Lake area and shoreline changes due to climate and permafrost-related drivers, Rankin Inlet area, Nunavut

A.-M. LeBlanc¹, O. Bellehumeur-Génier², G.A. Oldenborger³ and N. Short⁴

¹Natural Resources Canada, Geological Survey of Canada–Central, Ottawa, Ontario, anne-marie.leblanc@canada.ca
²Transport Canada, Ottawa, Ontario
³Natural Resources Canada, Geological Survey of Canada–Central, Ottawa, Ontario
⁴Natural Resources Canada, Canada Centre for Mapping and Earth Observation, Ottawa, Ontario

The Western Hudson Bay project is a Canada-Nunavut Geoscience Office–led geoscience compilation project in the Kivalliq Region of Nunavut, along the western coast of Hudson Bay from the Manitoba border to Rankin Inlet (NTS map areas 55D–F, K, L). The project objective is to compile all existing aggregate, mineral potential, surficial geology, land cover and permafrost data for this area. The project also involves the development of methods for regional characterization of permafrost conditions by integrating observations from different sources across different scales, from site-based data to remote sensing.


Abstract

The western coast of Hudson Bay is experiencing growth for which information on permafrost is required to ensure resilience of infrastructure in the context of climate warming. Using airphotos and satellite imagery from 1954 to 2017, climate data, surficial geology, field observations and ground-displacement data derived from remote sensing, the potential for climate and permafrost-related drivers are examined to explain the observed changes in lake area near the Hamlet of Rankin Inlet, Nunavut. Although there is some evidence that climate variables, such as precipitation, explain some variation in lake-water level, it appears that the response of permafrost to the warming climate since 1993 is a significant factor in modern shoreline changes. Lake expansion attributed to thermokarst processes was observed in fine-grained and ice-rich sediments. The permafrost thaw was likely induced by frequent inundation and was typically accompanied by significant localized shoreline disturbance that remained present even in dry years. In contrast, in coarse-grained and ice-poor sediments, thickening of the active layer likely causes the subsurface water storage to increase, contributing to lake drainage. Normal and wet years are now insufficient to refill lakes to their historical maximum, particularly in areas of high topographic relief. Visual assessment of shoreline morphologies provides a more robust indicator of lake instability than the extent of lake-area change alone. The link between surficial geology and lake instability provides useful insight into changes in near-surface permafrost conditions in the area of Rankin Inlet.

Résumé

La côte ouest de la baie d’Hudson connaît une croissance qui exige le recours à des informations sur le pergélisol en vue d’assurer la résilience des infrastructures dans un contexte de réchauffement climatique. À l’aide de photographies aériennes et d’images satellite captées de 1954 à 2017, de la géologie de surface et de données climatiques, ainsi que d’observations de terrain et de déplacements du sol à partir de données obtenues par télédétection, le potentiel des facteurs liés au climat et au pergélisol a été examiné en vue d’expliquer les changements observés dans la superficie des lacs à proximité du hameau de Rankin Inlet, au Nunavut. Bien que les variables climatiques, telles que les précipitations, expliquent en partie les changements qui accueillent le niveau de l’eau des lacs, il semble que la réaction du pergélisol au réchauffement climatique depuis 1993 soit un facteur important des changements récents du profil des rivages. Une expansion des lacs attribuée aux processus thermokarstiques dans les sédiments fins et riches en glace a été notée. Le dégel du pergélisol a probablement été provoqué par des inondations fréquentes et était accompagné de perturbations locales importantes du littoral qui ont persisté même pendant les années sèches. En revanche, dans les sédiments grossiers et pauvres en glace, l’épaississement de la couche active entraîne probablement une augmentation du stockage de l’eau sous la surface, ce qui contribue au drainage des lacs. Les années pluvieuses normales et supérieures à la moyenne ne suffisent plus
pour remplir les lacs à leur maximum historique, en particulier dans le cas de lacs associés à un relief topographique élevé. L’évaluation visuelle des morphologies de rivage fournit un indicateur plus robuste de l’instabilité des lacs que ne le peut le changement de la superficie des lacs à lui seul. Le lien entre la géologie de surface et l’instabilité des lacs fournit des informations utiles sur l’évolution des conditions de pergélisol près de la surface pour la région de Rankin Inlet.

