 km^2] and East [11.6 km^2], unofficial names; Fig. 1) along with a number of smaller nested catchments.

An end of winter (30 May–1 June) snow survey was carried out in both catchments based on 40 established transects that were previously marked with poles. Each 100-m-long transect consisted of 11 depth measurements and three density determinations with a snow tube and portable digital scale. Mean snow water equivalence (SWE) was determined from each transect and among transects with similar terrain characteristics to generate a terrain-weighted SWE for each catchment (McDonald and Lamoureux, in press).

Three meteorological stations were established in 2003 and were maintained during the 2007 season (Fig. 1). MainMet station included shielded air temperature and relative humidity measured with a Humirel HTM2500 sensor at 1.5 m above the surface (3% temperature, 2% RH accuracy); rainfall recorded at 1.5 m with a Davis industrial tipping bucket gauge (0.2 mm tip); a Davis incoming solar radiation sensor (5% accuracy) and Davis anemometer (5% velocity accuracy), both recorded at 3 m above the surface. All sensors were scanned at 5 minute intervals and hourly means were recorded with a Unidata Prologger. Meteorological instruments at WestMet and EastMet comprised shielded air temperature and precipitation only, and are not reported in this study. Soil stations were established in 2006 at a number of locations in the West catchment (Fig. 1). Installations included YSI 40333 thermistors (0.2% accuracy) at 10, 20, and 50 cm depth, all logged with an Onset Hobo H8 logger at 2 hour intervals.

Gauging stations were established on the West and East rivers at locations used in previous years (Fig. 1). Each station consisted of a stilling well with an Onset Hobo U20 water level and temperature logger (0.1% FS pressure, 0.37°C accuracy). Manual rating points were obtained daily using the velocity-area method

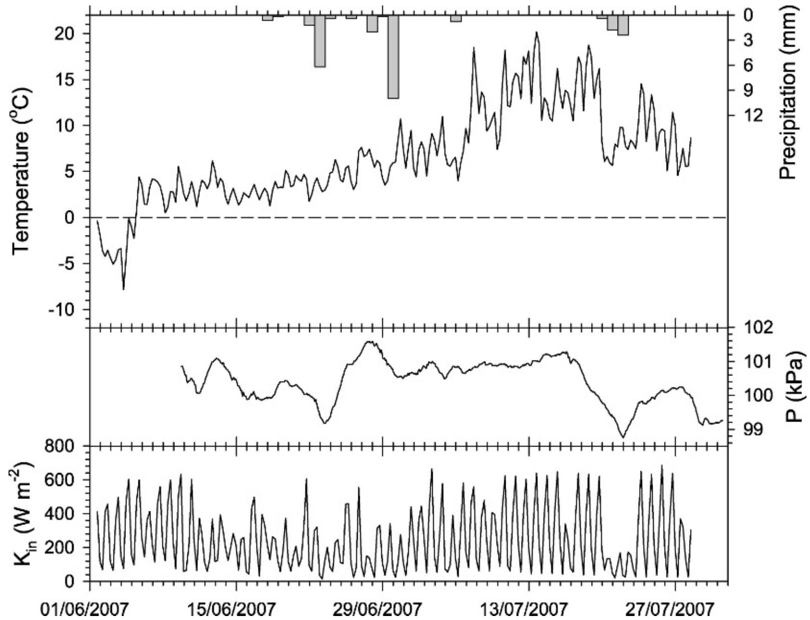

FIGURE 2. Meteorological conditions recorded during the summer of 2007 at MainMet (Fig. 1). All values are hourly, with the exception of daily precipitation.

and a Swoffer 2100 current velocity meter (1% accuracy). An aluminum boom was used to secure an Analite NEP9500 turbidity probe (0–3000 NTU, 3% accuracy) and Global Water WQ301F electrical conductivity sensor (0–500 μS cm^{-1}, 1% accuracy) and anchor the sensors 50 cm from the bank. Both sensors were recorded at 10 minute intervals on an Onset FlexSmart logger. The turbidity probe was calibrated for suspended sediment concentration (mg L^{-1}) before deployment using polymer standards and Cape Bounty–sourced materials. Early deployment of the East river stilling well resulted in the pressure transducer being out of water during much of the season. Missing data were extrapolated using a robust spline fit with daily manual rating points. Similarly, low flow left the turbidity and conductivity sensors out of water at some times and the data at these times are not reported. ISCO 3700C pump samplers were used to collect sediment and hydrochemical samples at three and six hour intervals, respectively. Sediment samples were filtered through Osmotics 1 μm glass fiber filters to determine suspended sediment concentration (SSC) following previous practice at CBAWO (Cockburn and Lamoureux, 2007).

Initial mapping of ALDs began on 26 July 2007 and continued during the last week of the field program. The perimeter of each ALD was mapped with a Garmin GPS 72 (±3 m) using either fixed waypoints to define the disturbance or by recording a track with points every 5 m. In cases where ALDs were too small (<10 m width) to resolve the edges, a single waypoint was obtained for the center. Each ALD was revisited several times during the week, and in instances where downslope movement was apparent, additional waypoints were collected. In the case of the ALD that dammed the West river (07-ALD-06), observations were collected at least twice daily. Additional observations were made regarding the discharge from the ALD, relative turbidity of runoff, and the depth of disruption or the presence of exposed ground ice. The West watershed was extensively traversed by foot and observations were verified by low elevation oblique aerial photographs taken on 1 August. Foot traverses were limited in the East watershed and similar aerial photographs confirmed the presence of only two small ALDs.

