GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Watershed delineation in areas of permafrost disturbance on eastern Banks Island, NWT: a geomatics approach for predicting water quality impacts

A.C.A. Rudy[1], S.F. Lamoureux[1], J. E. Holloway[1], M.J. Lafrenière[1], S.V., Kokelj[2], R. Segal[3], T.C. Lantz[3], R.H. Fraser[4], I.R. Smith[5]
[1]*Department of Geography, Queen`s University, Kingston, ON, Canada*
[2]*Northwest Territories Geological Survey, Government of Northwest Territories, Yellowknife, NT, Canada*
[3]*School of Environmental Studies, University of Victoria, Victoria, BC, Canada*
[4]*Canada Centre for Remote Sensing, Natural Resources Canada, Ottawa, ON, Canada*
[5]*Geological Survey of Canada, Natural Resources Canada, Calgary, AB, Canada*

ABSTRACT
The goal of this study was to develop a framework for informing water-sampling strategies to evaluate the relationships between thermokarst disturbances and impacts on water quality. A permafrost disturbance inventory for the Johnson Point area, eastern Banks Island was produced through a visual inspection of SPOT 4 and 5 satellite imagery. A total of 197 retrogressive thaw slumps were identified and digitized, ranging in size from 2600 to 885 500 m^2 with the majority of slumps located adjacent to lakes and streams. Watersheds were derived from the Canadian CDED DEM and NHN stream network data sets using ArcGIS with Spatial Analyst extensions. Specific criteria were used to create a hierarchy of nested watersheds. This contextual information will enable us to determine if: 1) the relative density of disturbance is related to the intensity of water quality effects; 2) if water quality is impacted more by the areal extent of disturbance or numbers of individual disturbances; and 3) whether the hydrological connectivity and distance of a disturbance to a water body affects downstream water quality. This knowledge will provide information suitable for researchers, communities and decision makers to assess the impact of permafrost disturbance on surface water environments.

RÉSUMÉ
Le but de cette étude était de développer un cadre afin de présenter les stratégies d'échantillonnage d'eau permettant d'évaluer les relations entre la dégradation des thermokarsts et les impacts sur la qualité de l'eau. Un inventaire des perturbations du pergélisol pour la région de Johnson Point, à l'est de l'île Banks, a été produit à partir des analyses d'images satellitaires SPOT 4 et 5. Au total, 197 glissements rétrogrades liés au dégel ont été identifiés et numérisés. Leurs tailles varient de 2600 à 885 500 m2 et la majorité des glissements sont situés à proximité de lacs et de ruisseaux. Les bassins versants ont été créés à partir des bases de données canadiennes CDED DEM et à l'aide du réseau de données sur les ruisseaux (RHN), à partir de l'extension Spatial Analyste d'ArcGIS. Des critères spécifiques ont été utilisés pour créer une hiérarchie de bassins versants imbriqués. Cette information contextuelle permet de déterminer: 1) si la densité relative de la perturbation est liée à la qualité de l'eau; 2) si la qualité de l'eau est davantage affectée par la taille de la perturbation ou par l'augmentation du nombre de perturbations; et 3) si la connectivité hydrologique et la distance entre une perturbation et un cours d'eau affectent la qualité de l'eau en aval. Ces résultats fourniront des renseignements appropriés pour les chercheurs, les communautés et les preneurs de décisions afin d'évaluer l'impact des perturbations du pergélisol sur les environnements d'eau de surface.

1 INTRODUCTION

Retrogressive thaw slumps (RTS) are a form of permafrost disturbance that can develop on permafrost terrain particularly where massive ground ice occurs. These disturbances typically develop alongside coastlines, lakeshores, and rivers/streams. Thaw slumping can release large amounts of sediment and solutes that alter the turbidity and chemistry of surface waters, which can impact aquatic ecosystems (Kokelj et al., 2005; Thienpont et al., 2013). Increasing numbers of surface disturbances have been observed across the Arctic reflecting changes in landscape stability resulting from a warming and changing climate, and increasing summer thaw depths (Lantuit and Pollard, 2008; Lantz and Kokelj, 2008; Lamoureux and Lafrenière, 2009) or intensification of precipitation regimes (Kokelj et al., 2015).