**Introduction**

Pour un même territoire et un climat, les changements de superficie des lacs peuvent être très hétérogènes, en raison de caractéristiques spatialement variables telles que la topographie, les caractéristiques des bassins versants, les régimes de glace (Roach et al., 2011, Arp et al., 2015) et les conditions de pergélisol environnantes (e.g., les conditions de glace fondue). Les causes potentielles de changements de pergélisol impliquées dans les changements de superficie des lacs incluent les processus thermokarstiques (Kokelj et Jorgenson, 2013), l’épaississement des couches actives (Marsh et al., 2009; Jepsen et al., 2013) et l’augmentation de la connectivité hydrogéologique latérale et verticale (Yoshikawa et Hinzman, 2003; Lamontagne-Hallé et al., 2018). Les lacs thermokarstiques sont une caractéristique de terrain de pergélisol qui se forme dans les dépressions formées par le rétablissement de la glace renfermée (French, 2007). Que ce soit pour les lacs thermokarstiques ou non, un lac situé dans une région de pergélisol peut évoluer par les processus thermokarstiques comme le glissement par régression thermique ou la dégradation des événements de glace冰淇淋, entraînant une expansion du lac, une évacuation du lac ou des changements de morphologie du rivage (Kokelj et Jorgenson, 2013). Au fil du temps, la superficie des lacs peut également refléter des changements annuels et saisonniers dans le climat, par exemple la précipitation (Plug et al., 2008) et la ratio évaporation/précipitation (Smol et Douglas, 2007). La surface d’un lac est donc un mélange complexe entre les variables climatiques et les conditions de pergélisol (Lafrenière et al., 2018).

La région de Rankin Inlet, sur la côte ouest du Baie d'Hudson, a récemment été signalée pour des observations de drainage de rivage par des détenteurs de connaissance locaux (Oldenborger et al., 2016). Le pergélisol dans la région est considéré comme ayant une faible quantité de glace renfermée, même pas dans des terrains thermokarstiques (Figure 1). Par conséquent, de nombreux lacs de la région sont susceptibles d’être associés à des processus thermokarstiques. De plus, les lits de glace sont largement distribués dans certaines zones (McMartin, 2002), les lits de glace sont observés ou observés dans le cadre de la recherche. Le pergélisol est une glace riche dans la croûte de sol superficiel. Les conditions actuelles pourraient être un indicateur potentiel pour les processus thermokarstiques. Les objectifs de cette étude sont 1) de déterminer si les processus thermokarstiques de drainage mentionnés ci-dessus, et non pas ceux associés à des lacs riche en pergélisol, pourraient expliquer les changements observés de la superficie des lacs et, 2) d’utiliser ces résultats pour déterminer la connaissance sur les conditions de pergélisol et la sensibilité à l’événement climatique. Cette étude s’appuie sur une étude préliminaire sur l’évolution du rivage des lacs (Bellehumeur.

**Study area**

La Ville de Rankin Inlet est située sur la côte ouest du Baie d'Hudson dans la Région de Kivalliq de Nunavut (Figure 1). La région a été couverte par le Ice Sheet Laurentide et le Kivalliq durant la Glaciation Wisconsin (Shilts et al., 1979). Le glaciers de la région commencèrent il y a 11 ka et tout le territoire était libre de glace il y a 5 ka (Shilts et al., 1979; Hivon et Sego, 1993). La postglaciaire Tyrrell Sea est étendue d’une distance de 150 km à l’intérieur du territoire actuel sur la surface d’isostasie déprimée, atteignant une altitude maximale d’environ 170 m au-dessus de la surface de mer actuelle (Dyke, 2004; Randour et al., 2016). L’isostasie s’est formée à l’emplacement du littoral et a continué à évoluer. Le pergélisol de la région de Rankin Inlet consiste en glaciaires, marins et fluvioglaciaires, y compris les esques, avec de nombreux outcrops de roches sous-jacentes (Brown, 1978; McMartin, 2002; Geological Survey of Canada, 2017). Rankin Inlet se trouve dans la zone de permafrost permanent (>90% de la surface). Les estimations de permafrost...
thickness in the Rankin Inlet region are 300 m near the coast and up to 500 m inland, and active-layer thickness may vary from 0.3 to 4 m, depending on local ground conditions (Brown, 1963, 1978; Golder Associates Ltd., 2014). Permafrost temperatures range from approximately -5°C to -7.5°C at depths of zero annual amplitude ranging from 10 to 30 m (Brown, 1978; Golder Associates Ltd., 2014; Oldenborger et al., 2017).