Results

HYDROMETEOROLOGICAL, RIVER, AND ACTIVE LAYER CONDITIONS

Compared to the previous four seasons (2003–2006) at CBAWO, meteorological conditions in 2007 were seasonal until July (Fig. 2). Initial catchment SWE in the West was 86 mm and 113 mm in the East. The season progressed with first flow in the rivers in mid-June. Discharge in both rivers reached moderate levels compared to previous years and lacked a well-defined period of peak flow (Fig. 3). Suspended sediment concentrations (SSC) were typically below 500 mg L^{-1} during this period in both rivers, and reached short-lived peaks of ~800 mg L^{-1}, compared to SSC exceeding 3000 mg L^{-1} in previous years (McDonald and Lamoureux, in press). Water temperatures were cold during the snowmelt period and electrical conductivity was low, typically below 40 μS cm^{-1} (Fig. 3).

Persistent high pressure during the first three weeks of July resulted in high incoming solar radiation receipts and unusually warm air temperatures (Fig. 2). Cumulative incoming solar radiation (K_{in}) for July 2007 was 46 and 29% higher than the same periods in 2004 and 2006, respectively. July mean daily temperature was 10.6°C, compared to the climatological mean (1971–2000) at Mould Bay (NWT, 200 km west) and during the previous four years at Cape Bounty (2003–2006) of 4.0°C. The maximum temperature observed at MainMet was 20.2°C on 13 July, and daily highs exceeded 15°C on eight days during July. On a number of days, daily minimum temperatures exceeded 10°C (Fig. 2).

Two moderate rainfall events occurred on 30 June and 20–21 July. These events totaled 9.2 and 4.0 mm at MainMet, respectively, although rainfall up to 10.8 mm was recorded at WestMet for the latter event. While there appear to be no systematic explanations for the difference between the WestMet and MainMet precipitation records, the substantial hydrological response to this event suggests the WestMet measurement is more likely to represent the watershed precipitation input.

Both rainfall events resulted in short-lived discharge and SSC transport responses that produced nearly identical seasonal

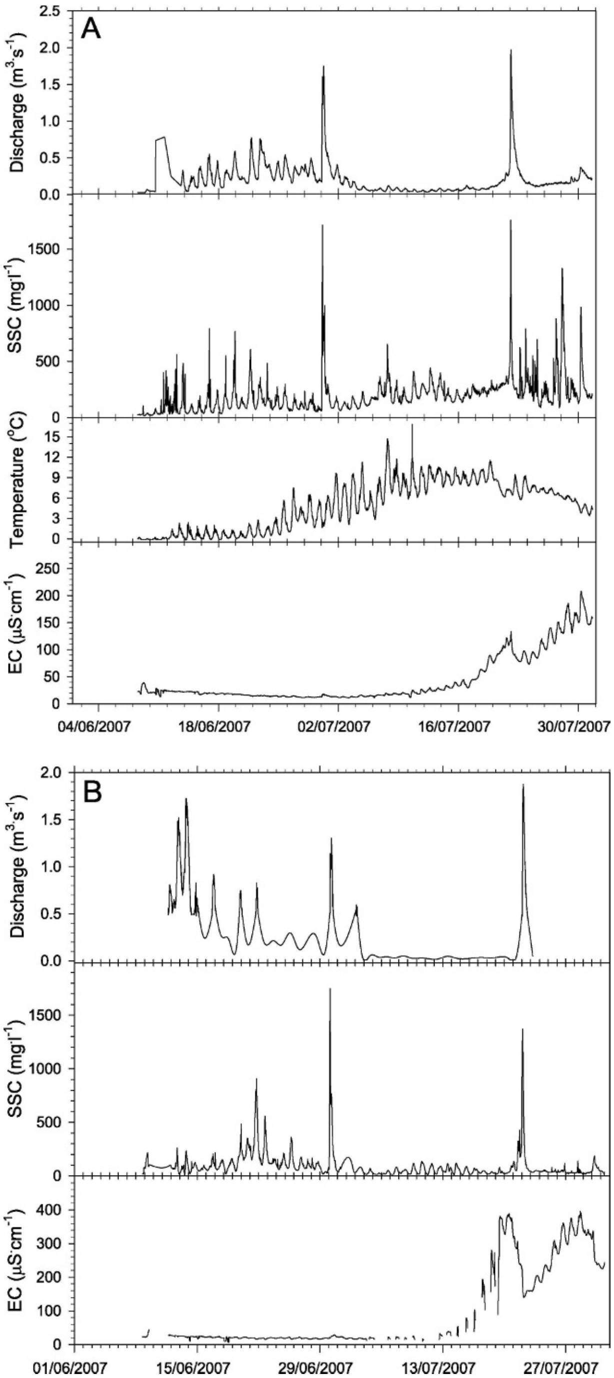

FIGURE 3. Hydrological measurements for the (A) West and (B) East rivers in 2007. All data are shown as hourly values. Note that due to intermittent isolation from the river during low stage, the water temperature measurements in East river were unreliable and are not reported.

maximum flow and sediment transport episodes. After the first rainfall event, exhausted snow cover caused stream recession and resulted in low discharge, SSC, and gradually increasing water temperatures (Fig. 3). Electrical conductivity (EC) remained low through most of early July before a gradual increase commenced in both rivers in mid-July. EC was higher in the East river and rose to higher levels in July prior to the rainfall (Fig. 3).

