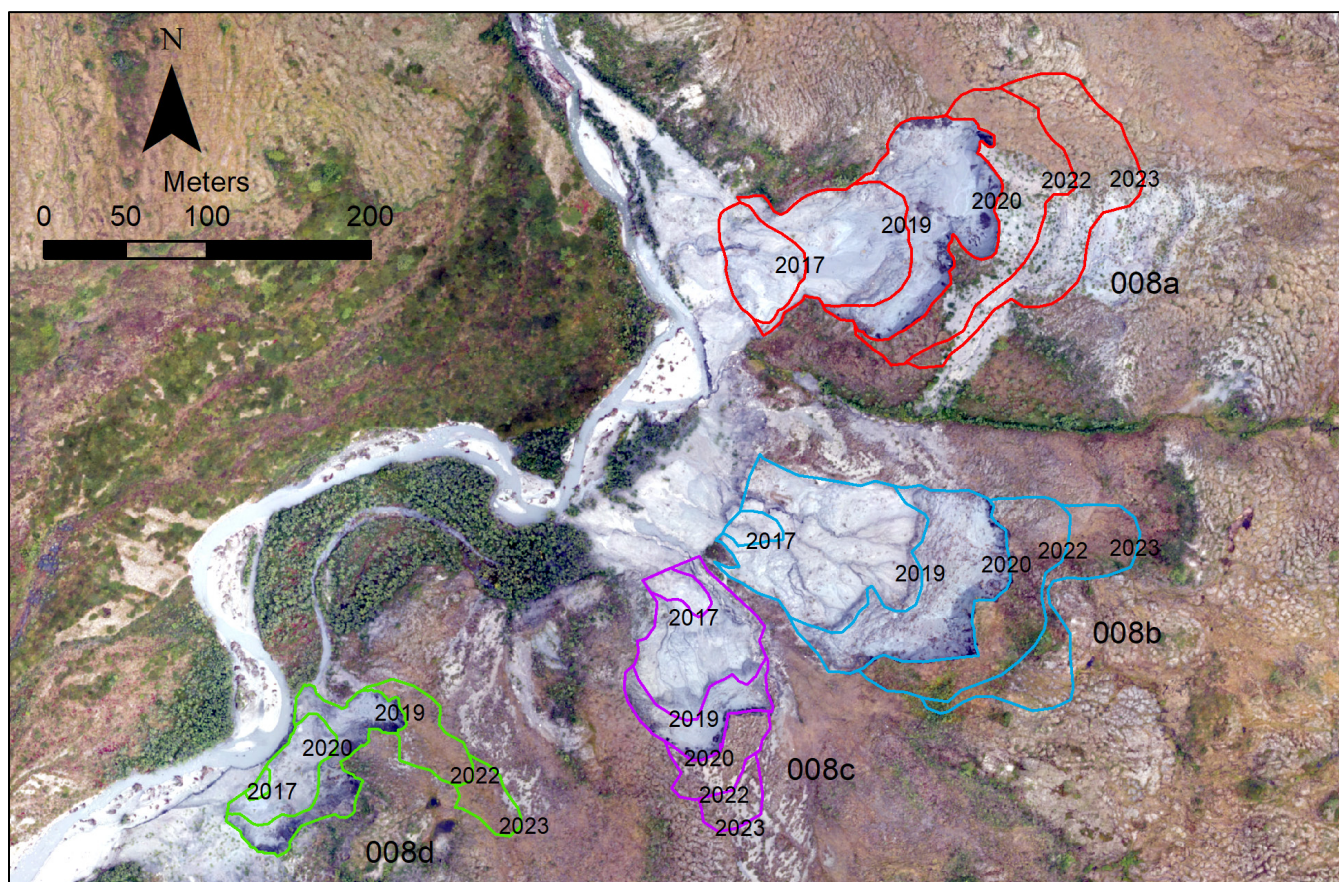




Growth of Retrogressive Thaw Slumps in the Noatak Valley, Alaska, 2006–2023

Natural Resource Report NPS/ARC/NRR—2024/2629



ON THE COVER

Growth of four retrogressive thaw slumps (labeled 008a, -b, -c, and -d) along Douglas Creek in Gates of the Arctic National Park. Perimeters of the slumps in years 2017 through 2023 are shown over an aerial orthophoto background from 2020. The slumps grew uphill to the right and shed material into the creek, which flows from the top to the bottom of the photo.

NPS

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Natural Resource Report NPS/ARC/NRR—2024/2629

David K. Swanson¹, Kenneth R. Hill¹, Graham E. Brady²

¹ National Park Service
4175 Geist Road
Fairbanks, Alaska 99709

² National Park Service
240 W. 5th Ave.
Anchorage, AK 99501

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Abstract

Retrogressive thaw slumps (RTS) are dramatic features of the Arctic landscape caused by thaw and subsidence of permafrost, followed by downslope flow of liquified sediment and water. RTS expose bare soil that can be transported into nearby water bodies. The National Park Service, Arctic Inventory and Monitoring Network monitors the growth of selected RTS in the Noatak Valley of northwestern Alaska. We studied the growth in area, the rate of advance of the main thaw escarpment, and the amount of subsidence using three-dimensional models created from small-format (35 mm) aerial photographs in multiple years from 2010 to 2020, supplemented with high-resolution satellite images from 2006 to 2023. We studied RTS growth in relation to thaw degree-days at the nearest weather station to account for the irregular time intervals between samples.

For the thirteen study slumps that were present before 2016, all except one grew fastest prior to 2012. Most of these slumps were initiated in the years 2004–2005. Eight slumps had largely stabilized by our previous sample date (2014 or 2016) and grew little from then to our most recent sample date (2019 or 2020). Four slumps continued growing rather uniformly from 2016 through 2020, with scarp migration rates of 7 to 37 m yr⁻¹ in 2019–2020. Just one showed markedly increased growth in recent years. Sediment transport into nearby water bodies from these slumps was greatly reduced relative to the early years in the slumps' lives because they were either growing very little, or the growth had progressed hundreds of meters from adjacent water bodies and the sediment mobilized at the advancing scarp was being deposited on the slump floor, usually in the form of a small ridge within 200 m of the scarp. The rather constant growth of the slumps over the past 6 to 8 years can be explained by the uniform geologic conditions at the sites plus the fact that slump growth is apparently related mainly to summer warmth (which has varied without much trend in recent years) as opposed to mean annual temperatures (which have increased in recent years).

The most striking development was the re-initiation of slump activity in the vicinity of stabilized slump GAAR008. Four new slumps were first visible on 2016 satellite images near Douglas Creek and grew rapidly through 2023 across an area of previously stabilized slumps. The scarps advanced at rates of up to 60 m yr⁻¹ and elevation loss at the scarp was up to 10 m. Approximately 137,000 m³ of material was lost from the slump footprints of three of the slumps as of 2020, of which an estimated 26,000 m³ accumulated in the adjacent floodplain, forcing the creek to migrate laterally up to 80 m. The missing 110,000 m³ consists of melted ice and sediment that was transported further by Douglas Creek. This outbreak of slumping at Douglas Creek appears to have been a localized event triggered by migration and erosion of the creek into ice-rich material, and not a widespread climate-driven event like the one that triggered many slumps in 2004–2005.

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Numerous people have helped through the years of this monitoring project. For aircraft operations, flight planning, and piloting: Curtis Cebulski, Stan Hermens, Quentin Slade, Matt Nolan, Chad Hults, Brett Nigus, Britta Schroeder, and Justin Junge. For processing of photos into orthophotographs and DEMs: Matt Nolan, Ken Hill, and Graham Brady. For on-the-ground field surveys: Ken Hill and Cody Priest. For review comments on this manuscript: Jon O'Donnell and Pam Sousanes. This project was funded mainly by the NPS Arctic Inventory and Monitoring Network, with important contributions by the NPS Alaska Region Structure-from-Motion team headed by Chad Hults.

Introduction

Retrogressive thaw slumps (RTS) are dramatic erosion features of the Arctic landscape caused by permafrost thaw. They occur where a cut-bank in ice-rich permafrost advances into undisturbed ground as material thaws in the steep bank, falls or slides onto the adjacent more gentle slope, and then is transported away by viscous flow or water erosion (Burn and Lewkowicz 1990). The advancing cut-bank, referred to here as the “main scarp” in keeping with standard landslide terminology (Beltran et al. 1993), is typically 2 to 10 m high, though it may reach 35 m (Crosby 2009). RTS often begin as escarpments produced by coastal, lakeshore, or fluvial erosion and then advance away from the shore by thaw and slumping. Very ice-rich material of substantial thickness (e.g., several meters) and lateral extent is needed to produce a RTS (Lacelle et al. 2010).

RTS often occur near rivers, lakes, or the ocean and can shed large amounts of sediment into the adjacent water body (Kokelj et al. 2005, Bowden et al. 2008). Disturbance of the vegetation and organic surface soil layers by slumping results in increased mean annual ground temperatures, soil pH, and shrub productivity (Burn 2000, Lantz et al. 2009). Warming temperatures of recent decades in the Arctic have been linked to increased activity of RTS (Lacelle et al. 2010, Lantuit and Pollard 2008, Lantz and Kokelj 2008, Lantuit et al. 2012, Segal et al. 2016).

Numerous RTS have been identified in the national parks of northern Alaska (Swanson 2014, Balser 2015). The National Park Service (NPS) has selected a set of relatively large and high-impact RTS for intensive monitoring by detailed three-dimensional (3D) modeling and analysis of changes over time (Swanson and Hill 2010, Swanson 2012, Swanson 2013, Swanson and Nolan 2018). This monitoring is a part of the long-term permafrost monitoring program of the NPS Arctic Inventory and Monitoring Network (ARCN) (Swanson 2017a, b).

We monitor the growth of RTS using time series of high-resolution orthophotographs and digital elevation models (DEMs) created by structure-from-motion (SfM) digital photogrammetry from photographs taken from aircraft using 35-mm cameras (Swanson and Nolan 2018). The orthophotos allow us to document growth in area, while the DEMs allow us to measure the amount of erosion/subsidence and deposition of material. High-resolution satellite images are also useful for filling in information about changes in slump area during gaps in the SfM record.

The present report is an update on the growth of RTS that we have monitored by SfM since 2010, supplemented by satellite images from as early as 2006. The most recent previous report (Swanson and Nolan 2018) was based on images taken through 2016. The present report incorporates orthophotographs and DEMs based on aerial photographs taken in 2020, as well as high-resolution satellite images from 2016–2023. Our detailed analysis ends in 2020 because 1) that is our last date with elevation data and 2) continuous climate data from the Noatak RAWS, which is very useful for understanding slump growth, was not available after 2020.

Methods

Study Area

We monitored the growth of RTS located in the Noatak River basin of northern Alaska (Figure 1). This is a region of continuous permafrost (Jorgenson et al. 2008) and arctic tundra vegetation of cotton sedge (*Eriophorum* spp.), sedges (*Carex* spp.), and various low to mid-sized shrubs (*Betula*, *Salix*, *Vaccinium*, and *Dryas* spp.)(Jorgenson et al. 2009).

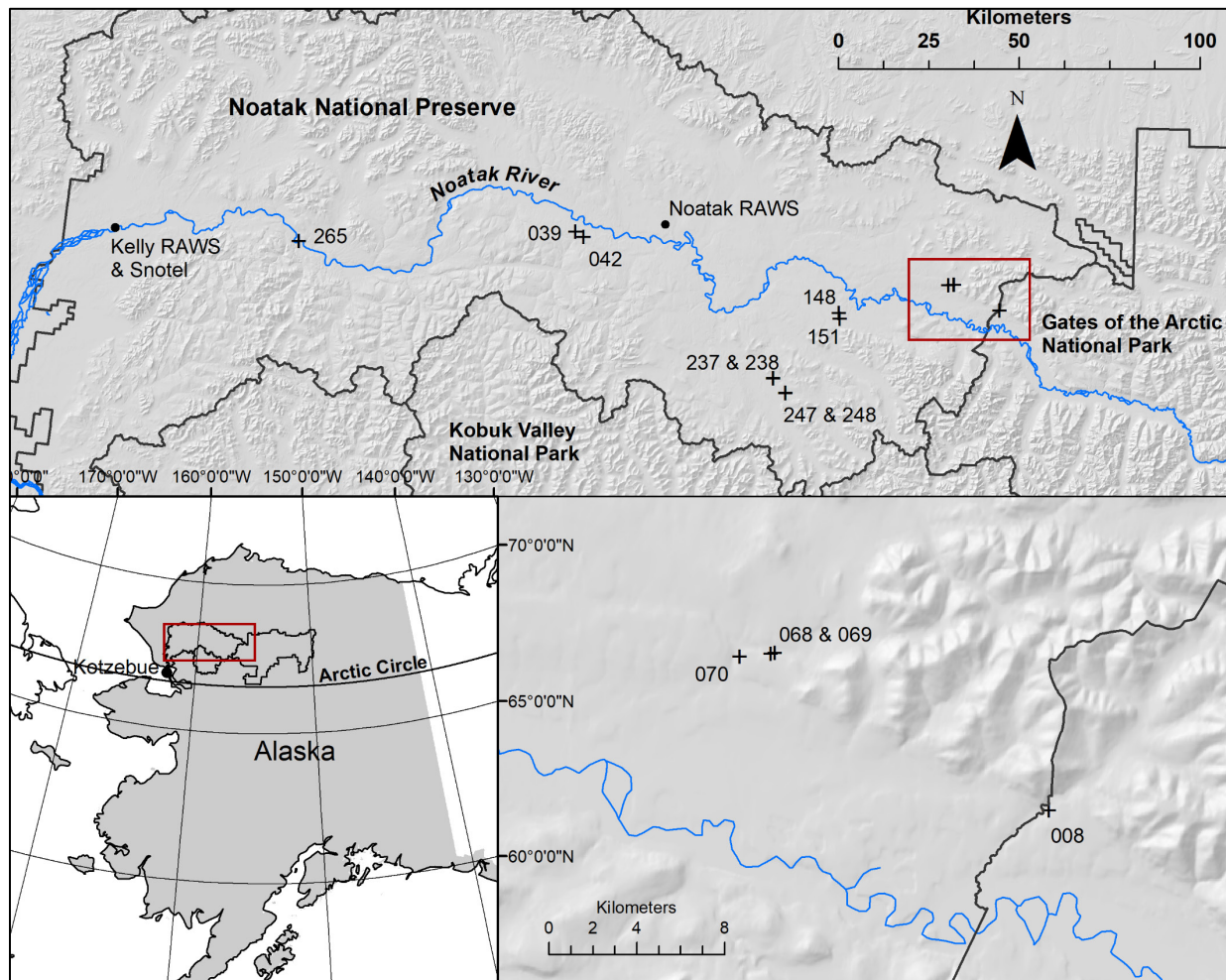


Figure 1. Location of the study slumps in northwestern Alaska. Here and in other figures, the NPS unit prefix is omitted to save space. It is “NOAT” (e.g., “NOAT265”) for all slumps except “GAAR008”.

The study area was glaciated during the late Pleistocene, and the study slumps are mostly in glacial deposits from the Itkillik I and Itkillik II glaciations (Hamilton 2010; Table 1). The Itkillik II glaciation coincided with the last worldwide glacial maximum (marine isotope stage II). The Itkillik I glaciations are older than the Itkillik II but occurred after the previous interglacial (Hamilton 2009, 2010). Relict glacial ice from these advances has been observed in escarpments of some of the study retrogressive thaw slumps (Balser 2015, Swanson and Hill 2010; Table 1). Some of the slump

escarpments exposed both glacial ice and ground ice in the form of large, dark-colored ice wedges that is interpreted to be Pleistocene in age.

Table 1. Location and setting of the study slumps.

Slump ID	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Ground Ice ^A	Surficial Geology ^B	Initiation Year ^C	Waterbody ^D
GAAR008	67.9007	-156.4862	612	g	id2	2005	Stream, 100 m
NOAT039	68.0359	-159.2914	327	wg	id1	Pre-1980	Lake
NOAT042	68.0239	-159.2346	323	wg	id1	2004–05	Lake
NOAT068	67.961	-156.7884	598	g	id1	2005	Stream
NOAT069	67.9606	-156.7926	600	g	id1	2005–06	Stream, 3 m
NOAT070	67.9588	-156.826	561	g	id1	2004–05	Stream
NOAT148	67.8768	-157.5324	452	wg	id1	2004–05	Stream, 10 m
NOAT151	67.8628	-157.5267	462	wg	id1	2004	Stream, 100 m
NOAT237	67.7049	-157.9354	421	g	igl1	2006	Lake
NOAT238	67.704	-157.936	412	p	igl1	2004	Lake
NOAT247	67.6697	-157.8517	454	p	igl1	2005	Lake
NOAT248	67.6707	-157.8528	444	p	igl1	2004–05	Lake
NOAT265	67.9475	-161.0918	158	n	tg?	2005	Stream

^A g: glacial ice, w: wedge ice, wg: wedge and glacial ice, n: massive ice not visible, p: poor exposure

^B From Hamilton (2010). id1: Itkillik phase I glacial drift, id2: Itkillik phase II glacial drift, igl1: Itkillik phase I glaciolacustrine deposits, tg? : possible Pleistocene terrace gravel.