Suspended sediment and solute concentrations in runoff from localized disturbances such as active layer detachments and thaw slumps can be orders of magnitude greater than the adjacent undisturbed landscape (Leibman and Streletskaya, 1997; Bowden et al., 2008; Kokelj et al., 2013; Lamoureux and Lafrenière, 2014). While the immediate effect of disturbance is localized, there is the potential for substantial downstream aquatic impacts. The magnitude of the impact will depend on a number of factors including: frequency and size of thaw slumps, the rate of headwall retreat and height of the headwall, hydrologic connectivity of slumps and watershed size. The goal of this study is to use a geomatics approach to characterize the intensity of disturbance using a watershed framework with the goal of understanding how local thermokarst are manifested across scales, and ultimately, to use these disturbance inventories to predict water quality impacts. Hence, the objectives of this work are two-fold: 1) to investigate the local impact of thaw slumps on water quality by examining varying sizes of watersheds with different magnitudes of disturbance; and 2) examine the downstream impact of thaw slumps through watershed scaling.

Watersheds provide a useful spatial framework to assess changes in water quality related to disturbance because they are static, allowing researchers to measure overall changes to water quality (Fraser et al., 2015). Using a geomatics approach, watersheds were delineated for an area around Johnson Point, eastern Banks Island, NWT. Combined with a thaw slump inventory, this watershed hierarchy provides knowledge of specific watersheds being impacted by retrogressive thaw slumps and allows for the development of detailed field sampling strategies for water quality assessment.

1.1 Retrogressive Thaw Slumps

Retrogressive thaw slumps are a form of permafrost disturbance often associated with massive ice bodies. Thaw slumps are initiated through a variety of processes that expose massive ice including mechanical and thermal erosion by waves and currents along shorelines and streams, degradation along ice wedges and from active layer detachments (Burn and Lewkowicz, 1990; Wolfe et al., 2001; Lantuit and Pollard, 2008; Kokelj et al., 2015). Exposure of ice-rich permafrost leads to ablation of the ground ice promoting back-wasting of ice-rich headwalls leading to horseshoe-shaped scars on the landscape (Burn and Lewkowicz, 1990; Lantuit and Pollard, 2008) (Figure 1). Thaw slumps will remain active and retreat headward provided that massive ground ice continues to be exposed in the headwall (Lacelle et al., 2010).

The scar zone of active thaw slumps often consists of a thawed slurry of material that flows downslope. Thawed materials within the slump are transported away from the headwall by rill erosion, fluvial transport and shallow and deep-seated mass flows and slides (Lacelle et al., 2010; Lantuit et al., 2012). Slump growth is perpetuated by these processes of downslope sediment removal so that factors which contribute to their intensification can lead to the development of larger thaw slumps (Kokelj et al., 2015). The location of the thaw slump, its size, activity level and its connectivity to adjacent water bodies, are factors that likely influence downstream water quality.

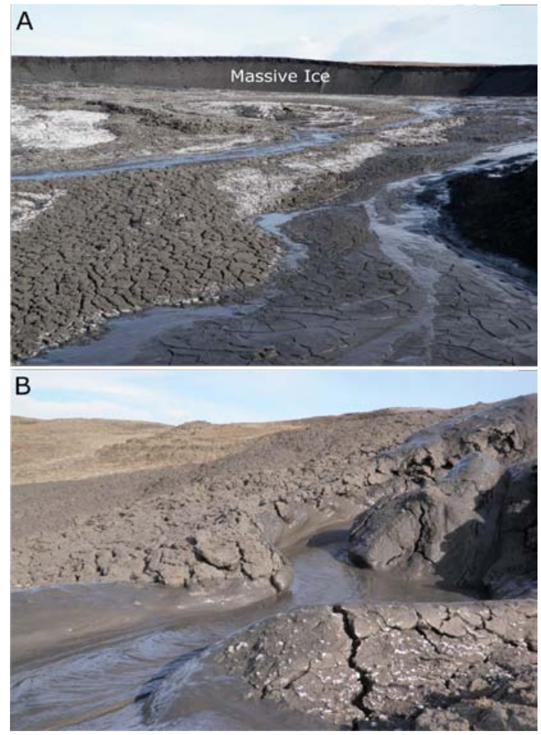

Figure 1. A) Photograph of thaw slump depicting massive ice in the headwall and fluvial activity over the scar zone. B) Photograph looking downslope of the same thaw slump showing downslope movement of the saturated sediment slurry. Channelization in the scar zone allows for transport of thawed materials out of the slump into the adjacent stream. Photographs from the Sabine Peninsula, Melville Island, NU, July 28, 2012.