The rise in EC prior to the rainfall of 21 July in West river was followed by similar increases in discharge and SSC, although no similar trends in flow or sediment delivery were apparent in the East river. The rainfall event on 21 July sharply increased discharge and SSC in both rivers, but EC dropped as discharge began to increase (Fig. 3). EC dropped more suddenly in the East, relative to the West.

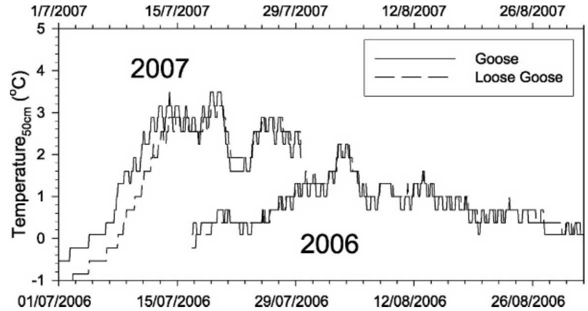

FIGURE 4. Soil temperature at 50 cm depth from two West watershed stations for 2006 and 2007. Note that the soil stations were installed in July 2006 and no data are available after the end of July 2007 when fieldwork ended.

These results suggest that both rivers were characterized by low flow, minimal sediment delivery, and limited solute fluxes during much of July. The increase in these measures in the West river that occurred in mid-July was not paralleled in the East, although both rivers ultimately responded to the 21 July rainfall. Given the diminished snow cover in early July and the absence of substantial rainfall, the source of this mid-July discharge increase is problematic.

Observations indicate the soil dried considerably during early July, but became increasingly wet as the month continued. Ground temperatures in 2007 warmed substantially beyond summer conditions in 2006 (Fig. 4). Thaw occurred at 50 cm depth on 3–4 July, compared to 17 July in 2006, and reached a seasonal maximum of 3.5°C, compared to 2.3°C at the same depth in 2006 (Fig. 4). These results suggest early and substantial active layer development, and melt of ground ice contributed to increased soil moisture in mid- to late July.

ACTIVE LAYER DETACHMENTS

Photographs indicated that some degree of ALD activity began in mid-July, but the extent was limited. Systematic mapping and observations began on 25 July and foot traverses revealed extensive and ongoing ALD formation during 25–31 July (Fig. 5). A total of 25 ALD sites were identified in the West catchment and two located in the East catchment (Figs. 1 and 5). The size of the detachments varied considerably, from <100 to 53,800 m^2. Most of the ALDs were characterized by a head scarp and broken soil blocks up to 1 m high (Figs. 5A and 5B). Downslope movement cleared a zone of the slide to expose clay slurries and occasionally ground ice. Displaced material was often fractured, but in many instances, the vegetated soil surface remained intact and moved downslope with minor ridging and fracturing. The lateral boundaries of most ALDs represented some combination of broken soil blocks or a pronounced shear zone (Figs. 5B and 5C). In some cases, lateral ridges formed where the ALD was transversely constrained by the slope topography. Fractures and other cracking were common beyond the ALD, but movement was not apparent. In some instances, clay slurry was ejected on the surface of the ALD (Fig. 5D), and similar ejections of slurry were noted in two locations in the lower West catchment in absence of an ALD.

During the observation period, a large number of the ALDs were actively advancing downslope, in several instances up to