^C Year the slump was first visible. From Swanson and Nolan (2018), based on remote sensing.

^D Type of water body at the foot of the slope. The distance from the end of the area obviously disturbed by the slump to the water body is given; where the distance is omitted, the disturbed area contacted the water body directly.

Remote sensing images indicate that most of the slumps we are monitoring became active beginning near the year 2004 (Swanson and Nolan 2018). Slumping also occurred in the vicinity of all of the study slumps (except NOAT148) in the 1970s and 1980s, but they stabilized prior to the current episode, and present activity is actually overlapping previously slumped areas in most cases (Swanson and Hill 2010). Re-occurrence of RTS on the footprint of earlier slumps is common (Lacelle et al. 2010, Lantuit and Pollard 2005, 2008, Lantuit et al. 2012, Kokelj et al. 2009). Repeated slumping in the same place shows that the prior pass by the main scarp of an RTS did not exhaust the supply of ground ice. Relict glacial ice provides particularly favorable conditions for repeated slumping, because many meters of nearly pure ice may be present.

The mean annual, mean July, and mean January temperatures at the nearest weather station, the Noatak Remote Automated Weather Station (RAWS; Figure 1) for the period of record (1990–2020) were -7.6, +13.0, and -25.3°C, respectively. (These long-term means were computed from period-of-record daily averages to minimize the effects of missing data.) The thaw season (daily means above 0°C) typically runs from mid-May through mid-September. The annual sum of thaw degree-

days (TDD) has been generally rising since the 1940s at Kotzebue, Alaska (the nearest long-term weather station, Figure 1), and the three warmest years as measured by TDD since 1943 were 2004, 2016, and 2018 (Figure 2). At the Noatak RAWs, the three warmest years since consistent records began in 1996 were 2004, 2007, and 2019 (Figure 3). The 2004 spike in TDD at both weather station locations (Figures 2 and 3) coincides with the initiation date of most current slump activity mentioned above.

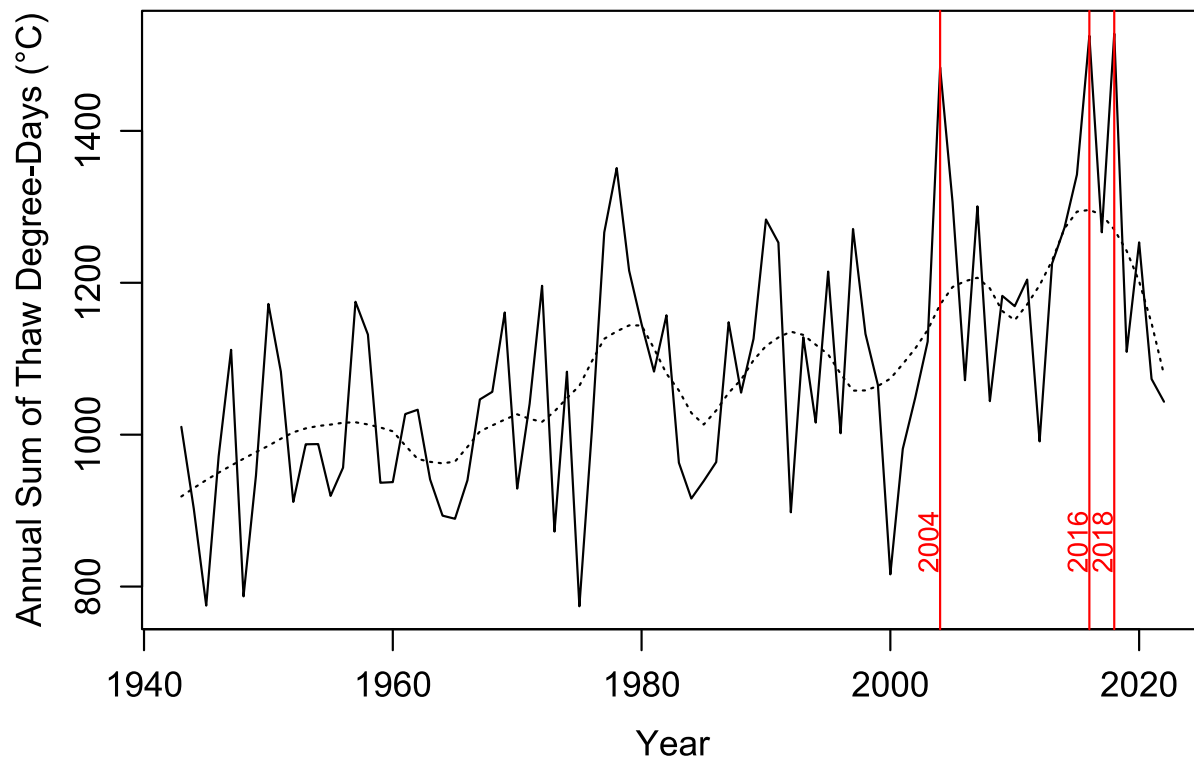


Figure 2. Annual sum of thaw degree-days at Kotzebue for 1943–2022, computed from monthly mean temperatures. The years with the three highest totals are indicated in red. The dotted line is a “loess” interpolation with span of 20 years and order of 2 (R Core Team 2021). Missing data from May–Aug 2019 were filled with values from the NPS Mt. Noak climate station, 33 km north–northwest and 255 m higher in elevation.

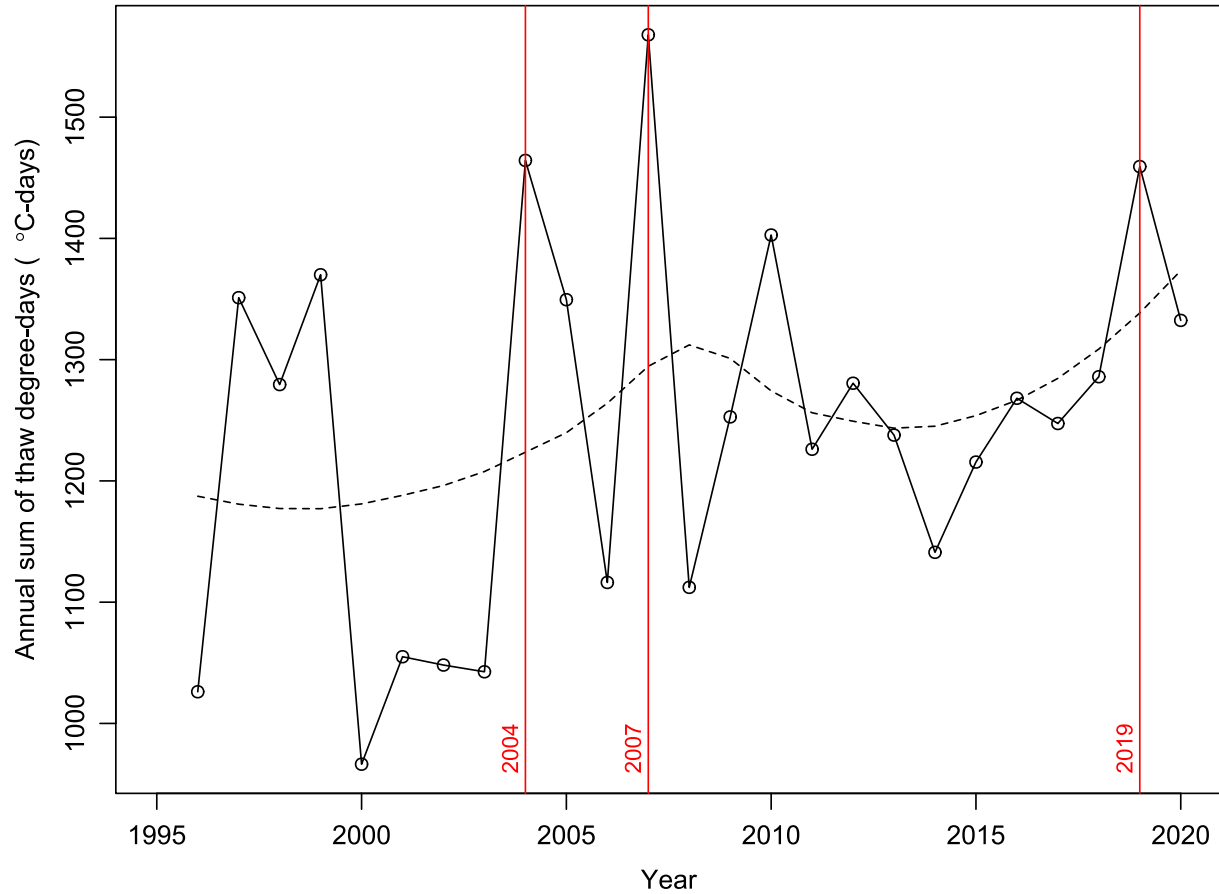


Figure 3. Annual sum of thaw degree-days at Noatak RAWS for 1996–2020. The years with the three highest totals are indicated in red. The dashed line is a “loess” interpolation with span of 20 years and order of 2 (R Core Team 2021). Missing data at Noatak RAWS were filled in by correlation with the Kelly RAWS, as described in the Methods.

Mean annual air temperatures (MAAT) at Kotzebue experienced stepwise increases in the late 1970s and again around 2014 (Swanson et al. 2021, Figure 4). Mean annual air temperatures at the Noatak RAWS are only available for 16 years due to missing data in the winter, but available years show MAAT there was 2 to 4°C lower than Kotzebue (Figure 4). MAAT at Noatak RAWS was –6 to –9°C, rising to near –4°C in exceptionally warm recent years (Figure 4). Permafrost temperatures under undisturbed soils vegetation in the vicinity of the study slumps during the 2000–2009 decade were estimated to be –4 to –7°C, based on modeling by Panda et al. (2016). Under the disturbed, unvegetated floor of an RTS the mean annual ground temperature is expected to be as much as 3°C to 4°C higher than in undisturbed areas nearby (Burn 2000). Active-layer thicknesses under undisturbed vegetation in the study area are currently approximately 0.5 m (Jorgenson et al. 2008, Panda et al. 2016, and our unpublished data) and larger by an unknown amount on the disturbed floor of active RTS.

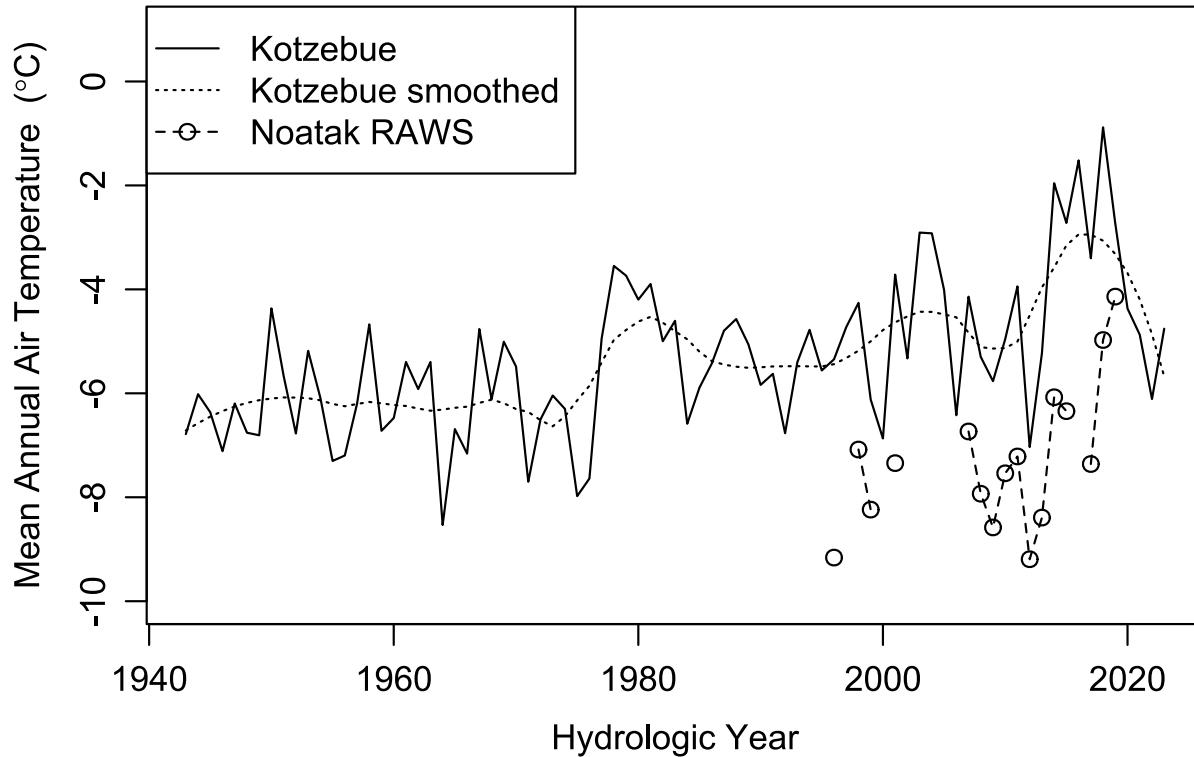


Figure 4. Mean annual air temperatures at Kotzebue and Noatak RAWS. The “Kotzebue smoothed” line is a loess curve (function “loess”, R Core Team 2021, with span of 20 years and order of 2). Missing data at Noatak RAWS were filled in by regression (by month) with Kelly RAWS. Only years where less than 40 days per year were missing from Noatak RAWS and less than 10 days were missing from both Noatak and Kelly RAWS are shown.

Imagery and Analytical Methods

The orthophotos and DEMs were created from oblique aerial photographs from 2010 to 2012 and vertical aerial photographs from 2013 to 2016 and 2020 (Table A1). The oblique photos were taken by D. Swanson from the window of a helicopter or fixed-wing aircraft with a Nikon D700 digital single-lens reflex camera and 50 mm lens, on multiple linear passes near the slump. All of the study slumps have two or three years of these images. The scale of oblique photos varies greatly across any given frame, but the photo centers were generally 200 to 400 m from the camera, yielding a ground resolution at the center of 4 to 7 cm. In one to three years between 2013 and 2016, M. Nolan took vertical aerial photographs from a fixed-wing aircraft of all of the study slumps except one (NOAT172) using a Nikon D800 digital SLR camera and 24 mm lens at 300 to 600 m above ground level, for an average ground resolution of 6 to 12 cm. Photo centers were located with accuracy of about 10 cm measured by on-board GPS (Nolan et al 2015). These photos were taken along pre-determined flight lines to optimize overlap and the photogrammetric bundle adjustment within the processing software. The 2020 photos were also vertical and taken by NPS with a Nikon D850 camera with a 35 mm lens. These photos were taken at 600 to 800 m altitude for a ground photo resolution of 8 to 10 cm per pixel.

Digital elevation models were produced from the aerial photos using Agisoft Metashape software (Agisoft 2023). The pre-2013 photos were georeferenced by selecting multiple points on landmarks around the slump perimeters on the 2013–2016 models; these points were then located on the earlier (unregistered) 3D models. We used these landmarks as pseudo-ground control points in the photogrammetric bundle adjustment in Photoscan to produce georeferenced models for 2010–2012. An assessment of the accuracy of these models using ground survey points is presented in Swanson and Nolan (2018). The post-2013 models were georeferenced using camera locations from aerial GPS (Nolan et al. 2015, Hults et al. 2021).

The 3D data described above was supplemented with two-dimensional (2D) slump perimeters from high-resolution (1 m or less) satellite images from various years by Satellite Imaging Corporation (2023). These were orthorectified and georeferenced by the manufacturer. Post-2020 sub-meter resolution images were not available for the study area, so for the most actively growing slumps we used images of somewhat lower resolution (3 m) by Planet Labs (Planet Labs 2021, 2023) to approximate perimeters from 2021–2023.