1.2 Study Site

Johnson Point is located on the eastern coast of Banks Island, NWT (Figure 2). This area is characterized as hummocky terrain, with rolling hills rising to over 300 m and is within the extent of the Jesse Moraine Belt that rims the eastern coastal zone of the island. Underlying materials are predominately silty and gravelly tills with areas of stratified sediments and outwash deposits (French, 1974; Lakeman and England, 2012). Numerous thaw slumps occur above and below marine limit in the Jesse till exposing both foliated clean ice and foliated sediment-rich ice that is overlain by 1-2 m of till (Lakeman and England, 2012). Within the sediment-rich ice, clasts, including striated boulders confirm its glacial origin (Lakeman and England, 2012).

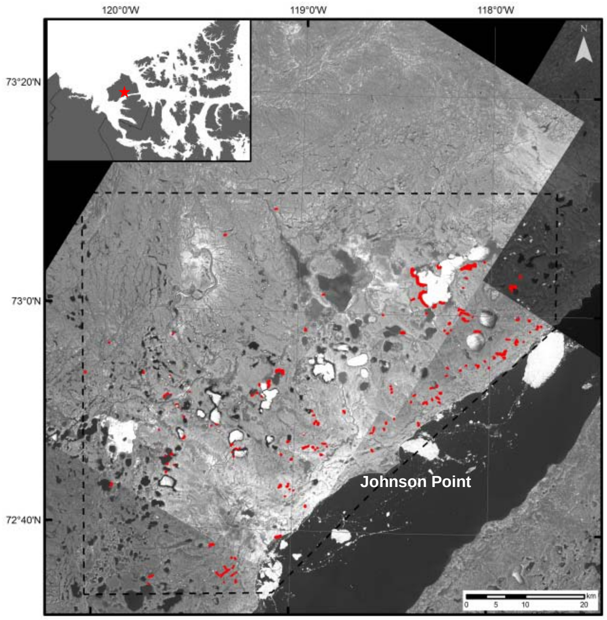

Figure 2 SPOT 4 and 5 images (10 m resolution) of the Johnson Point area. The study area is outlined by the dashed black line. Retrogressive thaw slumps mapped with the SPOT imagery are denoted by the red polygons.

2 METHODOLOGY

2.1 Data and Image Preparation

Several tiles from the 1:50 000 Canadian Digital Elevation Data (CDED) dataset were mosaiced to create a digital elevation model (DEM) for the study area, and additional stream vectors and lake boundaries were obtained from the National Hydro Network (NHN). All datasets were converted to a common NAD83 UTM Zone 11N projection. DEM pre-processing was performed prior to hydrological modelling and follows methods laid out by Fraser et al. (2015).

The lake dataset was separated into three classes: ponds (<1 ha), small lakes (1-20 ha) and large lakes (>20 ha). Due to poorly defined connections between ponds we chose to include only small and large lakes in this study.

Retrogressive thaw slumps were mapped using 2008/09 SPOT 4 and 5 satellite imagery (10 m panchromatic resolution) obtained from GeoGratis (Natural Resources Canada). Thaw slumps were identified using a criteria specific methodology (Rudy et al., in review) and subsequently mapped in ArcGIS v10.2.2. This methodology uses distinct morphologic and tonal characteristics such as a well-defined headwall, tone/contrast, and shape to identify and delineate thaw slumps.