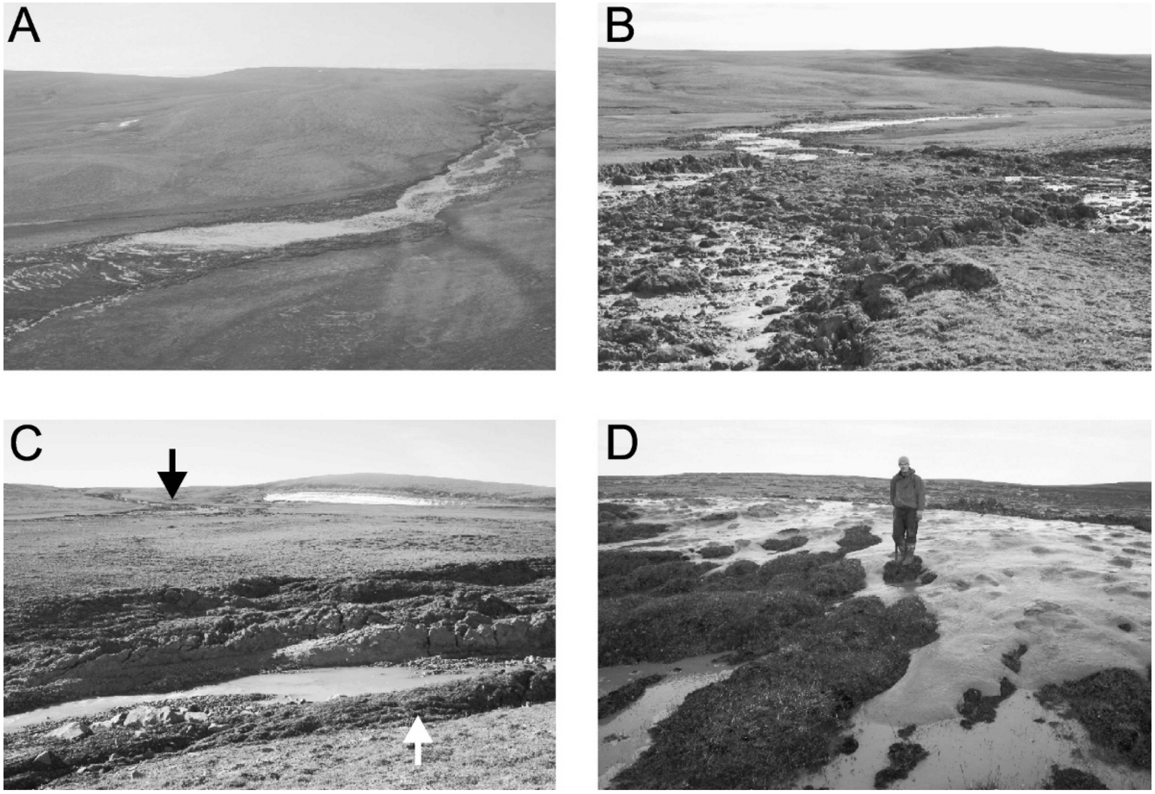

FIGURE 5. Photographic examples of observed ALDs and related landscape disturbances. (A) A low-elevation oblique aerial photograph of 07-ALD-06 on 25 July 2007, view southwest. (B) View downslope from near the headwall of 07-ALD-06. (C) A portion of the West river dam formed by 07-ALD-06. Note the ALD upslope (black arrow indicates the location of photograph [B]). Downslope displacement of vegetated soil formed the dam in the river and continued accumulation of slope material resulted in the displacement and folding of floodplain sediment on the opposite bank of the river (white arrow). (D) Surface flow of clay slurry over disturbed vegetation and soil on 07-ALD-01.

60 m in 24 hours. In the case of 07-ALD-06, the largest observed, the movement was measurable over four days. Notably, this large disturbance began near the interfluve, progressed 650 m downslope, and resulted in a soil dam along 200 m of the West river channel (Figs. 5C and 6). When this ALD reached the channel, continued displacement of the slope material generated multiple folds up to 3 m high, many of which split at the apex, sheared or collapsed. The ongoing movement of 07-ALD-06 also resulted in displacement and folds that incorporated the channel gravel and floodplain sediments from the opposite bank (Fig. 5C). The channel, previously approximately 10 m wide, narrowed to less than 1 m along a 40 m length that substantially restricted flow. A large pond formed upstream of the dam, although flow was maintained downstream throughout and after slope movement appeared to have ceased.

HYDROLOGICAL AND SEDIMENT TRANSPORT IMPACT OF ALDS

Late July rainfall (up to 10.8 mm at WestMet) rejuvenated most of the small slope tributaries that had ceased to flow in early July. As gauging had ended on the tributaries earlier (5 July), discharge and turbidity measurements were unavailable. Flow was moderate and typical of this time of year based on previous seasons' data and was estimated at less than 0.01 $m^3 s^{-1}$ (10 L s^{-1}). Turbidity in the tributaries downstream of several large ALDs abruptly increased, within 2–3 days after the initial disturbance. In several places turbid water pooled within the ALD and typically followed a convoluted drainage path through the disturbed soil to produce small ponds that interconnected to generate the emergent turbid water

In late July, discharge in the West river remained higher than during mid-July (Fig. 3a). It is uncertain to what extent the East river discharge remained elevated due to the lack of continuous stage measurements. EC in both rivers, which had been rising prior to the rainfall, dropped rapidly during the rainfall peak and then began to increase again in the last week of observations. West river EC reached a seasonal maximum on 28 July, while the late July conductivity levels in the East river were similar in magnitude to the July pre-rainfall period. However, the East river attained higher overall conductivity levels than the West river (Fig. 3).

Turbidity in the East river decreased immediately following the rainfall peak discharge on 22 July and remained below 50 mg L^{-1}, with the exception of three short periods when turbidity increased briefly to levels between 200 and 230 mg L^{-1} (Figs. 3b and 6). The last turbidity increase on 28–29 July was likely due to a short rainfall event (that occurred after the weather record was downloaded). This event also increased discharge and coincided with a rapid reduction in EC (Fig. 3b). By contrast, the West river turbidity exhibited a series of episodes characterized by sharp increases followed by more extended decay over several hours (Fig. 6). Maximum turbidity reached 1818 mg L^{-1} and the mean for the 22–31 July period was 298 mg L^{-1}, considerably higher than the July pre-rainfall period (Fig. 3) and also substantially higher than in the East river (Fig. 6).