**Climate**

The mean annual air temperature recorded at Rankin Inlet airport from 1981 to 2019 is -10.3°C (Environment and Climate Change Canada, 2019). The long-term record of air temperature at Chesterfield Inlet, approximately 100 km northeast of Rankin Inlet, shows statistically significant warming trends of 0.45 and 1.11°C/decade over the 1950–2013 and 1984–2013 periods, respectively (Brown et al., 2018). The record of air temperature at Rankin Inlet mimics that of Chesterfield Inlet closely (Figure 2a), and both communities are included in the broader eastern Canadian Arctic region, where the warming is mainly confined to the period since 1993 (Brown et al., 2018). Prior to 1992, temperatures were below long-term average and rose above that average after 1993. The 2009–2010 hydroclimatic year was the warmest in the historical record and was followed by a cooling period consistent with the observed anomaly over the eastern Canadian Arctic region (Brown et al., 2018). After 1993, the thawing degree-days (TDD) were mostly above the long-term average, whereas the freezing degree-days (FDD) were mostly below (Figure 2b). The average annual total precipitation recorded at Rankin Inlet airport from 1981–2019 is 311 m (Environment and Climate Change Canada, 2019); there are no significant trends in total precipitation (Figure 2c).

**Study sites**

Two areas of interest (AOI 1 and AOI 2) near Rankin Inlet were selected based on spatial and temporal availability of airphoto and satellite imagery, and the likelihood of occurrence of thermokarst processes based on surficial geology.
and geomorphological evidence. The two sites also represent two different landscape units representative of the region. The first area, AOI 1, is a till plain with drumlin ridges located approximately 12 km northwest of Rankin Inlet and west of the Iqalugaaarjuup Nunanga Territorial Park, in natural terrain unaltered by anthropogenic influence (Figure 3). The surficial geology consists mainly of glacial deposits dominated by till veneer (Tv), till blanket (Tb), and undifferentiated till and marine sediments (T.M). Present to a lesser extent are ridge moraine (Tr), hummocky till (Th), nearshore marine sediments (Mn) and marine beach sediments (Mr). Ice-wedge polygons are found predominantly in marine sediments (T.M, Mn and Mr). The 58 lakes in AOI 1 are of medium size relative to other lakes of the region; the average and median values of lake area are 63 500 and 101 200 m\(^2\), respectively, and 60 900 and 4900 m\(^2\) for the region (50–100 km around Rankin Inlet).

The second area, AOI 2, is approximately 10 km northwest of Rankin Inlet, within Iqalugaaarjuup Nunanga Territorial Park (Figure 3). This area is intersected by the territorial park access road, which was constructed on an esker in the 1970s and further developed in subsequent years. The esker is the most prominent landform in the Rankin Inlet area. The surficial geology of the western part of AOI 2 is dominated by ice-contact sediments (GFc, esker) and subaqueous outwash-fan sediments (GFf2) along with patches of beach sediments, whereas the valley east of the esker and Meliadine River is dominated by glaciofluvial hummocky sediments (GFh.T) and alluvial sediments (A). Glacial deposits are present on the western side of the esker and have been included in AOI 1 as they share a common landscape. Ice-wedge polygons are found in all deposits. Kettle lakes are present within and adjacent to the esker. The 76 lakes in AOI 2 are small relative to those in the region; the average and median values of lake area are 4640 and 1680 m\(^2\), respectively.