Registration differences between ortho images from different dates were less than 2 m and were corrected by simple affine transformation, based on visually digitized tie points with the ArcGIS Desktop 10.8 “Georeferencing” Toolbar (ESRI 2023).

We digitized slump perimeters by hand on the orthophotographs and satellite images. In some cases, the main scarp retreated by the formation of long fissures parallel to the scarp, separated by elongated turf blocks (Swanson 2012). Here, we defined the perimeter of the slump at the uppermost fissure. To compute the rates of scarp migration (in linear units per TDD), we manually digitized a baseline up the approximate centerline of the slump and measured linear distance along the centerline from the lower perimeter of the slump to the main scarp.

The time intervals between photography of any given slump varied: image dates ranged from 21 June through 25 September, and not all slumps were imaged every year. For this reason, simply dividing the change in slump area or scarp position by the number of calendar days or years separating these visits would be misleading. To correct for the irregular temporal spacing of samples and the fact that growth only occurred during the thaw season, we analyzed slump change in relation to accumulated thaw degree-days. Slump growth rates are controlled by complex energy balance conditions at the slump scarp (Lewkowicz 1987), but TDDs are a convenient integrator of the energy available for slump growth in the absence of detailed energy-balance measurements. We computed the change in slump area and linear change in position of the slump scarp per accumulated TDD using temperature data from the Noatak RAWs (NOAA Regional Climate Centers 2023, Figures 1 and 3).

The Noatak RAWs had missing temperature data for about 8% of the days in May–September (i.e., the thaw season) of 1996–2020 (Table A2). To compute cumulative TDD, we filled missing temperature data at Noatak RAWs with predicted values from a linear regression between thaw season (May–September) mean daily temperatures at Noatak RAWs and the next closest weather station with data for our period of observation, Kelly RAWs (Figure 1). Individual days were missing from both stations in 1991, 1997, and 2004, and these were filled by interpolation between

adjacent days. To compute mean annual temperatures at Noatak RAWs (Figure 4) required more data substitution because of more missing data in the winter. Here we computed regressions between Noatak and Kelly RAWs on a monthly basis and used these to fill in missing data at Noatak. Individual days missing from both stations in were filled by interpolation between adjacent days, and Figure 4 includes only years meeting the condition of less than 40 days missing at Noatak and less than 10 days from both stations (and thus requiring interpolation).

Growth in slump area and linear advance of the main scarp perpendicular to the scarp centerlines form smooth curves when plotted against TDDs (Swanson and Nolan 2018). Thus it was possible to compute the annual growth rate of a slump using interpolated values, even in the absence of images that were spaced a year apart.

Change in elevation was computed between DEMs created in 2016 and 2020. These models showed systematic differences in elevation due to the elevation datum used, GPS errors, and model computation errors. We adjusted the 2016–2020 elevation difference by examining the differences between the two models in a buffer zone outside of the slump, typically 10 to 50 m from the perimeter, where no change should have occurred. If the difference was uniform in this buffer zone, we simply computed the average difference between the models in the buffer zone and corrected the DEM difference with it. If the difference varied systematically across the model area, we computed a curved correction surface as described in Swanson (2017b, Standard Operating Procedure C6).

Results

Slump Area and Length

Growth in slump area and length are presented here both in relation to sum of thaw degree-days (Figures 5 to 8) and year (Figures 9 and 10). The latter are interpolated from the TDD curves since we don't have observations from every year or the same dates each year. The plots of slump growth in relation to TDD in principle remove the effect of differences in warmth between years. Thus a slowdown in the growth rate per TDD could indicate that the slump encountered less ice-rich sediment or a flatter topography. The plots of slump growth vs. year portray the actual growth over time, as influenced by both variations in warmth and the intrinsic susceptibility of the site to slumping.

Slump growth vs. thaw degree-days

For the thirteen slumps that were present in 2016, all except NOAT151 grew fastest prior to 2012 (Figures 5–8). The eight slumps that had nearly ceased to grow in 2016 added little new growth between 2016 and 2020. In four slumps, growth rates since 2016 were nearly constant or slightly declining. The exception was slump NOAT151, which grew faster in 2019–2020 than it had at any time since monitoring began in 2006.

Slump growth vs. year

Trends in slump growth rates in area or length per year (Figures 9 and 10) were similar to growth rates relative to TDD. Most slumps present in 2016 grew fastest prior to 2012, and growth rates have been steady or slightly declining since. Eight of the slumps showed little or no growth (less than 2 m of scarp migration) in the last year of observation (Table 2). Other slumps maintained about the same rate of growth per year during 2016–2020 as they had just prior to 2016. Again the exception was slump 151, which grew faster in 2019–2020 than it had at any time since monitoring began in 2006. Several of the pre-2016 slumps had main scarp migrations of more than 30 meters in the last year of observation (Table 2).

Slump re-initiation at GAAR008

The most striking development was re-initiation of slump activity in the vicinity of slump GAAR008. The original slump GAAR008 grew little after 2012, and no other slumps in its vicinity were active (though as will be shown below, there was much bare soil from prior slumping). Then four new slumps appeared at the base of the original slumps, near the creek. They were first visible on 2016 satellite images and grew rapidly through 2020. These are the only detailed remote-sensing records that we have for slumps in the first few years of their existence. Their rapid growth rates resemble those that must have occurred in the earliest years of other slumps: they match what would be required to extrapolate most other slumps back to their initiation dates around 2004–2005 (Figures 9 and 10).

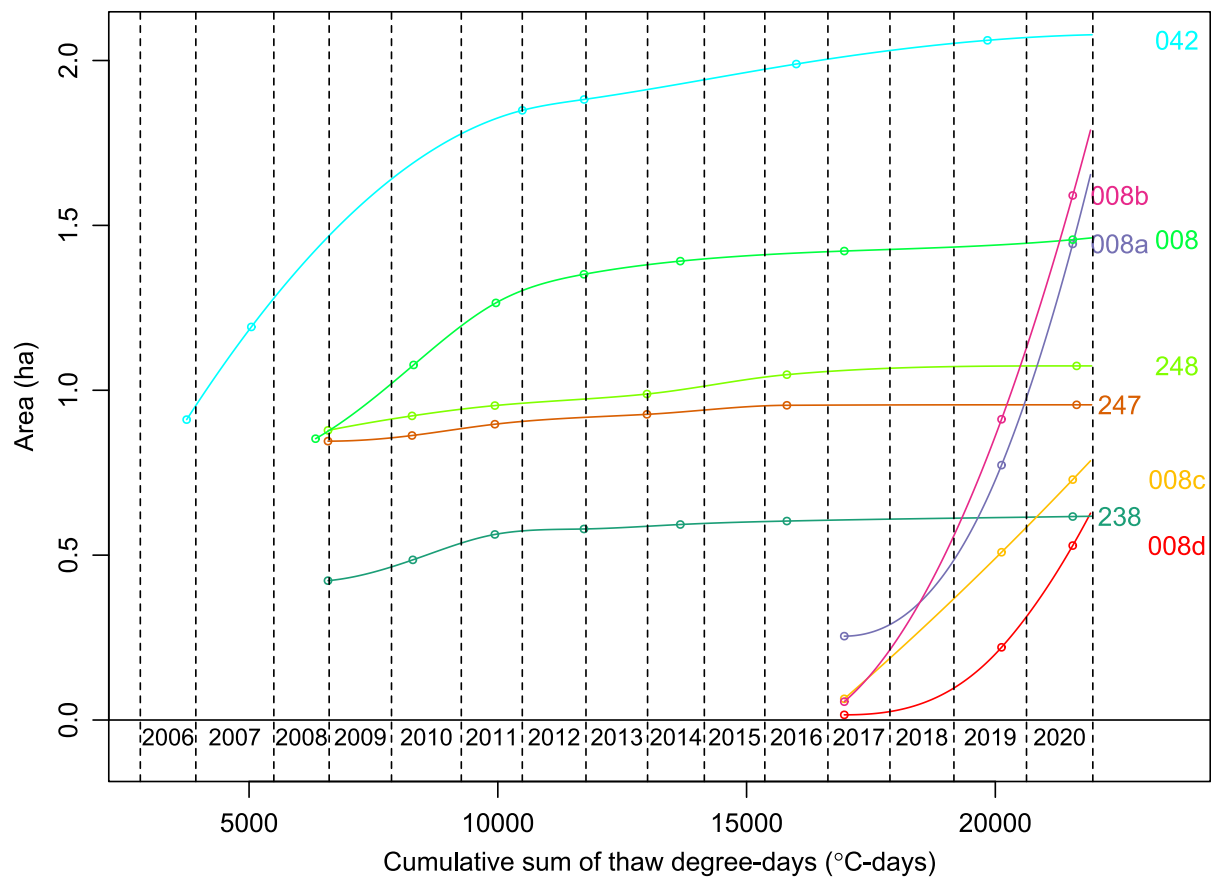


Figure 5. Growth in area of **small** slumps (final area 2 ha or less) vs. cumulative sum of thaw degree-days. The years represented by each range of TDD are given along the x-axis, and the color-coded slump identifiers are shown on the right.

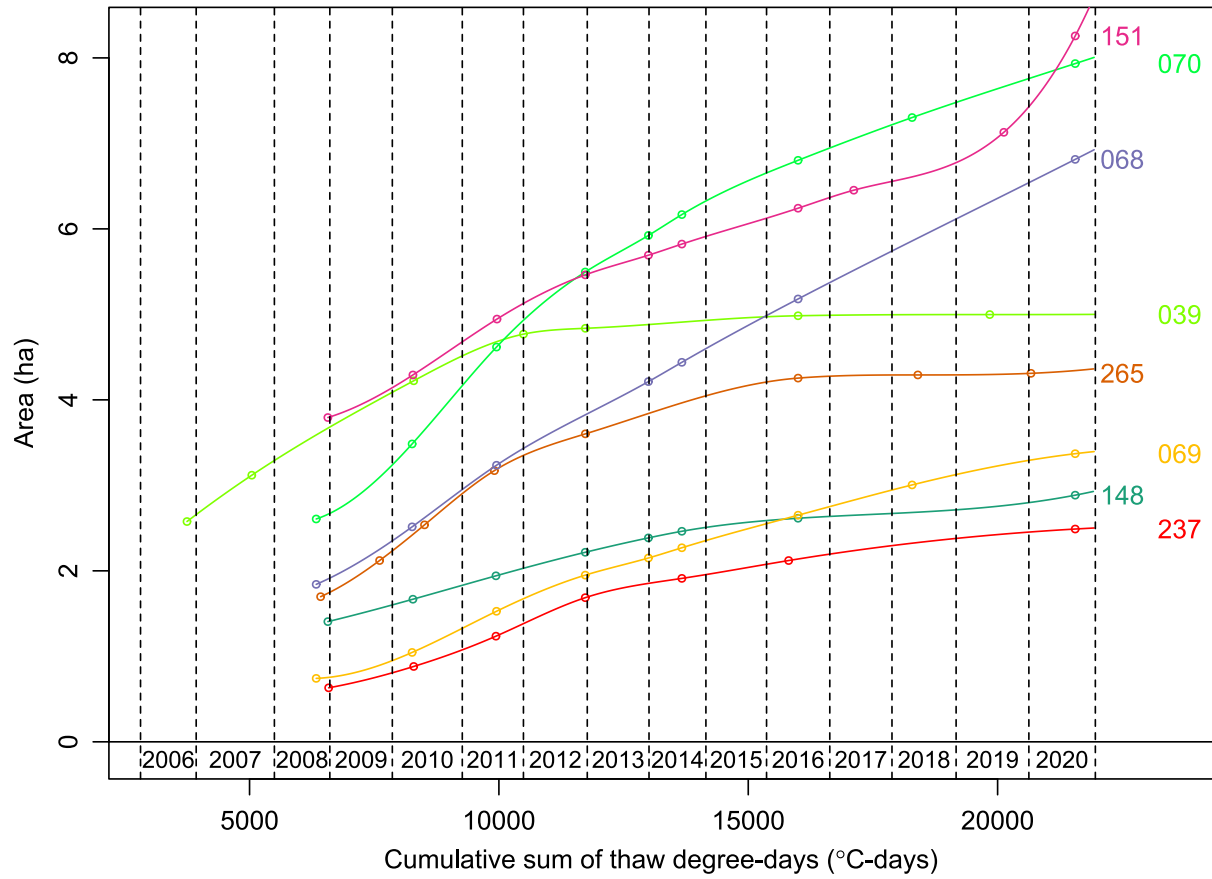


Figure 6. Growth in area of **large** slumps (final area more than 2 ha) vs. cumulative sum of thaw degree-days. The years represented by each range of TDD are given along the x-axis, and the color-coded slump identifiers are shown on the right.

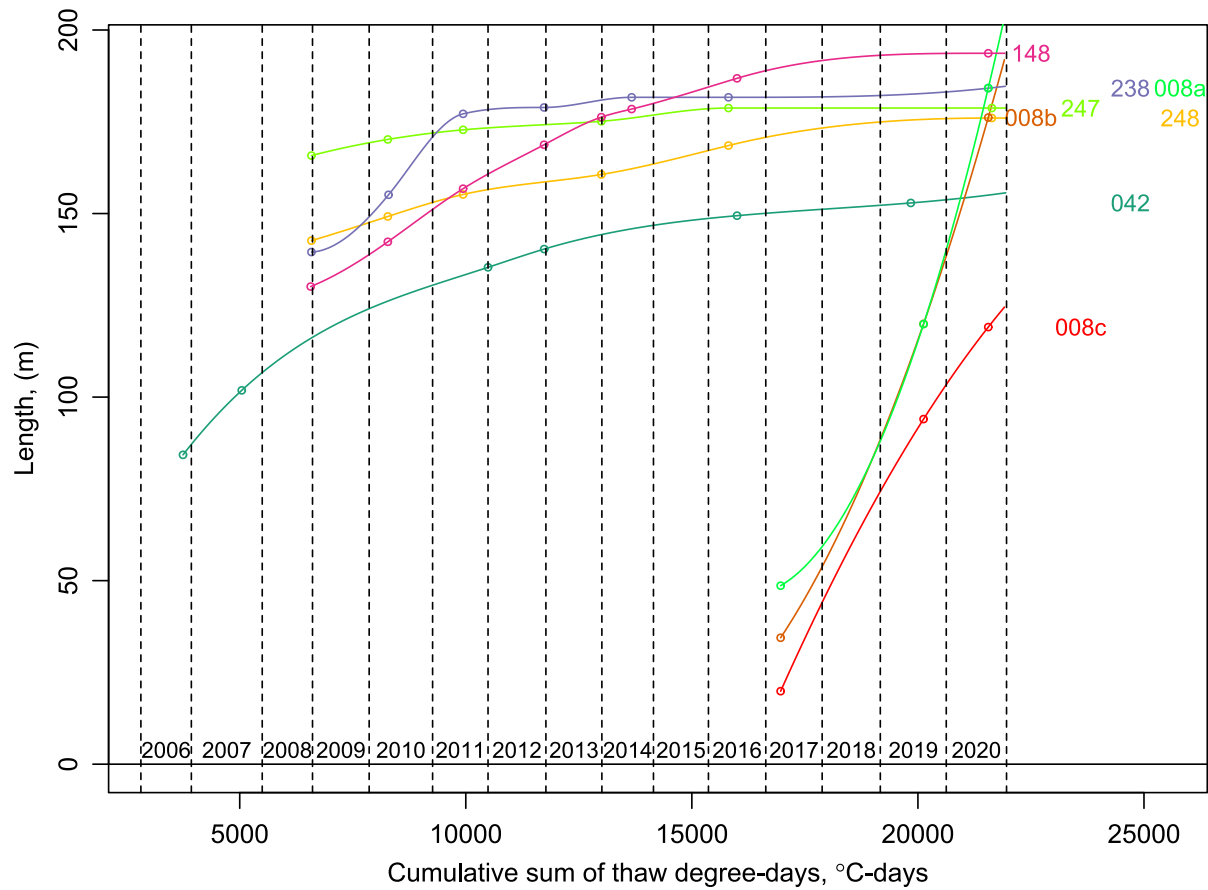


Figure 7. Growth in length along the centerline of **small** slumps (final length less than 200 m) vs. cumulative sum of thaw degree-days. The years represented by each range of TDD are given along the x-axis, and the color-coded slump identifiers are shown on the right.