In most cases, the episodes of increased turbidity in the West river can be directly attributed to the delivery of turbid water from a specific ALD (Fig. 6). As the drainage of relatively small flows

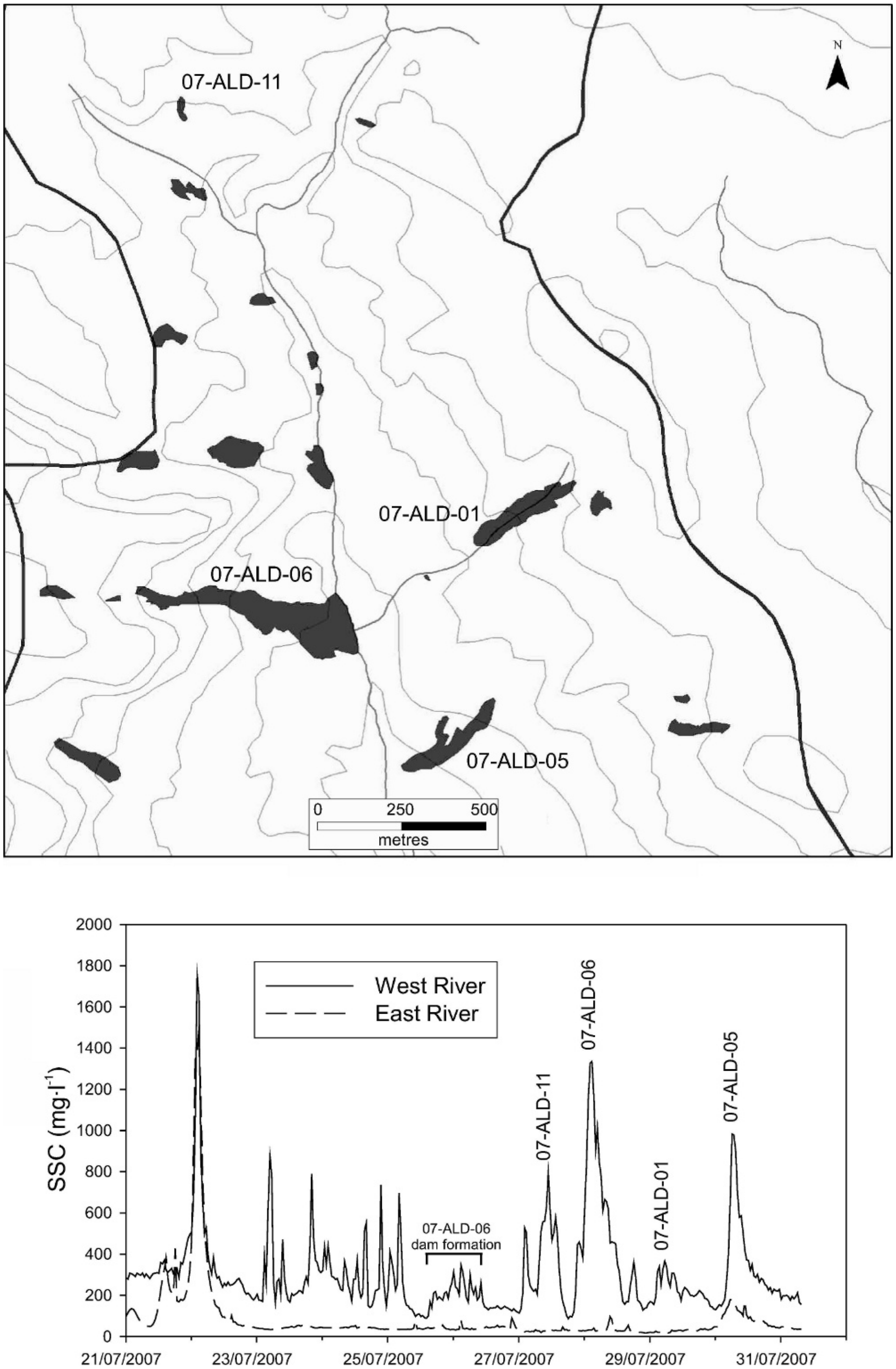

FIGURE 6. Late-season turbidity records from the West and East rivers after the 21 July rainfall event. Field observations indicated that increased turbidity events in the West river corresponded with hydrological connection of specific ALD, as indicated. Additionally, initial formation of the West river dam by 07-ALD-06 caused a period of increased turbidity. Locations of individual ALDs are shown in the map.

of sediment-laden water from each ALD reached the West River, measured turbidity rapidly increased and remained high for several hours (Fig. 6). When the largest ALD (07-ALD-06) established hydrological connection to the West river on 28 July, the increase in turbidity lasted 12–24 hours before returning to background levels of ~150–200 mg L^{-1} (Fig. 6). A short rainfall event on 28–29 July increased discharge and turbidity in both rivers, but turbidity increase was much greater in the West river (Fig. 6). The turbidity sharply increased to ~1000 mg L^{-1} between 0430 and 0600 h on 30 July, and field observations also indicate that turbid water from 07-ALD-05 reached the West river early in the morning of 30 July (Fig. 6). Hence, the sediment delivery response in the West river on 30 July reflected both a moderate increase due to rainfall runoff, along with an additional, more substantial, increase due to sediment from 07-ALD-05.