Methods

Lake area

The methodological approach is based on visual geomorphological analysis of historical airphotos and satellite imagery to establish lake area, shoreline dynamics and lake evolution since 1954. Aerial photographs were obtained from the National Air Photo Library for summer months (July and August) to maximize consistency in ground conditions, degree of thaw and the seasonal water level. Satellite imagery consists of WorldView 1 and 2 images (©DigitalGlobe, Inc. all rights reserved) from summer 2012 and 2014, and satellite imagery available from Google Earth Pro™ (Google, 2019) in 2005, 2016, and 2017 and provided by Maxar Technologies Inc. Table 1 presents the date of acquisition of the aerial photographs and satellite images.

Airphotos were orthorectified on the corresponding NTS map sheet with an average error of 0.5 m (Bellehumeur-Génier et al., 2017). Following orthorectification, shorelines of lakes and ponds were manually digitized in each AOI using ArcGIS for each year of available image data up to 2014, and for a subset of lakes for years 2016 and 2017 (not originally included in the study of Bellehumeur-Génier et al., 2017). Lake area was calculated based on the digitized polygons. To estimate errors associated with digitization, three independent operators repeated the shoreline delineation (e.g., Way et al., 2014). For a subset of 48 lakes from AOI 1, the average error was 8%. For all but the smallest lakes, the digitization error outweighs the orthorectification error and provides an estimate of the resolution of the manual shoreline mapping (Bellehumeur-Génier et al., 2017). Lakes presented in this paper were carefully reviewed to minimize error associated with marshy conditions and poor image quality.

Climate

Annual climatic factors can result in large fluctuations in lake area. Therefore, each year of the climate record was classified as wet or dry and warm or cold. Wet and dry years are defined when total precipitation, based on the hydroclimatic year, is higher or lower than the average total precipitation for the period 1981–2019, respectively (Figure 4). Warm and cold years are defined when TDD (summer period) are higher or lower than the average TDD for the period 1981–2019, respectively (Figure 4). For the

<table>
<thead>
<tr>
<th>Date of acquisition</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-Jul-54</td>
<td>Airphoto(^1)</td>
</tr>
<tr>
<td>11-Jul-65</td>
<td>Airphoto(^1)</td>
</tr>
<tr>
<td>25-Aug-69</td>
<td>Airphoto(^1)</td>
</tr>
<tr>
<td>29-Jul-76</td>
<td>Airphoto(^1)</td>
</tr>
<tr>
<td>09-Jul-86</td>
<td>Airphoto(^1)</td>
</tr>
<tr>
<td>13-Jul-89</td>
<td>Airphoto(^1)</td>
</tr>
<tr>
<td>24-Jul-92</td>
<td>Airphoto(^1)</td>
</tr>
<tr>
<td>29-Aug-05</td>
<td>Satellite image(^2)</td>
</tr>
<tr>
<td>18-Aug-12</td>
<td>Satellite image(^3)</td>
</tr>
<tr>
<td>21-Jun-14</td>
<td>Satellite image(^4)</td>
</tr>
<tr>
<td>11-Aug-16</td>
<td>Satellite image(^2)</td>
</tr>
<tr>
<td>24-Aug-17</td>
<td>Satellite image(^2)</td>
</tr>
</tbody>
</table>

\(^1\)National Air Photo Library, Natural Resources Canada
\(^2\)Google Earth Pro™
\(^3\)©WorldView-1, DigitalGlobe Inc., all rights reserved
\(^4\)©WorldView-2, DigitalGlobe Inc., all rights reserved
**Figure 3**: Surficial geology (from Geological Survey of Canada, 2017) and location of study sites (areas of Interest AOI 1 and AOI 2) near Rankin Inlet, Nunavut. Numbers attributed to lakes presented in this study refer to labels associated to lakes in Bellehumeur-Génier et al., 2017. Inset map displays location of study area. All UTM co-ordinates are Zone 15N, NAD 83.
years corresponding to the image dates, total precipitation and TDD anomalies based on the 1981–2019 averages up to acquisition date are shown in Figure 4.