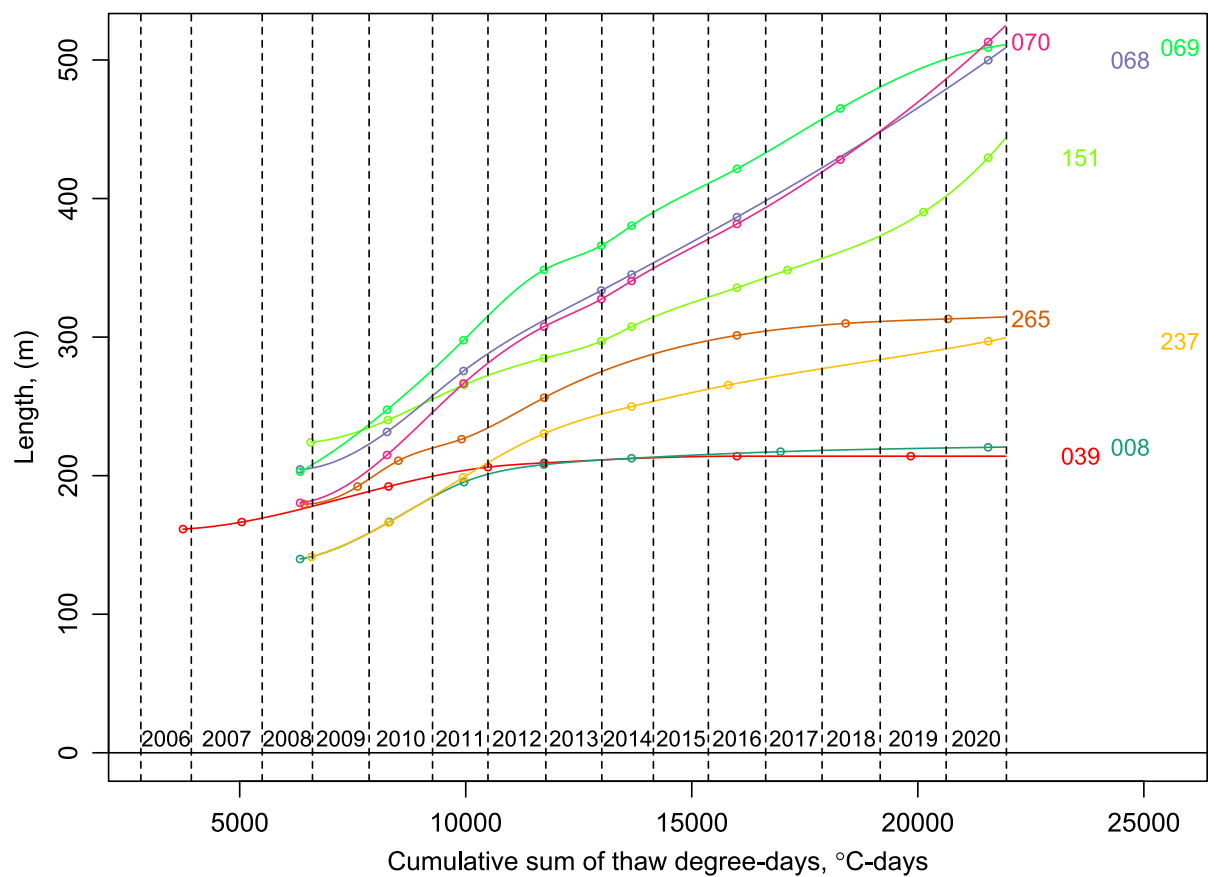


Figure 8. Growth in length along the centerline of **large** slumps (final length more than 200 m) vs. cumulative sum of thaw degree-days. The years represented by each range of TDD are given along the x-axis, and the color-coded slump identifiers are shown on the right.

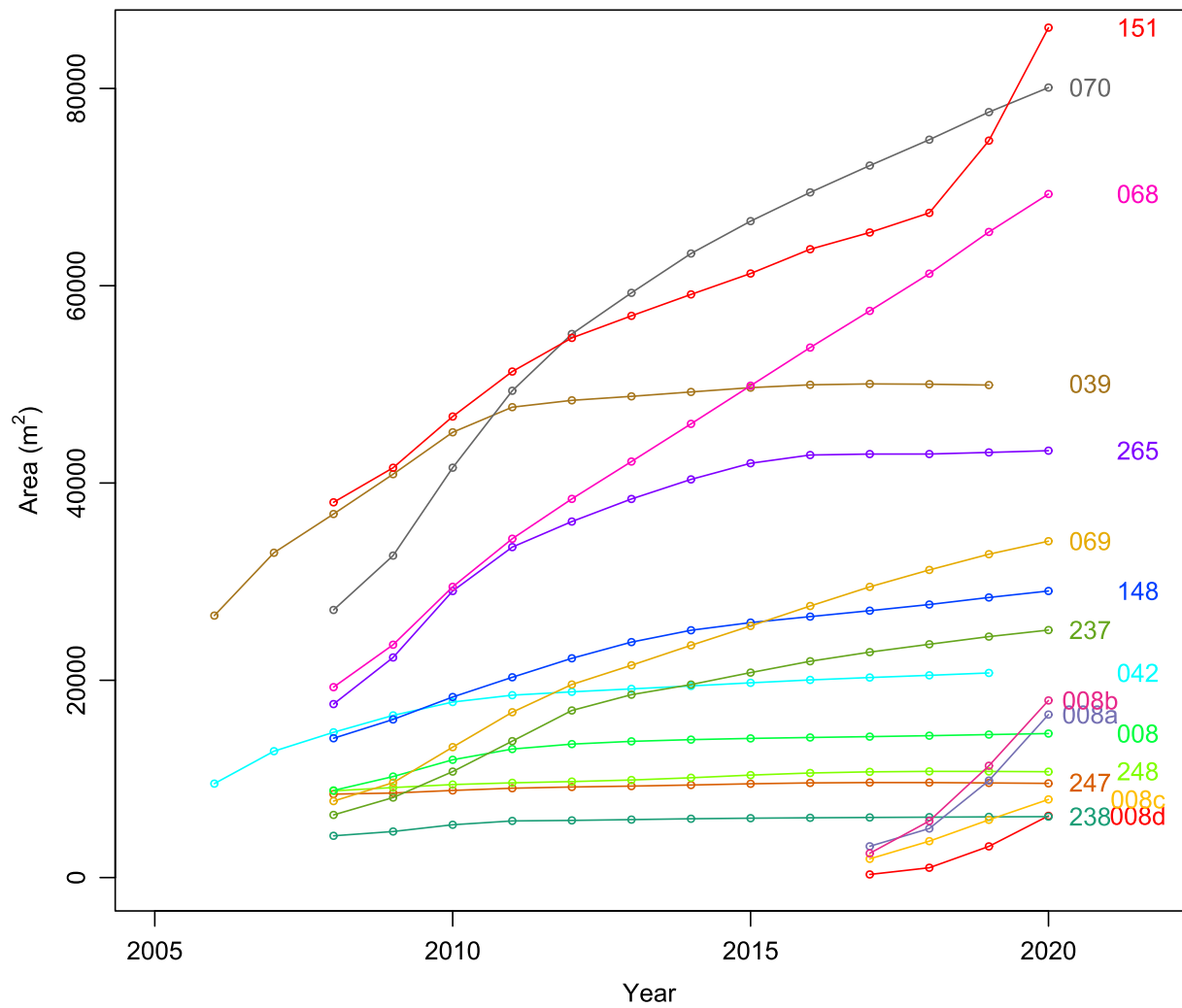


Figure 9. Growth in slump area by year. Dots represent areas estimated by interpolation (Figures 5 and 6) at the start of the indicated year.

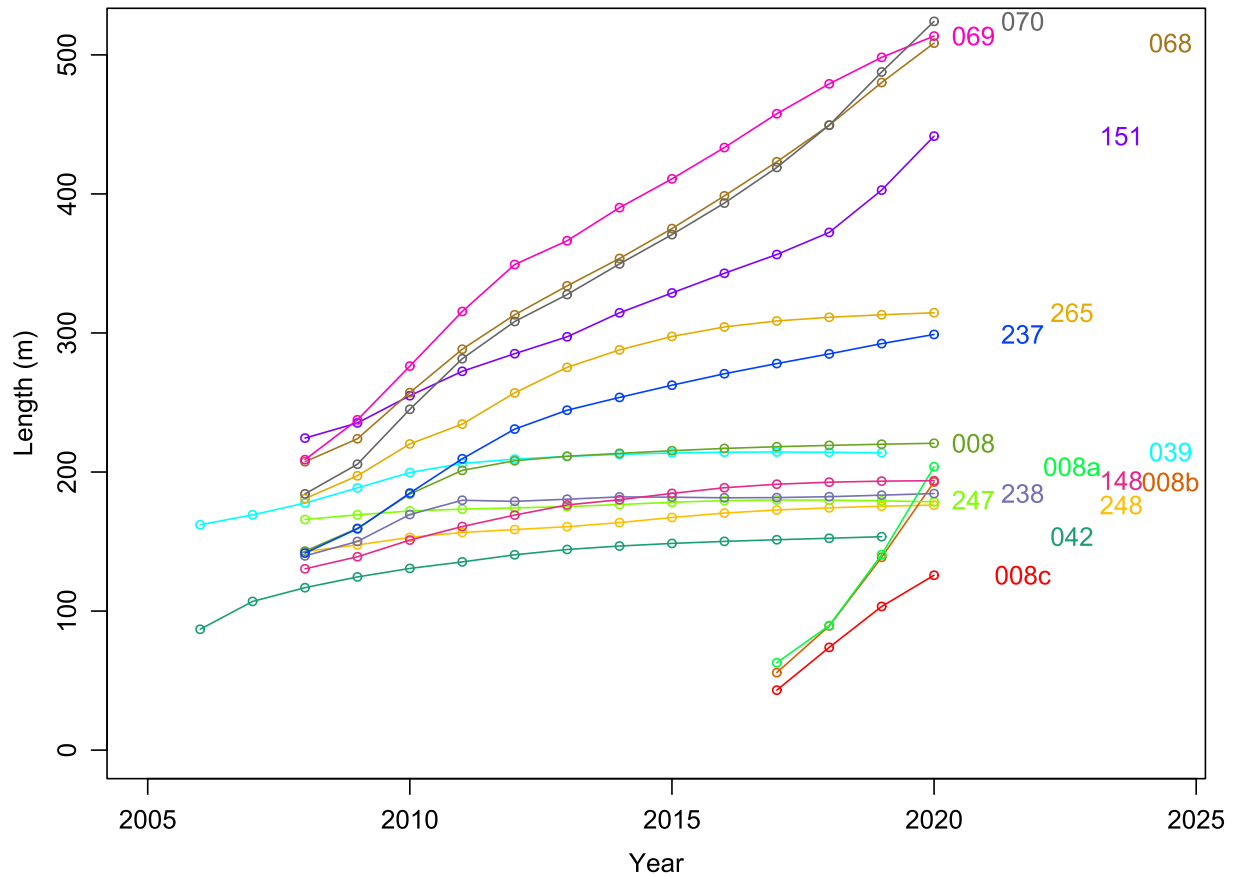


Figure 10. Growth in slump length along the centerline by year. Dots represent areas estimated by interpolation (Figures 7 and 8) at the start of the indicated year.

Table 2. Annual growth in the last year as expressed in change of the main scarp position on the centerline, and maximum elevation loss 2016–2020.

Slump ID	Last Sample Date (YYYYMMDD)	Last Annual Growth (m) ^A	Maximum Elevation Loss (m) ^B
gaar008	20200806	0.6	<0.5
gaar008a	20200806	58.9	11
gaar008b	20200806	51.2	8
gaar008c	20200806	22.4	7
noat039	20190707	0	ND
noat042	20190707	1.3	ND
noat068	20200806	28.8	2
noat069	20200806	12.4	2
noat070	20200806	36.5	2.5

^A Change in main scarp location between the last sample date and exactly one year previous; the latter position was estimated by interpolation (Figures 7 and 8).

^B Maximum DEM difference between the 2016 and 2020 DEMs; approximates the maximum scarp height.

Table 2 (continued). Annual growth in the last year as expressed in change of the main scarp position on the centerline, and maximum elevation loss 2016–2020.

Slump ID	Last Sample Date (YYYYMMDD)	Last Annual Growth (m) ^A	Maximum Elevation Loss (m) ^B
noat148	20200806	0.1	ND
noat151	20200806	36.3	7.5
noat237	20200806	7.4	2.5
noat238	20200806	1.3	1.5
noat247	20200813	0	ND
noat248	20200813	0.3	ND
noat265	20200518	1.8	ND

^A Change in main scarp location between the last sample date and exactly one year previous; the latter position was estimated by interpolation (Figures 7 and 8).

^B Maximum DEM difference between the 2016 and 2020 DEMs; approximates the maximum scarp height.

Slump Maps and Elevation Change

GAAR008

The original slump GAAR008 grew little after 2012 (Figure 11). Gray tones in Figure 11 on the slopes south and east of slump 008 (except sandbars of Douglas Creek itself) are older slumps that had not completely re-vegetated. Four new slumps (008a, b, c, and d) developed near Douglas Creek and were first visible on the image from 22 June 2017 (Figure 12). The amount of thaw that had occurred at that time appeared too great to have happened in that thaw season, and extrapolating the curves in Figure 7 to zero length suggested start dates in 2015 or 2016. There was no obvious sign of activity on the 27 July 2014 photographs. The new slumps grew very rapidly: in the year prior to our 2020 visit, slump 008a grew at an annual rate of 59 m yr⁻¹. The DEM difference between 2020 and 2014 (the pre-slump condition) in the vicinity of the main scarp on slump 008a was 8 to 10 m, indicating a scarp height of this height. The elevation drop on slump 008b was 6 to 8 m along much of its scarp, while on slump 008c it was 4 to 6 m. Elevation gains of as much as 7 m due to sediment accumulation occurred below the slumps, and as a result Douglas Creek was forced as much as 80 m west of where it had been prior to the slumping. Note that most of the apparent elevation gain upstream (north of) the slump was actually due to interference by vegetation, and not sedimentation.

The sum of pixels that lost elevation in GAAR008a, -b, and -c between 2014 and 2020, converted to volume using the pixel area, showed a loss of 137,425 m³ of material. A sum of pixels with elevation gain in the accumulation zone just below these three slumps showed a gain of 26,513 m³, much less than the loss from the slumps. The missing volume of about 110,000 m³ was lost to Douglas Creek, and consisted of both melted ice and sediment in an unknown proportion.

Approximate scarp locations digitized from Planet Labs scenes from 10 July 2022 and 12 August 2023 showed continued rapid growth, between 2020 and 2023 of about 30 m yr⁻¹ in GAAR008a, b, and d and 15 m yr⁻¹ in GAAR008c. Slump GAAR008a grew at similar rates within the footprint of the very recently stabilized slump GAAR008 and in undisturbed material north of it.

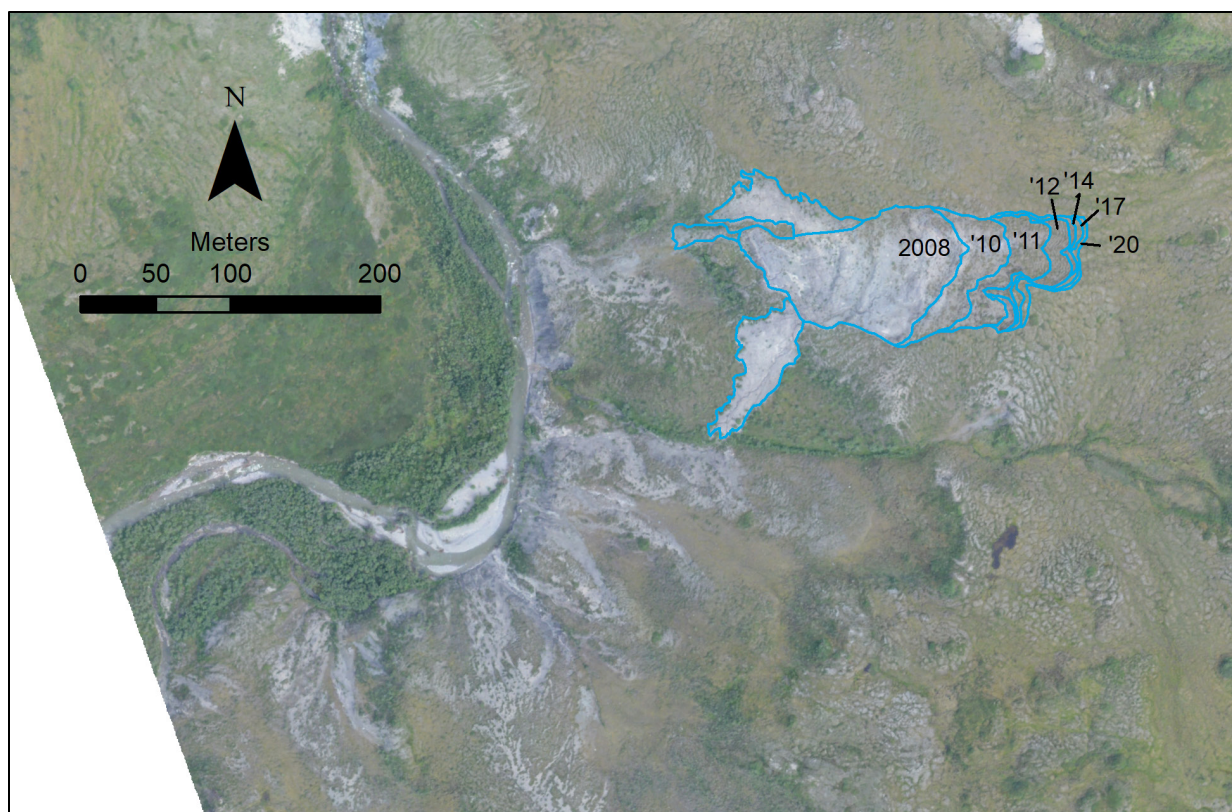


Figure 11. Outline of slump GAAR008 in the years 2008 through 2020. The background is an orthophotograph from 2014.