The dam formed by 07-ALD-06 along 200 m of the West river channel took several days to fully develop and was not characterized by delivery of turbid water. Direct flow of turbid water followed slope drainage and delivered the turbid water 100 m south of the dam on 28 July (Fig. 6). However, the initial formation of the dam, which began during the evening of 25 July and visibly continued until 28 July, generated localized channel and bank sediment disturbance and incorporated soil and vegetative material from upslope (Fig. 5C). Folds and ridges that

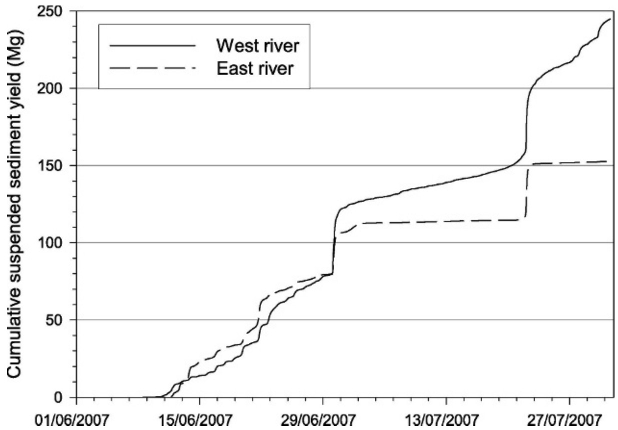

FIGURE 7. Cumulative suspended sediment yield from the West and East rivers for the 2007 season. Note the rise in sediment yield in the West river after 23 July associated with increased turbidity from the ALD (Fig. 6).

formed in the channel during this period were characterized by ridge fractures and a number of shear planes were in direct contact with the river flow. This activity was reflected downstream by turbidity increases of 100–200 mg L^{-1} that were apparent from late 25 July to 26 July (Fig. 6). Unlike the more turbid water on 28 July that originated from the ALD directly, the damming of the river resulted in modest increases in sediment transport.

There is also evidence that ALD contributions to turbidity occurred prior to detailed observations that began on 25 July. A number of short-lived turbidity peaks occurred in the West river after 23 July and were not clearly associated with rainfall runoff (Fig. 6). During the same period, there were no discernable turbidity perturbations in the East river.

ALD IMPACT ON CATCHMENT SEDIMENT YIELD

Despite the rejuvenation of tributary discharge and increased discharge in the West river after 23 July, the flow of water remained low compared to both the snowmelt period in June and the responses to the two major rainfall events (Fig. 3). Hence, the total volume of flow during this dynamic period (23–31 July) was small and represented 14.8% of the seasonal discharge in the West river. Stage instrument failure in the East river precluded similar quantitative calculations, but daily site visits indicated that discharge did not increase appreciably in the East river during the post-23 July period. Hence, we conservatively estimated the discharge in the East river during this period to be 5% of the total seasonal discharge, although there is considerable uncertainty in this value.

During the same period, suspended sediment discharge in the West river was 44.3 Mg (18.0%) of the seasonal 244.3 Mg (Fig. 7). By contrast, sediment transport in the East river was 2.2 Mg (1.4%) of the seasonal 152.8 Mg. We attribute some of the estimated lower seasonal sediment yield in the East river to uncertainty in the discharge during most of July due to stage instrument failure (Fig. 7). Regardless, these results point to a substantial divergence in hydrological and sediment transport behavior in the two watersheds after 23 July. In this short period, the discharge increase in the West river could only plausibly come from soil water sources, as residual snow in the watershed was the least observed in five years. Similarly, residual water from the 21 July rainfall affected both watersheds, but did not sustain or increase discharge in the East river after 23 July. If the difference in discharge between the two watersheds in this period is attributable to ground ice melt and contributions to the river flow, this suggests that soil water sources in the West catchment augmented flow by as much as 9% of the seasonal flow (Fig. 7). The high turbidity of the West river resulted in an additional 42.1 Mg of sediment transport compared to the East river for the same period. This represents as much as 16.6% greater sediment yield in the West river due to ALD contributions, if the East river can be considered an indication of the undisturbed sediment transport conditions. These estimates clearly represent minimums as measurements ended on 31 July and stream flow would have likely continued for several more weeks in a normal melt season.

Hence, the additional sediment transport from the ALDs in the West catchment contributed a substantial amount of sediment to the overall seasonal yield. Given that the mapped ALDs represent only 1.9% of the West catchment area, these contributions indicate the significant impact localized disturbances can have on watershed-scale, seasonal sediment yields. It is interesting to note that the additional sediment transport in the West river due to the ALDs was almost equivalent to the entire sediment yield in 2005, a warm, low flow season (Cockburn and Lamoureux, 2007).