2.2 Field Mapping

To corroborate the retrogressive thaw slump inventory produced using the SPOT imagery, thaw slumps were mapped in the field using a Garmin 60Cx GPS unit (± 5 m typical position uncertainty). For each mapped thaw slump the headwall height was measured using an Abney Level and headwall retreat was assessed as either active or inactive. When possible, channelization within the slump was mapped.

The fluvial impact of thaw slumps depends on their vicinity to a water source in addition to the hydrologic connectivity of the failed material entering the stream. To address this, slumps were classified into different classes based on geomorphic context and include slumps that are: lakeside, streamside, coastal or >50 m from a water source (Segal et al., 2014).

2.3 Watershed Delineation

A watershed is physically delineated by the contributing area upstream from a specified outlet point (pour point) at a lower elevation. Pour points at the outlets of large rivers or water bodies generally create large watersheds, whereas points near the headwaters correspond with smaller watersheds. Initial watershed boundaries were hierarchically delineated based on the order of Strahler stream segments. Subsequent boundaries were delineated based on pour points selected to address research objectives.

The watershed delineation procedure was completed in ArcGIS using the Hydrology toolbox. First, “Flow Direction” was computed for each cell so that its relation to the downstream neighbor with the steepest descent could be identified. The “Flow Accumulation” tool was then used to produce a flow accumulation grid representing the accumulated number of cells upstream or downslope of each cell in the input grid. A threshold was then applied to the flow accumulation grid to create a rasterized stream network where the selected cells have the highest flow accumulation. The threshold necessary to create a stream network with the highest flow accumulation will vary between locations and should be selected interactively. The stream network was then classified using Strahler stream order, which is based on a hierarchy of tributaries that define stream size.

Watersheds were initially delineated using pour points at the outlets of all streams that entered the ocean regardless of stream order. A series of nested watersheds were then delineated for second and third order streams with reference to the largest stream order in that watershed. Watersheds were also delineated above and below small and large lakes with extensive disturbance to assess the effect of lake size on overall downstream water quality. Water samples were collected at each pour point location.

3 RESULTS

3.1 Retrogressive Thaw Slump Inventory

Using the SPOT imagery 197 thaw slumps were digitized in the study area (terrestrial surface area ~1400 km^2) (Fig. 2). Thaw slumps range in size from 2600 m^2 to 885 500

m^2 and represent a disturbed density of 1.2 km^2 per 100 km^2 and 23 thaw slumps per 100 km^2.

A total of 80 thaw slumps were classified as lakeside which can be further divided into 75 slumps adjacent to 25 large lakes and 5 slumps beside 3 small lakes; three slumps were coastal. The majority of the remaining thaw slumps (109) were classified as streamside (within 50 m of a stream). Four thaw slumps were situated further than 50 m from a water source.

3.2 Watershed Assessment

Eighteen primary watersheds were delineated by pour points entering the ocean and ranged in size from 4 to 347 km^2 with an average watershed size of 57 km^2. Thirteen of these watersheds contained at least one thaw slump. The percent disturbed area in each primary watershed was calculated by comparing the total area of the thaw slumps and the area of the watershed, values ranged from 0.04% to 3.2%.