Seasonal and long-term lake area and shoreline behaviour

Mean daily and discrete measurements of the elevation of the lake-water surface at the Meliadine gold mine site from 1997–2000 and 2008–2009 combined with hypsographic (i.e., depth-lake area) curves were used to estimate lake-area change due to seasonal variation of water level (Golder Associates Ltd., 2012). Measurements indicated an average summer variability of 33 cm for 15 lakes. A conservative value of 40 cm for summer water fluctuation gave a normalized lake-area change of 12% during summer. Half of the summer water-level decrease occurred generally by mid-July (Golder Associates Ltd., 2012); therefore, end of June and mid-July image dates (Table 1) would typically show lake area of 12% and <6% higher than at the end of summer, respectively. Lakes that showed long-term change greater than the seasonal range of water-surface elevation and interannual fluctuation were defined as unstable. However, seasonal and annual climatic factors can result in large fluctuations of lake area that may mask long-term changes due to permafrost-related drivers. Therefore, in addition to surface area, lake shorelines were visually assessed for each year. Lakes with littoral dynamics (change in area or morphology) that are persistent after the change and inconsistent with climatic variables were classified as unstable (expansion or drainage).

Ground surface displacement

An interannual map of ground-surface displacement derived from differential interferometric synthetic aperture radar (DInSAR) data was used to interpret changing ground-ice conditions surrounding lakes. High (negative) displacement is interpreted as thaw subsidence due to the melting of excess ground ice. This information is used to assess whether permafrost-related drivers, such as thermo-karst processes, can account for lake-area changes if climatic factors fail to explain variations. To generate the interannual DInSAR map, PALSAR-2 (aboard Advanced Land Observing Satellite-2) interferometry data were acquired on 14 July, 2016, and 13 July, 2017, in fine mode, with ~9 m resolution, ascending orbit and an incidence angle of 31°. Processing of the InSAR-derived data was carried out using GAMMA software (Werner et al., 2000), following the procedure described in Short et al. (2011), and an elevation model (by PhotoSat Information Ltd.) derived from WorldView stereo-optical data (©DigitalGlobe, Inc. all rights reserved) from August 2012 and June 2014 (1 m resolution, 30–50 cm vertical accuracy). Displacement was converted from radar line of sight to vertical displacement using the satellite geometry. Stable ground represents locations where either no vertical change was calculated or where displacement was within the expected range of error (±1.0 cm). The L-band (23 cm wavelength) synthetic aperture radar data have the significant advantage of holding their coherence over the full-year interval, making them suitable for identifying areas of long-term permafrost degradation (Short et al., 2011), but may be more sensitive to
soil-moisture changes (Zwieback et al., 2017). However, LeBlanc et al. (2019) concluded that the soil-moisture changes (from 2016 to 2017) over most of the Rankin Inlet area would not be significant enough to affect radar penetration. The interannual DInSAR-derived displacements over AOI 1 and AOI 2 are presented in Figure 5.

**Results**

Lake areas were normalized based on the average lake area for the available image dates (Figures 6a, b, 7a–c). Only the lakes labelled in Figure 3 are presented in this study; they are the subset of lakes for which shorelines were manually digitized for years 2016 and 2017. However, all lakes in AOI 1 and AOI 2 were visually assessed for their shoreline dynamics and the subset of lakes represent typical examples of long-term changes within each AOI. Lakes are grouped by their dominant surficial geology unit. However, for AOI 1, and especially large lakes, more than one unit could intersect a given lake. Therefore, all lakes surrounded by multiple till units are grouped under a general till unit. Other surficial geology units present to a lesser extent in AOI 1 are not presented herein. Relative to lakes in their AOI, lakes shown in Figures 6 and 7 are also grouped as small and shallow (no visible lake pool on airphotos) or large and/or deep (visible pool and terrace on airphotos).

The general trend regardless of the lake size and surficial geology is toward lower water levels (decrease in lake area) in 2016 and 2017 (Figures 6 and 7). Both summers 2016 and 2017 were dry and warm years (Figure 4). Therefore, there is a clear signal from seasonal and annual climate variables explaining the 2016 and 2017 low-water levels. Other fluctuations prior to year 2016 also appeared in agreement with climate variables. For example, lakes areas in 1989 were relatively low (Figure 7a); 1988–1989 was dry and warm like 2015–2016 and 2016–2017. Climate data before 1981 are not available, but synchronization in lake fluctuation among lakes from low (1965), high (1969) and low (1976) likely reflects different precipitation and evaporation conditions (Figure 7). In Figure 6a, only lake 3 has data from 1965, 1969 and 1976 for comparison.