Discussion

CONTROLS OVER ALD OCCURRENCE

Meteorological conditions during July 2007 were exceptional compared to the previous four years at Cape Bounty (Cockburn and Lamoureux, 2007), and represent the warmest July since records at Mould Bay, NWT, were initiated in 1949. Mean and maximum daily temperatures resulted from persistent high atmospheric pressure and cloud-free conditions (Fig. 2). The latter is highly unusual in this region, where summer months are often characterized by persistent low clouds and fog due to sea ice (Maxwell, 1980). The conditions at Cape Bounty were not isolated and the unusually warm July contributed to record reduction of ice cover in the Arctic Archipelago and across most of the Arctic Ocean basin (Comiso et al., 2008).

Increased solar insolation warmed the soil earlier and raised temperatures at 50 cm depth substantially beyond the previous years' measurements at Cape Bounty. These conditions contributed to the formation of a deeper active layer and increased the potential to melt ground ice. Observations of a gradual increase in soil water after mid-July, together with increasing discharge and solute transport in the rivers suggest that active layer development was melting ground ice. Hence, prior to the rainfall on 21 July, conditions for permafrost disturbance were optimal compared to any time since 1949. Limited photographic evidence suggests that ALDs began to form in mid-July in some locations. Notably, the largest ALD observed (07-ALD-06; Fig. 6) had developed to some extent as early as 16 July. However, there is limited evidence from the river that this early permafrost disturbance had a measurable impact that can be isolated from catchment-wide ground ice melt.

The rainfall on 21 July had a major impact on hydrological conditions and generated a major runoff and sediment transport response in both rivers. However, unlike the East river, where discharge and sediment transport returned to low levels for the remainder of the monitoring period, the West river exhibited a major change in sediment delivery. Observations indicate that individual ALDs contributed identifiable sediment delivery pulses after 25 July, and likely did so as early as 23 July (Fig. 6). Moreover, the discharge and EC in the West river gradually increased during this period. The only plausible explanation for increased flow and conductivity was increased ground ice melt inputs, as residual snow and rainfall inputs were unlikely.

Hence, while unusually warm July conditions and active layer development provided suitable conditions for ALD formation that were similar to reports from other regions in the Arctic (e.g., Lewkowicz, 2007), the main phase of slope activity occurred after a major rainfall event. Rainfall has been previously linked to permafrost disturbance (Hodgson, 1977), and like ground ice melt, generates the potential for soil saturation, high porewater pressures and low soil basal shear strength (Lewkowicz, 2007).

Regardless of the absolute contribution from these two antecedent factors, the clear difference in ALD response between the West and East watersheds suggests that additional factors must play a role. Given that the underlying bedrock and Quaternary sedimentary cover are essentially identical at Cape Bounty (Hodgson et al., 1984), three likely conditions could have contributed to the observed watershed-scale differences in ALD occurrence. First, slope angles are slightly higher in the narrower and smaller West catchment due to the greater relief between the West river and the adjacent drainage divides than in the East watershed. In principle, ALDs occur on low slope angles (French, 2007), but steeper slopes could represent a fine-scale factor. Second, it is possible that the ground ice content in the West watershed is sufficiently different to enhance soil destabilization during active layer development. This possibility remains unlikely, given the similarity in the sedimentary and other physiographic characteristics of the area. However, we do not have systematic ground ice surveys or borehole data to evaluate this possibility further.

Finally, vegetation cover, particularly wet sedge and the moderate moisture community, is higher in the West catchment. The former covers 18 and 12% in the West and East, while the moderate moisture communities cover 11 and 8%, respectively (D. M. Atkinson, personal communication, 2008). While increased vegetation and root structures might reasonably be expected to strengthen soil and reduce the potential for slope disturbance, it is doubtful that vegetative differences are an important factor. The vegetation cover is highly heterogeneous, and most of the ALDs occurred in concavities that contain tributary streams or remain saturated for longer periods of time (Fig. 1). Moreover, ALDs appear to fail at the base of the soil profile where pore water pressures are high (Lewkowicz, 2007) and where root density is low. While this study did not evaluate these factors further, results suggest that microtopographic controls are the most likely factor to explain the observed difference in ALD occurrences at Cape Bounty in 2007.

ALD IMPACTS ON SHORT-TERM SEDIMENT YIELD

The sediment discharge record from 2003 to 2007 at CBAWO represents one of the longest data sets available in the Canadian Arctic. Yield in this environment is highly variable and depends primarily on the amount of pre-melt snow available (Cockburn and Lamoureux, 2007). It is also influenced by snow in the channel that limits access of stream flow to bank and bed sediment sources (McDonald and Lamoureux, in press). These observations appear to reflect conditions broadly in the High and Middle Arctic (e.g., Braun et al., 2000; Forbes and Lamoureux, 2005). Sediment transport is closely associated with peak discharge rates during the nival freshet, and quasi-exponential sediment-discharge relationships (e.g., Hardy, 1996) cause seasonal yield to increase disproportionately for a given increase in catchment snow water equivalence (SWE) (Cockburn and Lamoureux, 2007). In most years, the sediment transport during the nival freshet is the primary contribution to seasonal sediment yield.