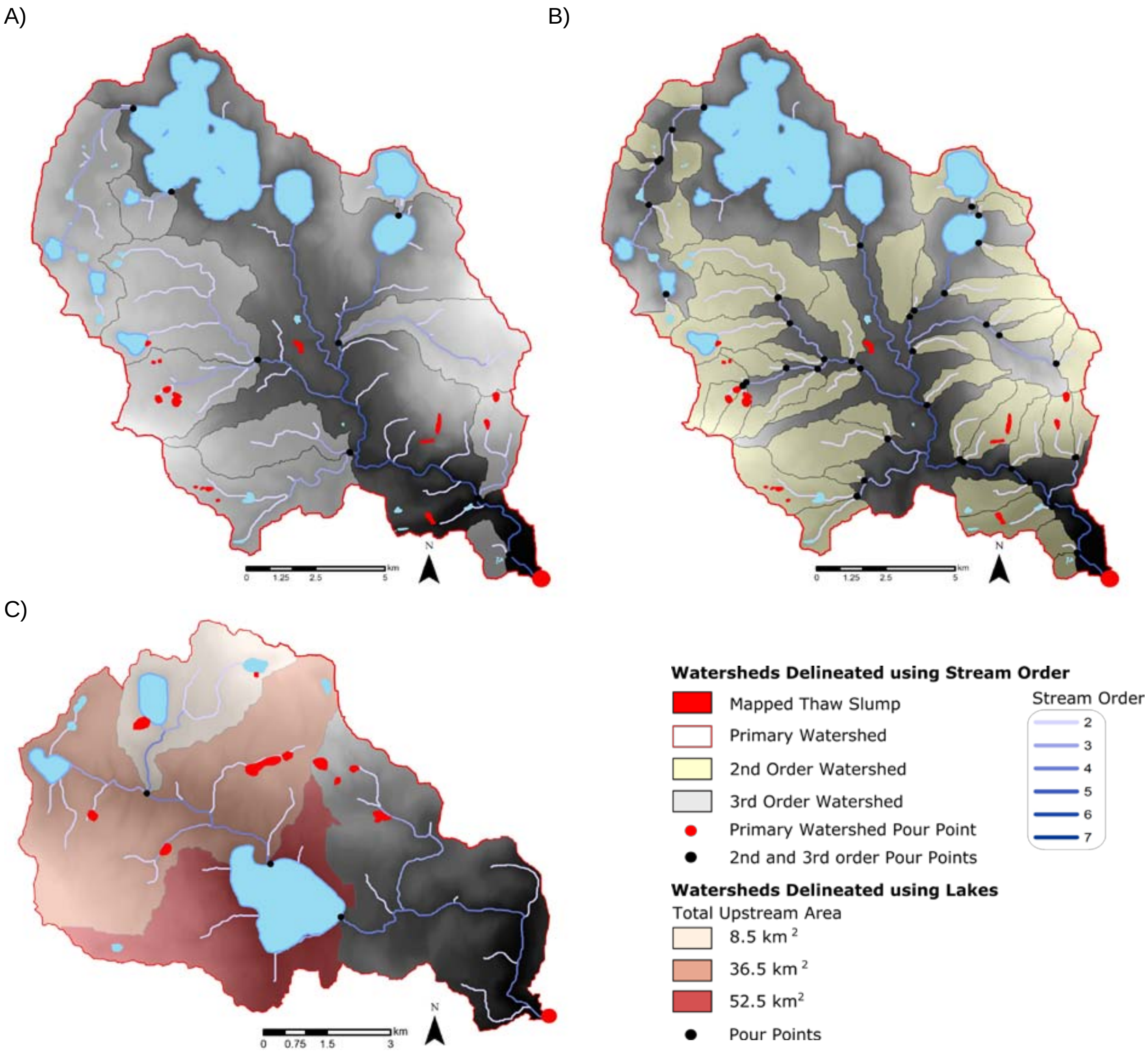

Figure 3 Examples of watershed delineation from the Johnson Point area. In all examples the primary watershed is outlined in red and the base map is the mosaicked CDED DEM. A) Watersheds delineated for third order streams are represented by the grey polygons. B) Watersheds delineated for second order streams are represented by the yellow polygons. C) Nested watersheds were delineated above and below the lake located in the middle of the watershed. An additional watershed was delineated for the disturbed headwater lake.

A hierarchy of nested watersheds were produced within each primary watershed (Figure 3). The average size of these smaller watersheds was less variable, ranging between <1 to 22 km^2. The proportion of disturbed area can be very high in the smaller nested watersheds compared to the primary watersheds. The purpose of delineating these smaller watersheds was to identify the local scale influence of disturbance and inform sampling designs to examine the effect of disturbance across a range of watershed scales.

Watersheds were also delineated when a lake was of large enough size to potentially act as a buffer to upstream disturbance. Pour points were located immediately upstream and downstream of the lake. Within the thirteen disturbed watersheds there were three lakes with upstream disturbance where watersheds were delineated.