Superimposed on interannual variations in lake area are longer term patterns of expansion or drainage. Lake expansion (shown by red lines in Figures 6 and 7) is more common in AOI 1, in the various till units (Bellehumeur-Génier et al., 2017). Both small and large lakes exhibit expansion, but the magnitude of increase is less for larger lakes. Expansion for specific lakes was first observed in 2005 and persisted in 2016 and 2017, despite two dry years with lower water levels. The lake area gained by shoreline collapse (change in morphology) exceeds the decrease in lake area due to the dry and warm conditions (Figure 8a, b).

Lake drainage is a rare phenomenon in AOI 1 (Bellehumeur-Génier et al., 2017). One of the most obvious cases of lake drainage in this area is a group of connected shallow lakes (lake 24; Figure 6b). The decrease in lake area is most pronounced from 2012 (a wet year). Proximal ponding is observed to develop south of lake 24 in 2005 in the T.M unit; these small ponds remain present in 2016 and 2017 and are consistent with ice-wedge degradation (Figure 9a–c).

Most of the lakes in AOI 2 are shallow. Lakes in the esker unit (GFc) are generally decreasing in size. Smaller shallow lakes are more sensitive to variation in precipitation and evaporation (Figure 7). This sensitivity is also enhanced because the esker only receives water from direct precipitation, so that any decrease in the ratio of precipitation to evaporation will lead to lake shrinkage. Up to 1992, the interannual variation in lake area of shallow lakes on the esker follows the cycle of wet and dry years. In 2005, all lakes areas decreased despite 2004–2005 being the second wettest year of the 1981–2019 period (Figures 2, 7). The 2005 image is from the end of August, when thaw depth is near its maximum, and could be compared with year 1969 in terms of climate (wet) and image date. In 2017, lake 11 almost completely drained and lake 9 reached a historical low level. In the river valley, similar patterns in lake-area changes were observed for GFe.T and A units, except for lake 55–58 (Figure 7c), which is discussed below. Lake 38, the largest and only potentially deep lake in AOI 2, shows a small relative decrease in lake area compared with shallower lakes. Nevertheless, lake 38 reached a historical low level in 2005 and, as the lake level continued to fall subsequently, it is considered to be draining.

Lake 55–58 is a clustered group of lakes, the expansion of which has been small in magnitude but is occurring through the collapse of the shoreline. The change occurred between 2005 and 2014, and the new shoreline remained more or less the same in the subsequent dry years of 2016 and 2017. In 1986, lake levels were also high at the same location (Figure 10a). However, lake levels receded post-1986 (Figure 10b), but remained high after 2005 despite subsequent dry years (Figure 10c, d), which behaviour supports the interpretation of lake expansion.

**Discussion**

The lakes in the two landscape units exhibit different behaviour, although relative low-water levels are generally observed for 2016 and 2017. Lakes on the till plain of AOI 1 are either stable or expanding. In contrast, most of the lakes on the esker and in the river valley (glaciofluvial and alluvial units) of AOI 2 have decreased in size, with some having drained completely by the end of summer 2017. In general, permanent changes in lake area occurred between 1992 and 2005 coinciding with a warming period in the eastern Canadian Arctic. Airphotos and satellite imagery are not available between these years and, therefore, the timing of the change cannot be determined more precisely.
Figure 5: Interannual ground-surface displacement between 2016 and 2017 acquired by differential interferometric synthetic aperture radar in the study area near Rankin Inlet, Nunavut. Selected lakes and lake numbers are from Bellehumeur-Génier et al., 2017.
From 1954 to 1992, observed changes followed seasonal and annual patterns of precipitation. Although climatic variables have played a role in impacting lake area in recent years, the changes in lake area for some lakes have been dominantly controlled by factors related to permafrost degradation from 2005 onward.