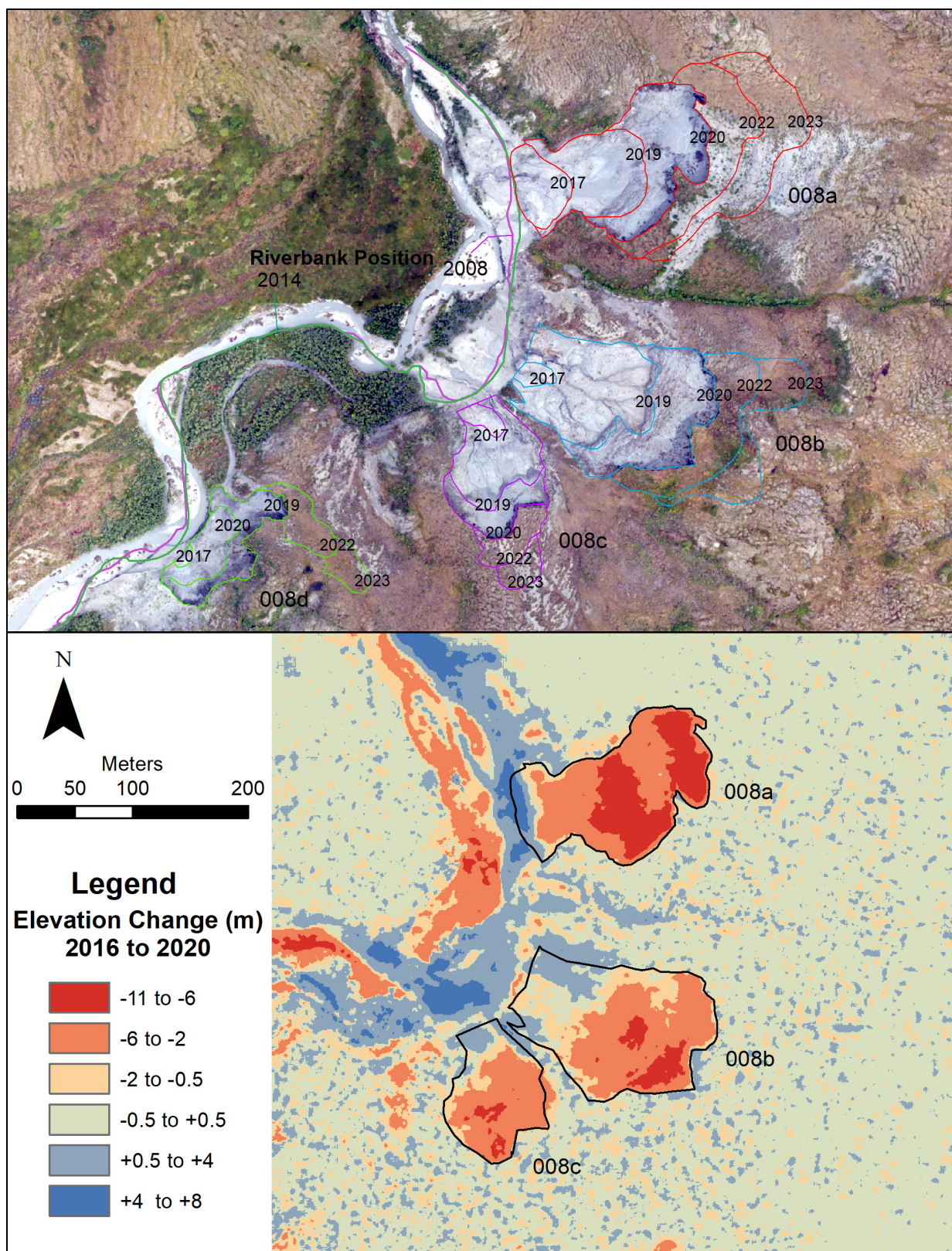


Figure 12. (Upper) Growth of slumps GAAR008a, b, c, and d, shown on a 2020 orthophoto; (Lower) elevation change of the slumps and vicinity between 2016 (prior to slump initiation) and 2020.

NOAT039

This large slump was once one of our largest and most active, with a main scarp about 10 m high in 2010. It has grown little since 2011 and we did not acquire new elevation data in 2020 (Figure 13). Most of the perimeter of the lake where NOAT039 occurs is lined by old slumps or steep banks that are probably actively thermokarsting. This slump began in the floor of a previous slump and has grown beyond it into undisturbed material. The slump floor appeared mostly covered by vegetation in 2019, though some persistent bare areas near the lake suggested some continued sediment movement.

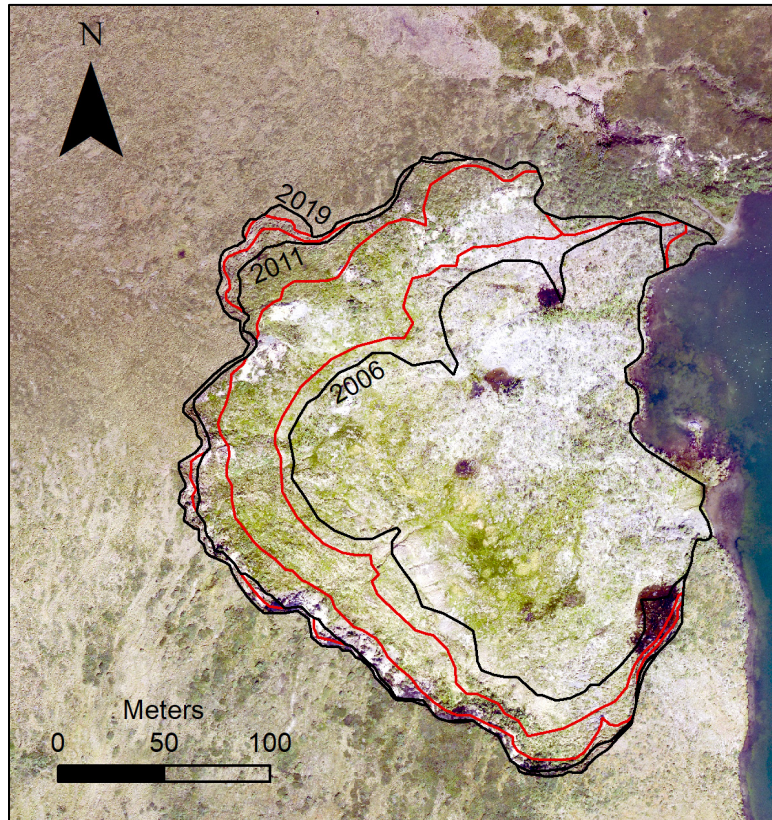


Figure 13. Growth of slump NOAT039 from 2006 to 2019, displayed over a 2016 orthophoto.

NOAT042

NOAT042 was active with a tall (nearly 10 m) main scarp in 2010 (Swanson and Hill 2010), but since 2011 it has grown little (Figure 14). The slump occurs on a lake shore, and over half of the lake's perimeter is lined by old, revegetated slumps. NOAT042 grew from the lakeshore across the floor of a previous slump (Swanson and Hill 2010) and has grown slightly beyond the outline of the previous slump into undisturbed material. The slump floor is currently mostly vegetated, but some bare ground in the northeast corner of the slump floor suggests some continuing sediment movement into the lake may occur.

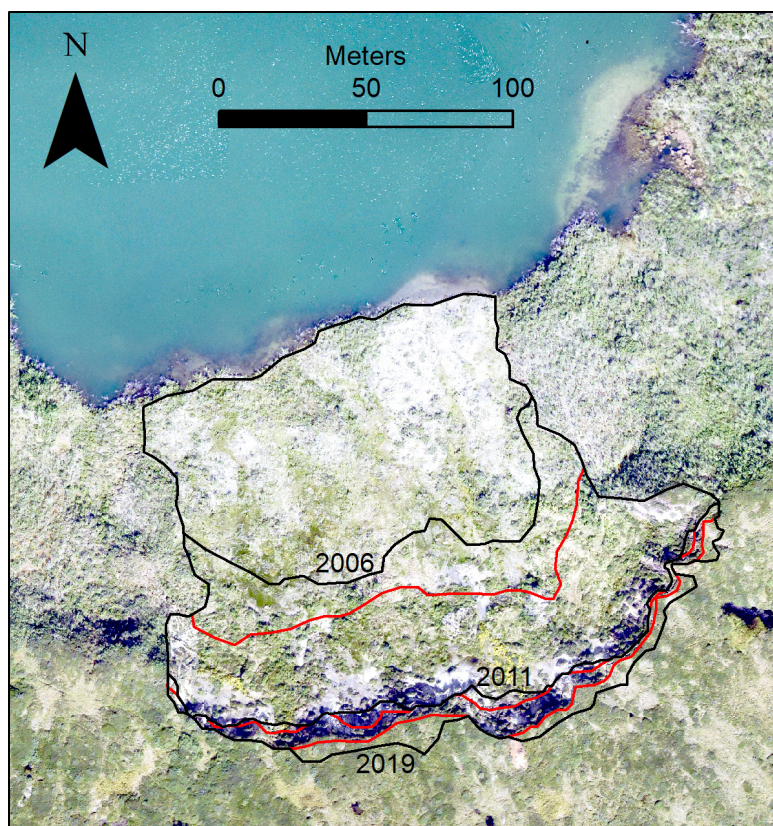


Figure 14. Growth of slump NOAT042, displayed over a 2016 orthophoto.

NOAT068 and NOAT069

These two slumps continued their rapid growth, with elevation losses of up to 2.5 m (Figure 15). Slump NOAT069 reached a bedrock knoll that has probably ended its growth. NOAT068 had grown uphill about as far as a previous slump that was parallel to it and active in the 1970s (see Figure 24 in Swanson 2014). Lower-resolution images from 2023 suggest that the growth of NOAT068 was still rapid but slowing, with 35 m of main scarp advance from Aug 2020 to Aug 2023 (Figure 15) as compared to 29 m of advance from Aug 2019 to Aug 2020 (Table 2).

An accumulation zone of sediment was clearly visible on both slumps as an elevation gain of up to 2 m just beyond (north of) the 2016 scarp positions. The small patches of apparent elevation gain visible at the top of the image along the creek were due mostly to shrub interference and not actual elevation gain. The lower ends of these slumps have been stable and gaining vegetation since about the year 2010.

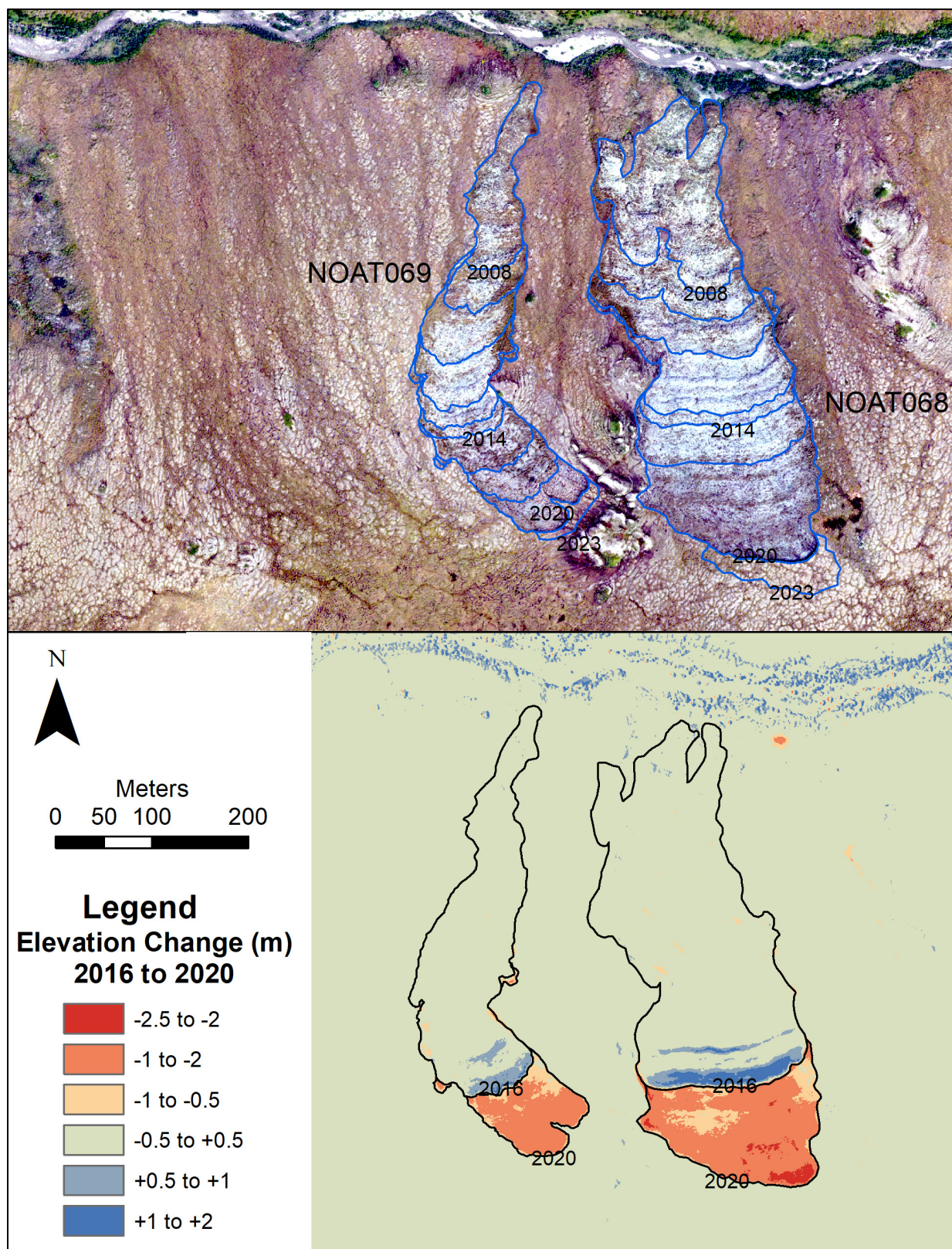


Figure 15. (Upper) Growth of slumps NOAT0068 and NOAT069, shown on a 2020 orthophoto; (Lower) elevation change of the slumps.

NOAT070

NOAT070 is located close to NOAT68 and NOAT069 and had similar characteristics: it grew rapidly and had an elevation loss of up to 2.5 m (Figure 16). Its narrowing footprint suggests a potential slowing of its rate of areal growth in the future. The main scarp migration of about 60 m from Aug 2020 to Aug 2023 (Figure 16) was still quite rapid, though somewhat slower than the 36.5 m observed in 2019–2020 (Table 2).

An accumulation zone of sediment was clearly visible as elevation gain of up to 2 m just beyond the 2016 scarp position. The small patches of apparent elevation gain visible to the left of the slump and along the creek were due mostly to shrub interference and not actual elevation gain. The fan in the lower portion of this slump has been stable and gaining vegetation since at least 2013. The brushy area below NOAT070 (darker green and to the left of the slump) is actually part of revegetated slump that was active in the 1970s (Swanson and Hill 2010). The current slump has advanced well into undisturbed territory above the previous slump.