4 DISCUSSION/CONCLUSION

Research has shown that permafrost thaw may drive increases in nutrient, ionic and dissolved organic matter (DOM) fluxes in circumpolar rivers (Frey and McClelland, 2009; Kokelj et al., 2013; Lamoureux and Lafrenière, 2014; Louiseize and Lafrenière, 2014). Highly localized disturbance such as thaw slumps are one of the many processes that can influence water quality in permafrost environments. Broader influences on water quality include thickening active layer resulting from warmer temperatures. Deeper thaw introduces the potential for new flow pathways allowing for the mobilization of solutes from the upper permafrost layer (Kokelj et al., 2013; Lamoureux and Lafrenière, 2014). In both cases, regardless of the type of disturbance downslope connectivity must be present for there to be a measurable effect (Fryirs et al., 2007).

Classifying thaw slumps by geomorphic context provides key information on the aquatic environment they are likely to impact, but this does not necessarily indicate that hydrologic connections exist. Confirmation of a connection must be examined in the field as the SPOT imagery and DEM used in this study are too course to allow for this. When a selected disturbance is hydrologically connected (i.e., immediately adjacent to stream and/or channelization within a slump allowing for removal of material, or infilling of the valley bottom with slump derived debris) rate of headwall retreat, magnitude of snowmelt and rainfall events will control the amount of material able to enter a water source. In addition to hydrologic connectivity the frequency and size of disturbances in a watershed are expected to have an impact on water quality. Existing research on permafrost disturbance and water quality has implied that without hydrologic connectivity, chemical and sediment contributions to downstream channels is indiscernible from changes resulting from deeper active layer thaw (Bowden et al., 2008; Kokelj et al., 2013; Lamoureux and Lafrenière, 2014). The ability to scale up localized disturbance is important for understanding how fluvial systems and stream ecosystems will be impacted as the intensity of disturbance increases across the circumpolar Arctic as a consequence of climate change (Kokelj et al., 2013; Lamoureux and Lafrenière, 2014).

Results from this study led to the development of a water sampling strategy aimed at scaling the impacts of localized disturbance for different watershed scales. A number of comparable watersheds with respect to size and magnitude and frequency of disturbance were selected for water quality sampling. Additionally, within many of the primary watersheds there are disturbed and undisturbed nested watersheds that provide contrasts in geochemical conditions.

Hydrogeomorphic changes in periglacial environments can be expected to continue with a rapidly changing climate, in particular, where thermokarst disturbance intensifies. A framework designed to assess the sedimentological and geochemical effects of thaw slumps on water quality at both local and broader scales is necessary for understanding the present and future state of the hydrological system.

5 ACKNOWLEDGEMENTS

This work is supported by the NWT Cumulative Impacts Monitoring Program. The primary author A.C.A. Rudy was supported by a scholarship from the W. Garfield Weston Foundation. We thank the Geological Survey of Canada Geo-Mapping for Energy and Minerals (GEM) Program for logistical support

6 REFERENCES

Bowden, W.B., Gooseff, M.N., Malser, A., Green, A., Peterson, B.J., Bradford, J. 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. *Journal of Geophysical Research*, 113: G02026. doi. 10.1029/2007JG000470

Burn, C. R., Lewkowicz, A. G., 1990. Canadian Landform Examples - 17 Retrogressive Thaw Slumps. *Canadian Geographer*, 34: 273–276. doi:10.1111/j.1541-0064.1990.tb01092.x

Fraser, R.H., Deschamps, A., Kokelj, S.V. 2015. Nested watershed mapping as a reporting framework for the NWT Cumulative Impacts Monitoring Program (NWT-CIMP). Northwest Territories Geoscience Office, Yellowknife NWT. Open File (in press).

French, H.M. 1974. Active thermokarst processes, Eastern Banks Island, Western Canadian Arctic. *Canadian Journal of Earth Science*, 11: 785-794.

Frey, K.E. and McClelland, J.W. 2009. Impacts of permafrost degradation on arctic river biogeochemistry. *Hydrological Processes,* 23: 169-182. doi: 10.1002/hyp.7196

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M. 2007. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena,* 70: 49-67.