For lakes in the till plain of AOI 1, the change in shoreline morphology first observed in 2005 and maintained over subsequent dry years is a clear indication of permafrost degradation. Much of the lake expansion was localized, while most of the shoreline was largely unchanged. In general, ground-surface displacements are observed close to lakes where changes in shoreline morphology were observed through time (e.g., lakes 8 and 43 in Figures 5 [inset map a], 8). This suggests that the lakes identified as expanding have been subject to thermokarst processes at their margins, likely caused by the melting of ice-rich sediments at the base of the active layer. Most of the localized expansion of lakes 8 and 43 occurred in the T.M unit, which was cored a few kilometres away from these lakes. There was no intact core recovery at the top of the permafrost, only a muddy grey sediment typical of a mixture of fine-grained sediments with high water content. However, thick ice lenses were found approximately 30–40 cm below the top of the permafrost. Shorelines at the locations of expansion are typically of low-relief and thus their configuration is highly sensitive to water level. It has been observed that permanent shoreline recession occurs where the shorelines have been flooded in the past and permafrost thaw was likely induced by frequent inundation.

The drainage of lake 24 in the till plain of AOI 1 is associated with both stable and high interannual ground-surface displacements (Figure 5, inset map b). Stable areas are found around the two lakes of this group of connected shallow lakes (northwest) that are experiencing the most drainage, whereas higher displacements (2–3 cm) are located around the two lakes that show less change. Lake drainage could be a consequence of the proximal ponding associated
with ice-wedge degradation and possibly the thawing of ice-rich T.M sediments at the base of the active layer (Figure 9b, c). Permafrost degradation may have changed the surface and subsurface connectivity between lakes, although the general connectivity remains from north to south according to topography. Ice-wedge degradation, ponding and lake drainage are not contemporaneous; degradation and ponding precede drainage (Figure 9b, c). However, the degradation observed in 2005 in the T.M unit is not co-located with maximum ground displacement for 2016–2017. This may indicate that thawing took place prior to 2016–2017 and that the high ground displacement observed east of lake 24 may foreshadow future changes in lake area in the region. This uncertainty highlights the limitation of using only one interannual ground-displacement map to support the interpretation.

For lakes on the esker and in the Meliadine River valley (glaciofluvial and alluvial units) of AOI 2, high ground-surface displacements are observed exclusively in the vicinity of the group of expanding lakes (Figure 5, inset map c). Furthermore, recent subsidence in proximity to these expanding lakes, deduced from new ponding areas in 2016–2017 compared with 2005 imagery, is likely to increase lake area soon (Figure 10c, d). The alluvial deposits are located 2 m lower than the GFh.T unit and are poorly drained. Alluvial deposits with similar surface expression to those in the river valley were cored nearby and found to be ice rich near the top of the permafrost and thus susceptible to thaw subsidence upon thawing. As in AOI 1, the permanent degradation occurs where the low-relief shorelines have been flooded in the past.

Outside of this area of high displacement, AOI 2 exhibited mostly stable ground in 2016–2017. Stable ground implies little excess ice but does not preclude active-layer thickening. Draining lakes on stable ground may be the result of increased groundwater storage due to active-layer thickening.
in permeable glaciofluvial and alluvial sediments. In this case, lake drainage may not be a strictly thermokarst phenomenon because thawing of ice-poor sediments may be the dominant drainage process.

Field observations from AOI 2 in June and September 2018 and 2019 support the interpretation that lake drainage is not solely due to seasonal and annual climatic factors. Observations from June 2018 show that water levels of many lakes were lower than their maximum level, whereas very low water levels or completely dry lakes were observed in September 2018, despite average precipitation (Figure 11a, b). Although high precipitation in 2019 partially refilled lakes that were previously dry, a shift in lake levels toward lower values was still apparent. For example, in September 2019, water levels were about the same as the previous dry and warm years (Figure 11c, d) even though 2018–2019 had more than twice the rain and total precipitation than those dry and warm years. Low water levels in normal and above-average wet years is consistent with increased groundwater storage due to active-layer thickening in permeable soils. Ice wedges intersect many lakes in AOI 2 (McMartin, 2002) but the current data do not support conclusive interpretation that their degradation opens drainage pathways.