NOAT148

NOAT148 continued to grow slowly by subsidence and extensional cracking (Figure 17). We have no recent DEM to determine how much subsidence occurred. The most interesting development in 2020 was the appearance of gullies along the main scarp, which made its outline much more irregular than in the past. We observed large Pleistocene ice wedges exposed in this slump (Swanson and Hill 2010), and these new gullies are almost certainly progressing by thermo-erosion along these ice wedges. The toe of this slump has been stable and gaining vegetation since our observations began in 2008.

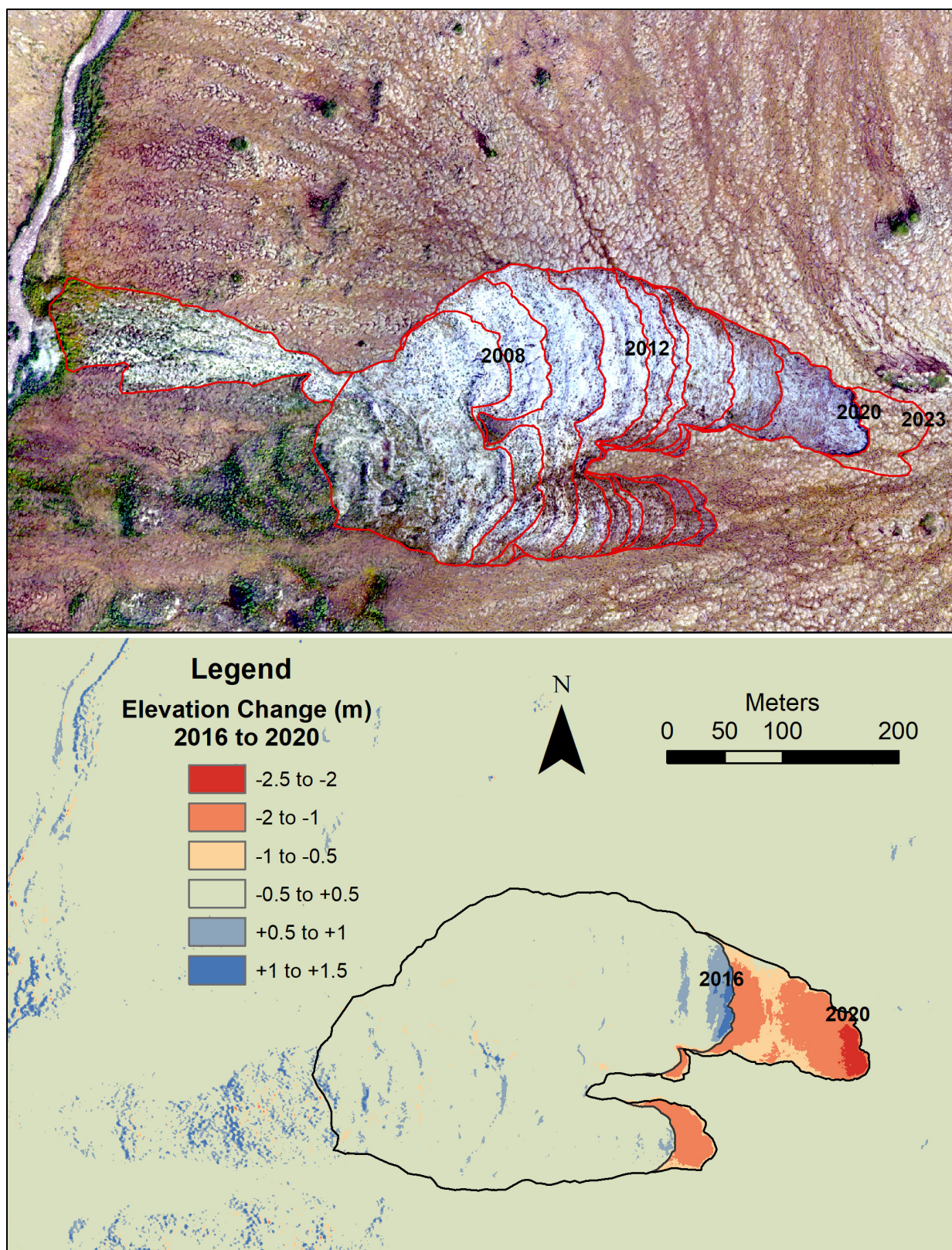


Figure 16. (Upper) Growth of slump NOAT070, shown on a 2020 orthophoto; (Lower) elevation change of the slump from 2016 to 2020.

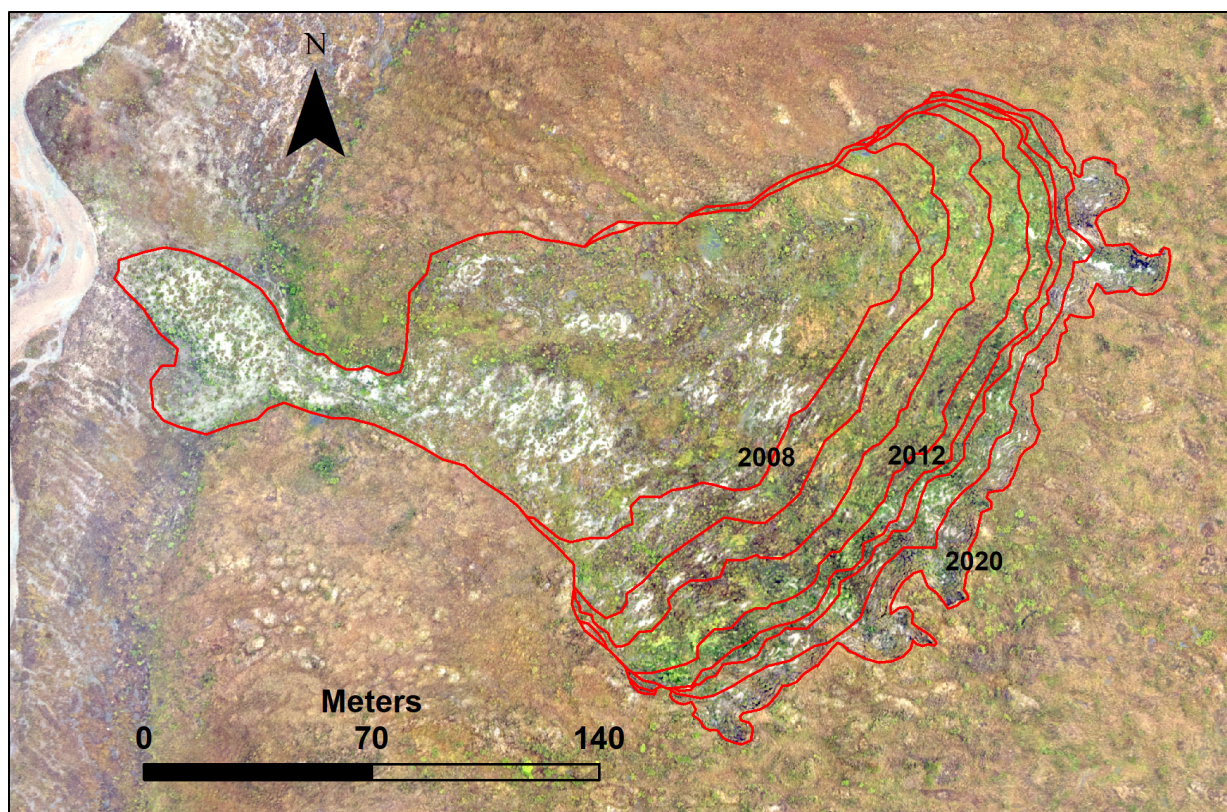


Figure 17. Growth of slump NOAT148, shown on a 2020 orthophoto.

NOAT151

NOAT151 continued to expand rapidly through 2020, with an elevation loss of 6 to 8 m and increasing rate of expansion that reached 36 m yr^{-1} between Aug 2019 and Aug 2020 (Figure 18, Table 2). The perimeter from September of 2023, based on lower resolution Planet images, revealed continued rapid growth of about 25 m yr^{-1} from 2020 to 2023. For comparison, the annual growth rate from 2008–2017 was about 14 m yr^{-1} , and the DEM difference between 2013 and 2016 was about 3 m. Elevation gain in the lower part of the slump indicates sediment accumulation there. The largest accumulation occurred in the southeastern corner of the slump, where material from the main scarp flowed along the southern edge of the slump and filled in a former closed depression. Elsewhere much of the elevation gain of +0.5 to +3 m occurred under a vegetated surface. The former pond at the northeastern end of the slump also drained or filled in with sediment. The main scarp continued to advance both in the floor of a slump that was active in the 1970s and in undisturbed material (see Swanson and Hill 2010, Figure 35). The previously disturbed area is located to the left of the active slump in Figure 18 and is bright green due to shrubs. The 8 Sept 2023 Planet Labs image showed that the main scarp was approximately coincident with the upper limit of the previous slump.

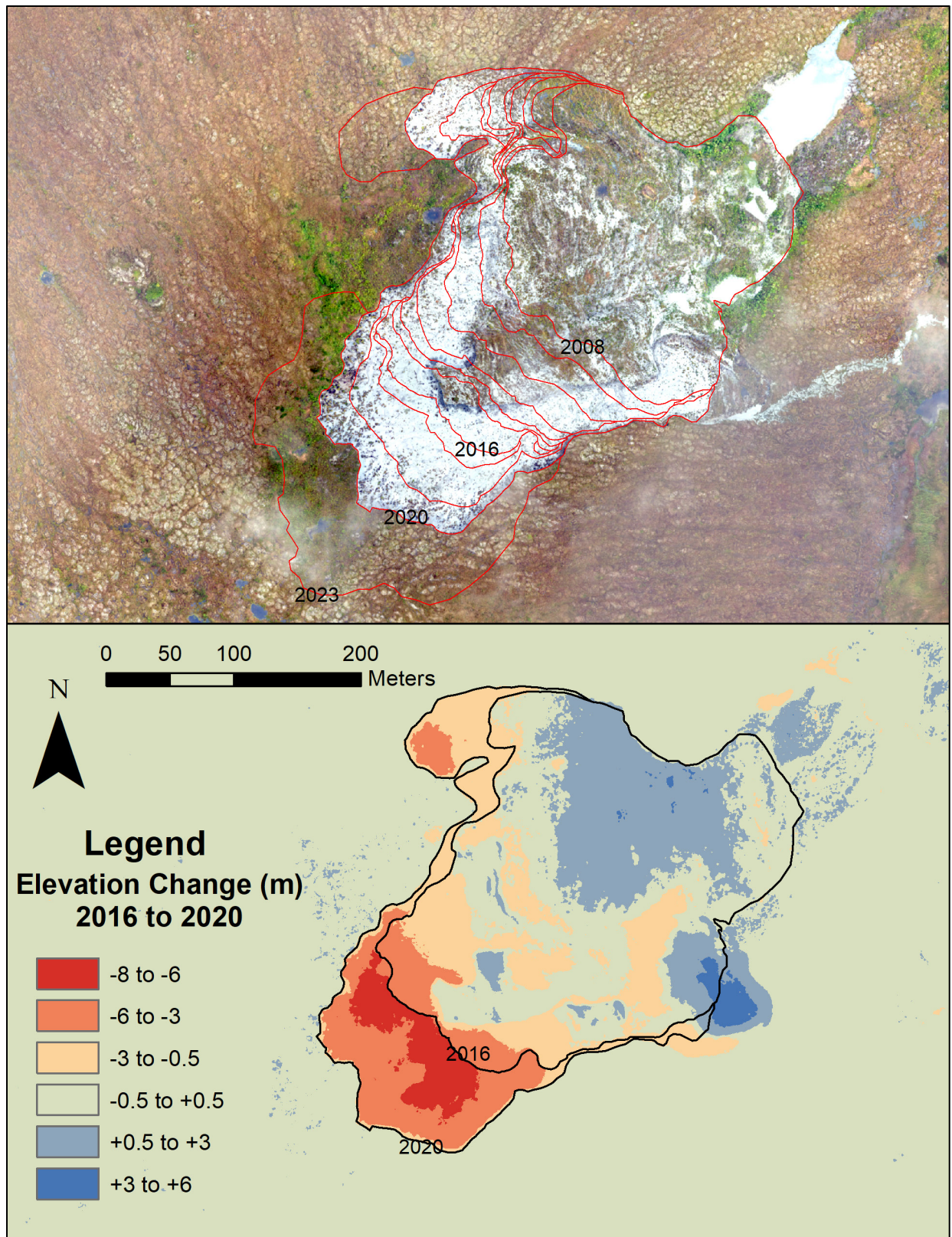


Figure 18. (Upper) Growth of slump NOAT151, with nearly annual perimeters from 2008 to 2023 shown over a 2020 orthophoto; (Lower) elevation change of the slump from 2016 to 2020.

NOAT237 and NOAT238

Slump NOAT237 continued its gradual growth and modest elevation loss of 1 to 2.5 m (Figure 19). There was little accumulation of material below the active area, indicating little transport of material. The smaller slump NOAT238 has grown very little in area or length since 2011, but the upper part of the slump floor continued to subside, 1 to 2 m from 2014 to 2020. This indicates continued substantial ground ice loss from the upper permafrost, in the absence of much material transport. The pre-2008 portions of both slumps are well vegetated and suggest little transport of sediment to the lake.

NOAT247 and NOAT248

These two slumps have grown slowly since our monitoring began in 2008 (Figure 20). They were very active immediately prior to that time, as shown by the relatively high and vertical scarp visible at our first ground visit in 2010, the extensive bare mud floor at that time (Swanson and Hill 2010), and their inferred rapid growth of 120 m (NOAT248) to 160 m (NOAT247) between their probable initiation in 2004 or 2005 (Swanson and Nolan 2018) and 2008. Since that time gradual growth has continued by the “extensional flow” mechanism (Swanson 2012). The entire slump floors are well vegetated now. We did not acquire new elevation data for these slumps in 2020.

NOAT265

This slump was once one of our most active slumps, with the tallest main scarp that we have observed, just over 20 m in 2011 (Swanson 2012) with an active debris fan in the Noatak River below. It has grown little since 2016, though most of the slump floor remains sparsely vegetated (Figure 21). We did not acquire new elevation data for this slump in 2020.

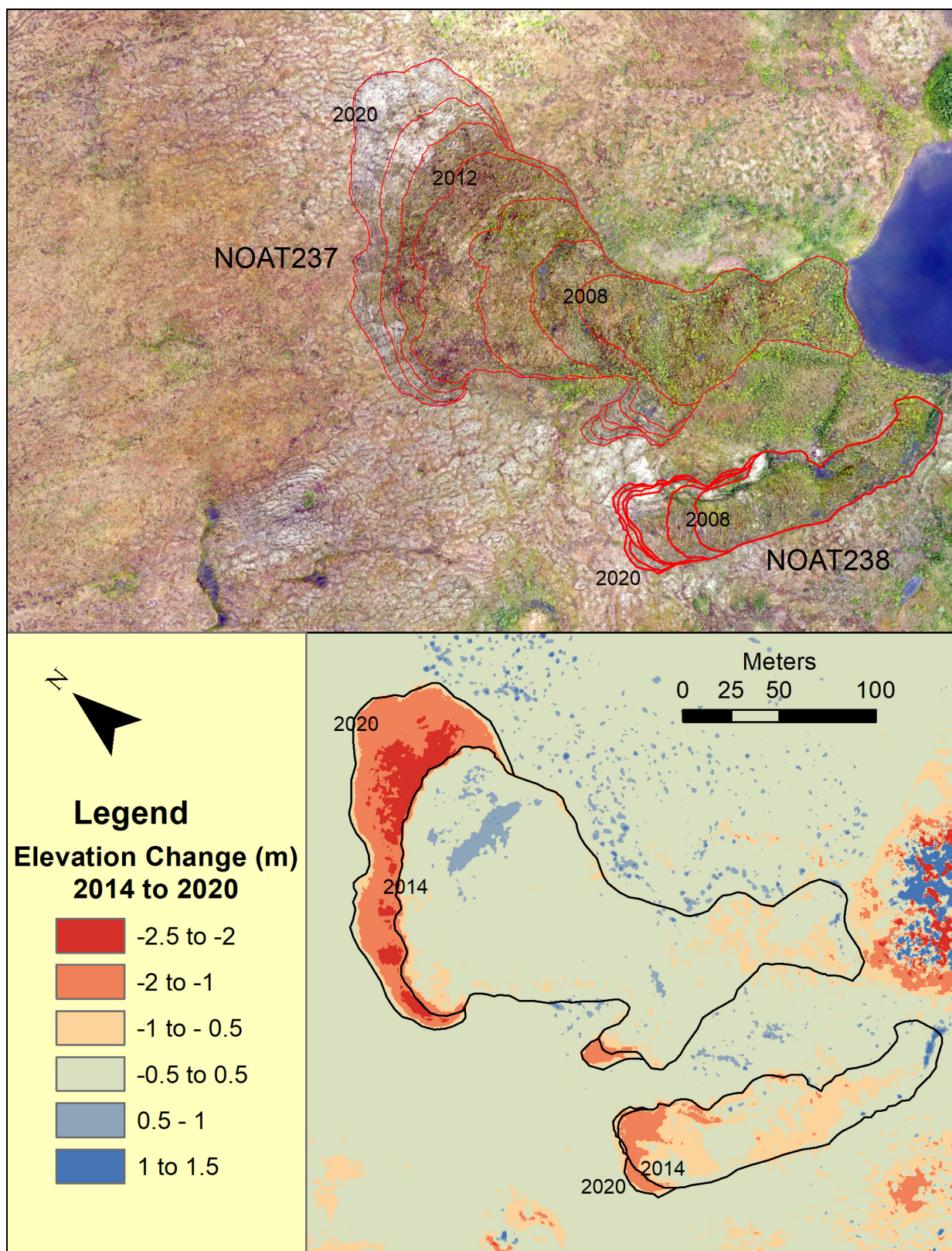


Figure 19. (Upper) Growth of slump NOAT237 and NOAT238, with nearly annual perimeters from 2008 to 2020 shown over a 2020 orthophoto; (Lower) elevation change of the slump from 2014 to 2020.