Kokelj, S.V. and Burn, C.R. 2005. Near-surface ground ice sediments of the Mackenzie Delta, Northwest

Territories, Canada. *Permafrost and Periglacial Processes,* 16: 291-303. Doi: 10.1002/ppp.537

Kokelj, S.V., Lacelle, D., Lantz, T.C., Tunnicliffe, J., Malone, L., Clark, I.D., Chin, K.S., 2013. Thawing of massive ground ice in mega slumps drives increases in stream sediment and solute flux across a range of watershed scales. *Journal of Geophysical Research: Earth Surface*, 118: 681–692.

Kokelj, S.V., Tunnicliffe, J.F., Lacelle, D., Lantz, T.C., Chin, K.S., Fraser, R., 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. *Global and Planetary Change*, 129: 56-68. doi: 10.1016/j.gloplacha.2015.02.008.

Lacelle, D., Bjornson, J., Lauriol, B., 2010. Climatic and geomorphic factors affecting contemporary (1950–2004) activity of retrogressive thaw slumps on the Aklavik Plateau, Richardson Mountains, NWT, Canada. *Permafrost and Periglacial Processes*, 21: 1–15. doi:10.1002/ppp.666

Lakeman, T.R., England, J.H. 2012. Paleoglaciological insights from the age and morphology of the Jesse moraine belt, western Canadian Arctic. *Quaternary Science Reviews*, 47: 82-100.

Lamoureux, S.F., Lafrenière, M.J. 2009. Fluvial impact of extensive active layer detachments, Cape Bounty, Melville Island, Canada. *Arctic, Antarctic, and Alpine Research,* 41(1): 59-68.

Lamoureux, S.F., Lafrenière, M.J. 2014. Erosion dynamics following localized permafrost slope disturbances. *Geophysical Research Letters,* 41: 5499-5505. doi. 10.1002/2014GL060677

Lantuit, H., Pollard, W.H. 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. *Geomorphology*, 95: 84-102.

Lantuit, H., Pollard, W.H., Couture, N., Fritz, M., Schirrmeister, L., Meyer, H., Hubberten, H.-W., 2012. Modern and Late Holocene Retrogressive Thaw Slump Activity on the Yukon Coastal Plain and Herschel Island, Yukon Territory, Canada. *Permafrost and Periglacial Processes*, 23: 39–51. doi:10.1002/ppp.1731

Lantz, T.C., Kokelj, S.V., 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T. *Geophysical Research Letters*, 35, L06502.

Liebman, M.O. and Streletskaya, I.D. 1997. Land-slide induced changes in the chemical composition of active-layer soils and surface-water runoff, Yamal Peninsula, Russia. In *Proceedings of the International symposium on physics, chemistry and ecology of seasonally frozen soils, Fairbanks, Alaska,* June 10-12, 1997. CRREL Special Report 97-10, CRREL, Hanover, New Hampshire: 120-126.

Louiseize, N.L. and Lafrenière, M.J. 2014. Stable isotopic evidence of enhanced export of microbially derived NO_3^- following active layer slope disturbance in the Canadian High Arctic. *Biogeochemistry*, 121: 565-580.

Rudy, A.C.A., Lamoureux, S.F., Treitz, P., Van Ewijk, K., Bonnaventure, P.P., Budkewitsch, P. Terrain Controls and landscape-scale modelling of permafrost slope disturbance susceptibility. *Permafrost and Periglacial Processes,* in review.

Segal, R.A., Kokelj, S.V., Lantz, T.C, Durkee, K., Gervais, S., Mahon, E., Snijders, M., Buysse, J., and Schwarz, S. 2015. Broad-scale inventory of retrogressive thaw slumping in Northwestern Canada. Northwest Territories Geoscience Office, Yellowknife NWT. Open File 2015-04

Thienpont, J.R., Rühland, K.M., Pisaric, M.F.J., Kokelj, S.V., Kimpe, L.E., Blais, J.M., Smol, J.P. 2013. Biological responses to permafrost thaw slumping in Canadian Arctic lakes. *Freshwater Biology*, 58:337-353.

Wolfe, S.A., Kotler, E., Dallimore, S.R. 2001. Surficial characteristics and the distribution of thaw landforms (1970-1999), Shingle Point to Kay Point, Yukon Territory. *Geological Survey of Canada,* Open File 4115.