The impact of rainfall on sediment delivery in the Arctic is limited due to the rarity of observations of major events (e.g., Lewis et al., 2002). Anecdotal observations of the influence of major rainfall events on sediment transport are more common (Cogley and McCann, 1976; Hodgson, 1977; Lamoureux, 2000), but the influence of rainfall on sediment yield has largely been demonstrated indirectly with sedimentary records (Lamoureux, 2000).

Unlike the preceding sediment delivery mechanisms that operate over a large proportion of the catchment, the results from 2007 at CBAWO indicate that ALDs affecting a small proportion of a watershed significantly increase sediment yield. In the case of the West catchment, 1.9% of the land was disturbed; in the week that followed, this disturbance increased the annual sediment yield by approximately 18%. Comparison with the remainder of the season indicates that the sediment transport associated with all of the ALDs was comparable to each of the rainfall events. This sediment transfer is significant as it departs from general stream power-sediment transport relationships that have been documented (McDonald and Lamoureux, in press). A similar unusual sediment delivery event was documented by Lewis et al. (2005) on Ellesmere Island, where 32% of the annual sediment load was transported in four hours. While unconfirmed, the authors suggested that the event was due to a mass movement in the catchment (Lewis et al., 2005). In the case of disturbances at CBAWO, impact of individual ALDs was identified in the hydrometric record and also exhibited rapid increases in sediment delivery over hours, to as much as two days. Therefore, these results provide a crucial link between the observations of intense, localized catchment, permafrost disturbance, and watershed-scale sediment yield and also provide data to support hypotheses regarding the sediment yield impact of permafrost instability (Woo and McCann, 1994).

LONG TERM IMPACT OF ALDS

The short observations we present in this paper indicate a rapid and intense response to ALDs discernable at a catchment scale. However, the ALDs we have mapped remain highly disturbed and can be expected to undergo further erosion. We anticipate that the first snowmelt period (2008) will result in significant flow through these disturbed areas and increase erosion substantially. The extent to which this will be apparent beyond typical nival sediment transport is uncertain, but continued observations at CBAWO will investigate this further.

Previous research suggests that accelerated erosion at nivation hollows may continue for many years, perhaps decades (Kokelj and Lewkowicz, 1998). After a number of years, erodible sediment diminishes as flow paths stabilize and vegetation recovery ensues. The absence of any long arctic sediment transport data sets precludes further direct assessment of the time scale for recovery of these disturbances. Long sedimentary records can provide some indication of sediment yield dynamics (Lamoureux, 2002), but these have typically been interpreted in the context of sediment delivery changes due to hydroclimatic variability (e.g., Lamoureux and Bradley, 1996). Lamoureux (2000) investigated a 487-year annually resolved sedimentary record and noted that high-yield years were associated with major rainfall events after 1950. Larger sediment yields were noted in the past and inferred to be associated with rainfall as well, but these major yields (up to 15 times the long-term mean) could logically be attributed to permafrost disturbance. Similar outliers in sedimentary records are common (e.g., Lamoureux and Bradley, 1996) and are difficult to reconcile with meteorological and hydrological delivery (Chutko and Lamoureux, 2008). Epoch analysis of one annual-laminated sedimentary record indicated that yield remained above the mean for an average of 17 years after events estimated to have 100-year or greater recurrence (Lamoureux, 2002). These results suggest that arctic fluvial systems may take a decade or longer to fully respond to the impact of a major perturbation in one year.

These results are consistent with periglacial studies that indicate long recovery times (Kokelj and Lewkowicz, 1998) and provide reason to believe that the ALDs at Cape Bounty will have a sustained impact on sediment delivery processes in the West river. Given that these disturbances have demonstrated high sediment erosion during low flow conditions, the seasonal distribution of sediment and solute delivery may also be affected, with implications for hydrochemical and aquatic processes in the river and downstream lake. Moreover, the formation of a 200-m-long constriction in the channel will also likely affect sediment transport characteristics that have been thoroughly documented in recent years (McDonald and Lamoureux, in press).

Conclusion

Exceptional warm temperatures and clear skies during July 2007 resulted in accelerated and deep active layer formation at Cape Bounty. Evidence suggests that ground ice melt was becoming discernable in the West river by mid-July prior to a major rainfall event. After the river receded from the rainfall runoff, at least 25 active layer detachments (ALDs) occurred, totaling 0.15 km^2, or 1.9% of the watershed area. Subsequent episodic increases in river turbidity that lasted less than 24 hours occurred as individual ALDs established flow connections to the main river. In the week following disturbance, discharge increased moderately and sediment transport increased substantially and resulted in an 18% increase in seasonal yield. The adjacent and similar East watershed was not subject to any significant disturbance and late season flow was characterized by low discharge, low turbidity, and high electrical conductivity. Subtle differences in slopes or other microtopographic characteristics likely explain the different degree of watershed disturbance observed. Future work will evaluate the impact of the ALD-induced disturbance on sediment yield, which is expected to last potentially for years to decades.

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