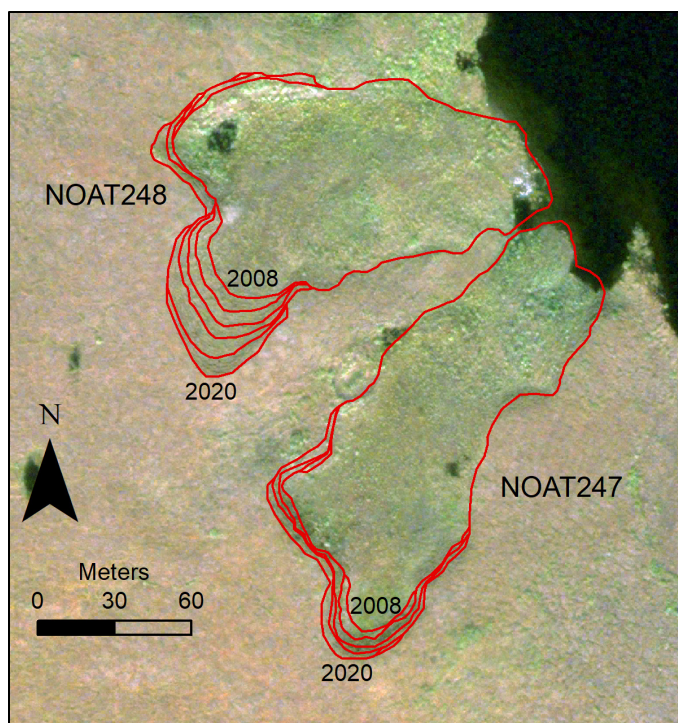


Figure 20. Growth of slumps NOAT247 and NOAT 248, displayed over a satellite image from 13 August 2020.

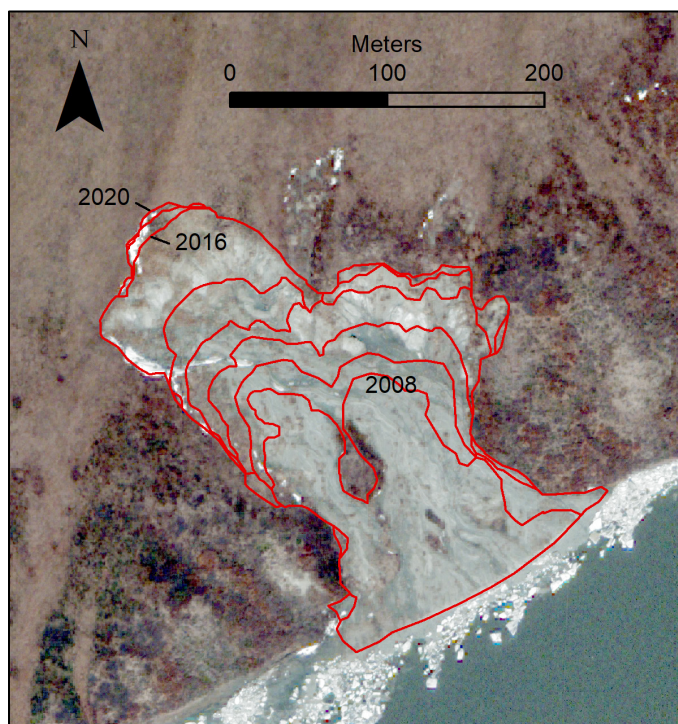


Figure 21. Growth of slump NOAT265. Slump perimeters are displayed over a satellite image from 20 May 2020. The Noatak River with ice floes is visible at the bottom right.

Discussion

Continuation of previous growth trends at most locations

The uniform growth of slumps relative to accumulated TDD confirms the usefulness of TDD as an index of energy available for permafrost thaw and slump growth. In uniform materials, slumps should grow steadily in relation to accumulating TDD. Declining growth relative to TDD over time suggests geologic conditions for slumping became less favorable as the scarp moved uphill; possible causes include declining slope (Swanson and Nolan 2018), less ground ice, or thicker overburden as the scarp moved uphill.

The growth rate in terms of area or length vs. TDD of most of our slumps was fairly constant (negligible in some cases), or gradually declining since 2012, and slower than it was prior to 2012. The one slump that showed accelerating growth over time relative to TDD (NOAT151) must have encountered more favorable geologic conditions in recent years, and though we don't know exactly what they were; it is probably connected to the increase in main scarp height from about 3 m in 2016 to over 6 m in 2020.

Record warm mean annual temperatures occurred during the period 2014–2019 over much of Alaska, especially northwestern Alaska (Figure 4; Swanson et al. 2021). Under a warming climate, we would expect slump growth per year to generally increase (except where deteriorating geologic conditions inhibit growth). However, we did not observe generally higher slump growth rates vs. year during the period 2014 to 2020. Two possible reasons for this are: 1) summer warmth during 2014–2020 was not significantly greater than the preceding period, from slump initiation in 2004–05 to 2014. Our best information about this is the annual sum of TDD at Noatak RAWS, which varied greatly but without an obvious upward trend from 2004 to 2020 (Figure 3). The overall warming of MAAT was thus driven mainly by warming of the cold-season, not the summer, which controls the sum of TDD and slump growth. 2) The energy balance at the main scarp was not strongly influenced by permafrost temperature. If winters are warming, the near-surface permafrost will generally be warmer, and intuitively one might think that it would be easier to thaw at the main scarp of an RTS. However, the energy demand of thawing permafrost is dominated by the latent heat of fusion of water (the energy needed to thaw ice: 333 J g^{-1}) and not the specific heat of ice (the energy needed to warm ice up to the thawing point, which is just $2 \text{ J g}^{-1} \text{ }^{\circ}\text{C}^{-1}$; Harvey 2016). As long as the winters remain cold enough to re-freeze the active layer, then slump growth rates will be limited mainly by thaw-season warmth and the latent heat of fusion of water and not the antecedent temperature of the permafrost.

While trends in annual TDD since 2004 in the study area have been weak and this has contributed to steady or declining RTS activity, this has not been the case everywhere or over the longer term. The annual sum of TDD at Kotzebue has clearly increased since records began in the 1940s (Figure 2), and RTS activity has probably increased as a result. Also, anomalously warm years such as 2004 can have long-term effects (Swanson 2021).

Implications of Recent Warming

While the annual sum of TDD in the study area has shown weak trends since 2004, increases in MAAT continue, with important implications for stability of the disturbed ground on slump floors. The MAAT at Noatak RAWS averaged about -8°C from 1996–2013, rising to about -6°C in 2014–2015, -5.0°C in 2018, and -4.1 2019 (Figure 4; data are missing after 2019). Based on temperature monitoring of an RTS in the Yukon Territory by Burn (2000), MAATs of -4°C to -5°C could represent a critical threshold for permafrost stability on the floors of RTS. Burn’s study area had a MAAT of -4.1°C and -4.2 in two years of study, i.e., similar to our warmest year at Noatak RAWS. In Burn’s study area, this resulted in mean annual ground temperatures at 1 m depth of -2.4°C in an undisturbed area, and about $+1.5^{\circ}\text{C}$ at multiple locations on the slump floor, where permafrost was degrading. Our study area could have somewhat colder ground temperatures relative to the MAAT due to thinner snow cover in the tundra of the Noatak Valley (vs. the boreal forest of Burn’s study area), but the implications are still clear: if the MAAT stays below -6°C , then permafrost will reform in the newly deposited sediment on the slump floor once it is thick enough, and stabilize any remaining ice beneath, even in the absence of vegetation. But if the MAAT rises above -5°C , then permafrost is likely to continue to degrade on the slump floor. As our polycyclic slump behavior shows, a thick layer of ice (e.g., glacial ice) can persist even after passage of a RTS scarp across the surface. Under historic cold conditions, once a sufficient thickness of sediment (probably several meters) had accumulated over the ice to accommodate annual freeze-thaw, permafrost would reform below and degradation of the buried ice would cease. Under conditions where the MAAT is warmer than -5°C , permafrost could continue to degrade on the slump floor for decades until vegetation is re-established (Burn and Friele 1989). Where glacial ice is present, this could result in continuing subsidence and instability on the slump floor for many years.

Renewed activity at GAAR008

The initiation of four new RTS along Douglas Creek near GAAR008 in 2015 or 2016 appears to have been a localized event. Our survey of the RTS-rich region of the eastern Noatak Valley area (Swanson 2021, study area 2) actually recorded a decline in number and area of RTS in 2019 relative to an earlier survey in 2008. The current study and our informal inspection of 2023 images by Planet Labs (2023) also did not encounter new slumps in the study area. This presents the interesting question of what was unique about Douglas Creek that caused such extraordinary activity. This location has buried Pleistocene glacial ice (Swanson and Hill 2010), which means that substantial thickness of nearly pure ice may be present and thus the landscape is particularly susceptible to repeated thaw slump activity (Segal et al 2016, Kokelj et al. 2017). Slopes with incomplete vegetation cover as a result of previous slumping were present adjacent to Douglas Creek. The lack of vegetation cover made them both susceptible to erosion and to deep thaw. The convex outer bank (i.e., eroding bank) of two distinct bends in Douglas Creek were located at the foot of fairly steep, nearly unvegetated slopes. Comparison of the river locations in 2008 and 2014 suggested continuing gradual outward migration of the channel toward the slump-susceptible areas (Figure 12), which could have exposed glacial ice and initiated the new round of slumping.

While gradual erosion may have been responsible for triggering the slumps, the fact that four slumps were all triggered in 2015 or 2016 suggests a possible unique erosion event on Douglas Creek during

those years. Summer precipitation data are available for 2013–2019 from the NPS Howard Pass climate monitoring station (Sousanes and Hill 2020), which is 30 km northwest of GAAR008 and at 628 m elevation, about the same elevation as the GAAR008; the watershed of Douglas Creek ranges upward from that point to 1290 m. Although summer precipitation is spatially variable, the 2015–2016 summer rainfall data at Howard Pass do not suggest unusual monthly totals relative to other years (Figure 22). Besides summer precipitation, snowmelt runoff has the potential to cause flooding and erosion. The only climate station that measures snow in the Noatak Valley is the Kelly Snotel, about 240 km west of GAAR008 and at lower elevation (94 m). It registered average snowfall in 2014–15 and missing data in 2015–16 (USDA-NRCS NWCC 2023). The Bettles Snotel (240 km east-southeast of GAAR008) registered slightly below average snowfall for 2015 and 2016. National Weather Service data from Kotzebue (near sea level 285 km west of GAAR008 at 195 m elevation) had below average snowfall in 2014–2015 and near-average snowfall in 2015–2016. Thus available snowfall data do not suggest exceptional amounts of stored water in the snowpack during the years when the new slumps were initiated.

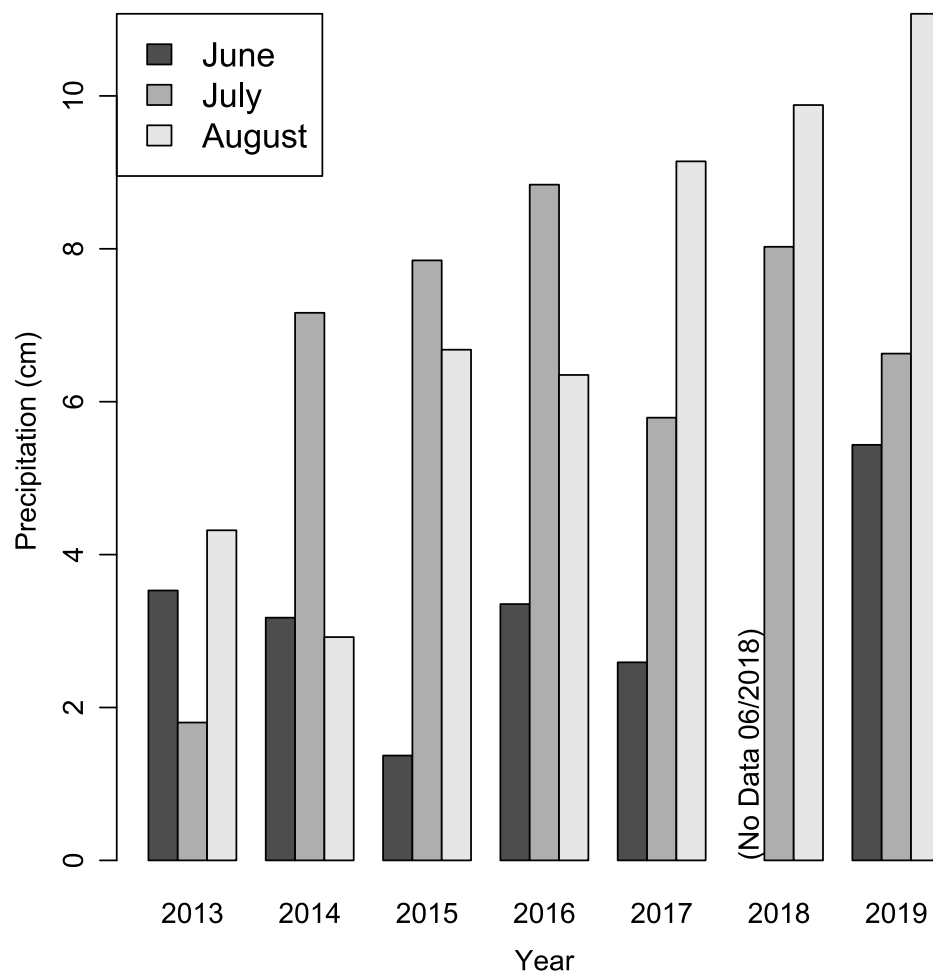


Figure 22. Summer precipitation at Howard Pass climate monitoring station, 2013–2019.

The most unusual climatic event in 2015–2016 was probably the very early warm weather in May of 2015 (Figure 23). Daily mean temperatures over 5°C began on May 12 (day 132) and persisted for over two weeks, such that by May 30 (day 150), 166 TDD had accumulated. This TDD sum is more than adequate to melt all but deep snowdrifts in this area (Swanson 2021, Figure 11). In a typical year, as illustrated by the median curve in Figure 23, above-freezing temperatures first arrive in early May (as they did in 2015), but TDD accumulate very gradually through the rest of May and early June. By May 30 of a median year, only 70 TDD has accumulated (less than half of the 2015 total at this time), meaning that snowmelt typically takes much longer than it did in 2015, allowing much more gradual runoff. Note that the other recent rapid spring warming years occurred in 2019 and 2020, i.e., after the slump re-initiation at GAAR008, when an erosive spring runoff event would have enhanced removal of slumped material from the toe of the slump and contributed to its continued growth.