The behaviour of lakes in the river valley is probably more complex than that of those on the esker because the latter are mostly isolated lakes dominated by groundwater flow within the active layer and precipitation. In the river valley, many lakes show connectivity and receive surface and groundwater discharge from a larger area. Assessment of the water balance for each watershed, including evapotranspiration, runoff and discharge, as well as the lake-ice thickness and ice-out timing, would have likely provided additional indications of the cause of observed lake-area changes, but studying the water balance and the lake-ice regimes was outside the scope of this project.

Conclusions

The lake area, shoreline dynamics and lake evolution since 1954 of representative landscapes and surficial units around Rankin Inlet were studied to gain knowledge on permafrost conditions in the region. Climate data, field observations and ground displacements derived from remote sensing were used to interpret the changes. The results show that interannual climate variability plays an important role in lake-water fluctuation. However, it appears that permafrost response to the recent climate warming (since 1993) is a significant factor in modern shoreline changes. Lake drainage was the dominant phenomenon in coarse sediments such as glaciofluvial and ice-poor alluvial deposits. For these draining lakes, relatively low water levels have been observed after recent normal (2017–2018) and wet (2018–2019) years. Drainage of these lakes is attrib-
ulated to active-layer thickening and increased groundwater storage. In contrast, lake expansion was the dominant phenomenon in fine-grained sediments. Expansion is typically accompanied by significant localized shoreline disturbance that remains present through dry years. Lake expansion occurs often within ice-rich till and alluvial sediments (T.M and A.M units). Permafrost thaw was likely induced by frequent inundation. One exception in a T.M unit was the drainage of a group of lakes; in that case, drainage may have been initiated by adjacent ice-wedge degradation. Combining lake area with the assessment of individual shoreline morphologies helps to isolate lake instability from climatic variables and provides a more robust indicator of lakes affected by permafrost degradation. Changes in shoreline morphology combined with observations of other geomorphological features further reduces the uncertainty in this interpretation of permafrost-related drivers. Interannual ground displacement derived from remote sensing is a good indicator to locate thaw-sensitive ground and associated lake expansion, whereas stable ground is associated with lake drainage. However, multiyear displacements would be needed to reinforce the links between lake instability and ground displacement derived from remote sensing.

**Economic considerations**

The western coast of Hudson Bay in the Kivalliq Region of Nunavut is undergoing significant infrastructure development associated with natural resource development and community growth; information on permafrost and ground ice is required to ensure resilience in the context of climate warming. Thermokarst processes at lake shoreline serve as a proxy for ice-rich ground and can help identify surficial geology units prone to instability. Prior to future infrastructure development near Rankin Inlet, attention should be paid to the distribution of till and alluvial material mixed with marine sediments, which are ice rich and unstable. Coarse sediments remain more stable when subjected to thaw, but the engineering design may need to account for a thicker active layer. Freshwater systems, including lakes, are the foundation of major ecosystems and represent a key resource for northern communities (Lafrenière et al., 2018); understanding the drivers behind changes in lake-water level is therefore important.

**Acknowledgments**

This work was supported by Natural Resources Canada Climate Change Geoscience Program and the Canada-Nunavut Geoscience Office. The Canadian Northern Economic Development Agency’s (CanNor) Strategic Investments in Northern Economic Development (SINED) program provided financial support for this work. The authors would like to thank the participants of the 2016 community workshop on permafrost and landscape change (Rankin Inlet Hamlet office, the Kivalliq Inuit Association, the Hunter and Trappers Association of Rankin Inlet, the Arctic College of Nunavut and the Government of Nunavut) who generously shared their knowledge and observations of the land, especially on lake-level changes. The authors also want to acknowledge the critical reviewer H.B. O’Neill for his constructive comments on the paper.
References


Environment and Climate Change Canada 2019: Historical climate data; Environment and Climate Change Canada, URL <http://climate.weather.gc.ca/> [October 2019].


Natural Resources Canada, Lands and Minerals Sector contribution 20190351