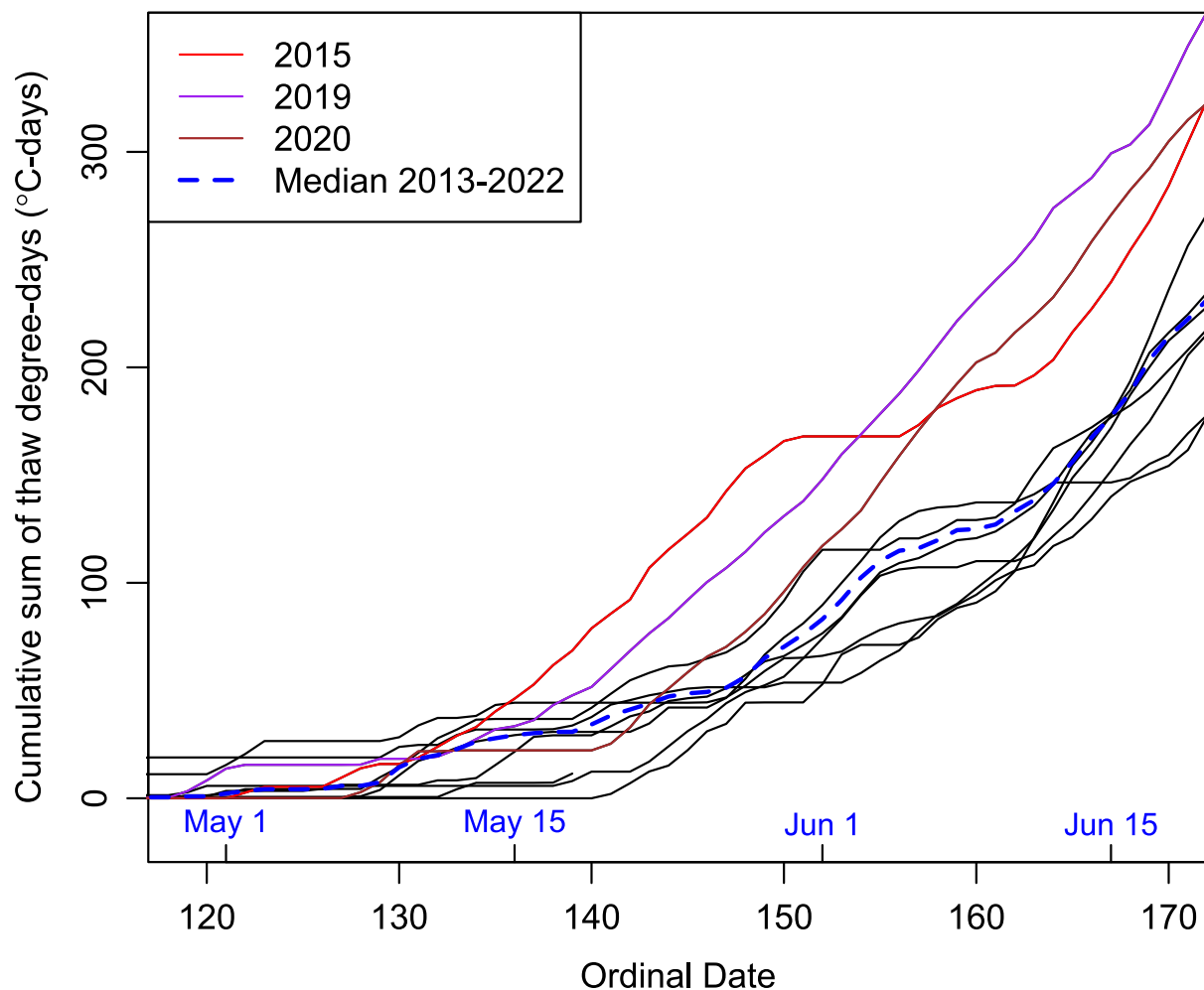


Figure 23. Cumulative sum of thaw degree-days at Howard Pass climate monitoring station for the springs of 2013–2022.

Implications for water quality

Active RTS can shed large amounts of sediments into nearby water bodies (Kokelj et al. 2005, Bowden et al. 2008). Our study RTS are conveniently placed into 3 broad groups according to their implications for water quality.

- 1) Slumps with little or no new growth. These are slumps with recent annual rates of main scarp advance of less than 2 m per year (GAAR008, NOAT039, NOAT042, NOAT148, NOAT238, NOAT247, NOAT248, NOAT265). Where the main scarp is still advancing it is by the “extensional flow” mechanism (Figure 2 in Swanson 2012) without exposed ice in the main scarp. The floors of these slumps are stable and gaining vegetation. Vegetation cover is incomplete and surface organic layer on the soil is mostly absent, so some erosion by running water is still possible. Where these slumps are immediately adjacent to a water body, some sediment delivery to the water body is still probably occurring, though at greatly reduced rates compared to when the slumps were active.
- 2) Active slumps with a deposition zone far from any water body. These are slumps with relatively rapid rates of main scarp advance that have been active for over 10 years. The main scarp is now hundreds of meters from the water body at the foot of the slump (NOAT068, NOAT069, NOAT070, NOAT151, NOAT237). In these slumps, ice is exposed at the head scarp and a zone of liquified mud is present that flows downhill from the scarp vicinity; but the liquified mud de-waters, solidifies, and accumulates on the slump floor far from the water body (see Figure 4 in Swanson 2012,). A band of sediment accumulation is visible on the slump floor, far from the water body at the foot of the slump and separated from it by a stable zone that is gaining vegetation. The potential for water quality impacts here are similar to the preceding group: the slump floor near the water body is stable and gaining vegetation, but since there is still exposed bare soil it is possible that some erosion of sediment into the adjacent water body is still occurring, though at greatly reduced rates compared to early stages in the slumps’ growth when liquified mud was flowing directly into the water body.
- 3) Newly active slumps adjacent to a water body. This group includes only GAAR008a, b, c, and d. These slumps became active in 2015 immediately adjacent to Douglas Creek. They grew rapidly and lost large amounts of material that was deposited directly in the channel of Douglas Creek. Our estimate was that over 100,000 m³ of material, consisting of both melted ice and sediment, was transported away by Douglas Creek. Sediment accumulation there caused the channel to shift as much as 80 m to the west. Douglas Creek is not listed as an anadromous stream by the Alaska Department of Fish and Game (ADFG 2023), though due to data gaps in this remote region, this does not preclude the possibility that salmon or other fish were impacted by this sediment pulse.

Conclusions

- 1) Most of the retrogressive thaw slumps in the upper Noatak River valley that had ceased to grow or were growing very slowly at the time of our last sample in 2016 remained stable or very slow-growing during the period 2016 to 2020.
- 2) Most of the slumps that were active in 2016 continued growing at a rather uniform pace in relation to accumulated thaw degree-days through 2020. This is what would be expected in geologically uniform materials. One slump (NOAT151) clearly increased its rate of growth and showed an increase in main scarp height after 2016.
- 3) The rate of slump growth per year was rather steady over our last sampling interval (2016–2020), in spite of generally warming temperatures since 2014. The sum of thaw degree-days has not clearly increased over recent decades in the study area, because most of the overall warming has been due to warming of the cold season. As a consequence, slump growth per year has not increased markedly in concert with overall climate warming.
- 4) The resistance of slopes in the study area to increased slumping in the face of overall warming probably depends on the fact that our climate has been cold enough for active layers to freeze back entirely and permafrost to re-form in unvegetated slump floors and thereby stabilize them. Our historical mean annual air temperatures of about -8°C have recently approached -4°C , which the literature suggests is a threshold beyond which permafrost may not re-form in unvegetated slump floors, leading to continued subsidence and instability.
- 5) Four new slumps were initiated at Douglas Creek, a tributary of the Noatak River. This area had historical slump activity and a 2005-era slump that stabilized. The new slumps grew rapidly beginning in 2015–2016, shedding large amounts of sediment and meltwater into the creek. This was apparently an isolated event triggered by migration and erosion of the creek into ice-rich material.

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Appendix A: Supplemental Data Tables

Table A1. Locations and sample years of the study slumps.

Slump ID	Visit Date ^A	Image Type	Image Author ^B	Georeferencing
gaar008	20080809	satellite_image	IKONOS	satellite
gaar008	20100625	oblique_photo	D. Swanson	survey
gaar008	20110720	oblique_photo	D. Swanson	survey
gaar008	20120910	oblique_photo	D. Swanson	image tie-points
gaar008	20140727	vertical_photo	M. Nolan	aerial_gps
gaar008	20170622	satellite_image	WV2	satellite
gaar008	20190724	satellite_image	WV2	satellite
gaar008	20200806	vertical_photo	NPS_SfM	aerial_gps
gaar008	20220710	satellite_image	Planetscope	satellite
gaar008	20230812	satellite_image	Planetscope	satellite
noat039	20060901	vertical_photo	T. George	image tie-points
noat039	20070808	satellite_image	IKONOS	satellite
noat039	20100624	oblique_photo	D. Swanson	survey
noat039	20110925	vertical_photo	M. Nolan	image tie-points
noat039	20120911	oblique_photo	D. Swanson	image tie-points
noat039	20160711	vertical_photo	M. Nolan	aerial_gps
noat039	20190707	satellite_image	WV2	satellite
noat042	20060901	vertical_photo	T. George	image tie-points
noat042	20070808	satellite_image	IKONOS	satellite
noat042	20100624	oblique_photo	D. Swanson	survey
noat042	20110925	vertical_photo	M. Nolan	image tie-points
noat042	20120911	oblique_photo	D. Swanson	image tie-points
noat042	20160711	vertical_photo	M. Nolan	aerial_gps
noat042	20190707	satellite_image	WV2	satellite
noat068	20080809	satellite_image	IKONOS	satellite
noat068	20100622	oblique_photo	D. Swanson	survey
noat068	20110719	oblique_photo	D. Swanson	image tie-points
noat068	20120910	oblique_photo	D. Swanson	image tie-points
noat068	20130916	vertical_photo	M. Nolan	aerial_gps
noat068	20140727	vertical_photo	M. Nolan	aerial_gps
noat068	20160711	vertical_photo	M. Nolan	aerial_gps

^A Date format is YYYYMMDD.

^B The “Authors” GEO1, IKONOS, WV2, WV3 refer to high-resolution satellite images by Satellite Imaging Corporation (2023); NPS_SfM is photos taken by the NPS aerial photography team from the Alaska Regional Office; Planetscope is satellite images by Planet Labs (2021).

Table A1 (continued). Locations and sample years of the study slumps.

Slump ID	Visit Date ^A	Image Type	Image Author ^B	Georeferencing
noat068	20180628	satellite_image	GE01	satellite
noat068	20200806	vertical_photo	NPS_SfM	aerial_gps
noat068	20200812	satellite_image	Planetscope	satellite
noat069	20080809	satellite_image	IKONOS	satellite
noat069	20100622	oblique_photo	D. Swanson	survey
noat069	20110719	oblique_photo	D. Swanson	image tie-points
noat069	20120910	oblique_photo	D. Swanson	image tie-points
noat069	20130916	vertical_photo	M. Nolan	aerial_gps
noat069	20140727	vertical_photo	M. Nolan	aerial_gps
noat069	20160711	vertical_photo	M. Nolan	aerial_gps
noat069	20180628	satellite_image	GE01	satellite
noat069	20200806	vertical_photo	NPS_SfM	aerial_gps
noat069	20200812	satellite_image	Planetscope	satellite
noat070	20080809	satellite_image	IKONOS	satellite
noat070	20100622	oblique_photo	D. Swanson	survey
noat070	20110719	oblique_photo	D. Swanson	image tie-points
noat070	20120910	oblique_photo	D. Swanson	image tie-points
noat070	20130916	vertical_photo	M. Nolan	aerial_gps
noat070	20140727	vertical_photo	M. Nolan	aerial_gps
noat070	20160711	vertical_photo	M. Nolan	aerial_gps
noat070	20180628	satellite_image	GE01	satellite
noat070	20200806	vertical_photo	NPS_SfM	aerial_gps
noat070	20200812	satellite_image	Planetscope	satellite
noat148	20080906	satellite_image	IKONOS	satellite
noat148	20100623	oblique_photo	D. Swanson	survey
noat148	20110718	oblique_photo	D. Swanson	image tie-points
noat148	20120910	oblique_photo	D. Swanson	image tie-points
noat148	20130916	vertical_photo	M. Nolan	aerial_gps
noat148	20140727	vertical_photo	M. Nolan	aerial_gps
noat148	20160711	vertical_photo	M. Nolan	aerial_gps
noat148	20200806	vertical_photo	NPS_SfM	aerial_gps
noat151	20080906	satellite_image	IKONOS	satellite
noat151	20100623	oblique_photo	D. Swanson	survey
noat151	20110720	oblique_photo	D. Swanson	survey

^A Date format is YYYYMMDD.^B The “Authors” GEO1, IKONOS, WV2, WV3 refer to high-resolution satellite images by Satellite Imaging Corporation (2023); NPS_SfM is photos taken by the NPS aerial photography team from the Alaska Regional Office; Planetscope is satellite images by Planet Labs (2021).

Table A1 (continued). Locations and sample years of the study slumps.

Slump ID	Visit Date ^A	Image Type	Image Author ^B	Georeferencing
noat151	20120910	oblique_photo	D. Swanson	image tie-points
noat151	20130916	vertical_photo	M. Nolan	aerial_gps
noat151	20140727	vertical_photo	M. Nolan	aerial_gps
noat151	20160711	vertical_photo	M. Nolan	aerial_gps
noat151	20170703	satellite_image	WV2	satellite
noat151	20190724	satellite_image	WV2	satellite
noat151	20200806	vertical_photo	NPS_SfM	aerial_gps
noat151	20230908	satellite_image	PlanetScope	satellite
noat237	20080914	satellite_image	IKONOS	satellite
noat237	20100624	oblique_photo	D. Swanson	image tie-points
noat237	20110718	oblique_photo	D. Swanson	survey
noat237	20120910	oblique_photo	D. Swanson	image tie-points
noat237	20140727	vertical_photo	M. Nolan	aerial_gps
noat237	20160627	satellite_image	WV2	satellite
noat237	20200806	vertical_photo	NPS_SfM	aerial_gps
noat238	20080914	satellite_image	IKONOS	satellite
noat238	20100624	oblique_photo	D. Swanson	image tie-points
noat238	20110718	oblique_photo	D. Swanson	survey
noat238	20120910	oblique_photo	D. Swanson	image tie-points
noat238	20140727	vertical_photo	M. Nolan	aerial_gps
noat238	20160627	satellite_image	WV2	satellite
noat238	20200806	vertical_photo	NPS_SfM	aerial_gps
noat247	20080914	satellite_image	IKONOS	satellite
noat247	20100623	oblique_photo	D. Swanson	survey
noat247	20110718	oblique_photo	D. Swanson	image tie-points
noat247	20130916	vertical_photo	M. Nolan	aerial_gps
noat247	20160627	satellite_image	WV2	satellite
noat247	20200813	satellite_image	WV3	satellite
noat248	20080914	satellite_image	IKONOS	satellite
noat248	20100623	oblique_photo	D. Swanson	survey
noat248	20110718	oblique_photo	D. Swanson	image tie-points
noat248	20130916	vertical_photo	M. Nolan	aerial_gps
noat248	20160627	satellite_image	WV2	satellite
noat248	20200813	satellite_image	WV3	satellite

^A Date format is YYYYMMDD.

^B The “Authors” GEO1, IKONOS, WV2, WV3 refer to high-resolution satellite images by Satellite Imaging Corporation (2023); NPS_SfM is photos taken by the NPS aerial photography team from the Alaska Regional Office; PlanetScope is satellite images by Planet Labs (2021).

Table A1 (continued). Locations and sample years of the study slumps.

Slump ID	Visit Date ^A	Image Type	Image Author ^B	Georeferencing
noat265	20080705	satellite_image	IKONOS	satellite
noat265	20080819	vertical_photo	George	image tie-points
noat265	20110715	oblique_photo	D. Swanson	survey
noat265	20120911	oblique_photo	D. Swanson	image tie-points
noat265	20160711	vertical_photo	M. Nolan	aerial_gps
noat265	20180706	satellite_image	WV3	satellite
noat265	20200518	satellite_image	WV3	satellite

^A Date format is YYYYMMDD.

^B The “Authors” GEO1, IKONOS, WV2, WV3 refer to high-resolution satellite images by Satellite Imaging Corporation (2023); NPS_SfM is photos taken by the NPS aerial photography team from the Alaska Regional Office; Planetscope is satellite images by Planet Labs (2021).

Table A2. Days of Missing Data by Year and Month at the Noatak RAWs.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
1990	31	28	31	22	0	0	0	0	0	0	6	4	122
1991	30	28	31	30	31	30	31	31	12	17	26	9	306
1992	12	4	3	0	0	0	0	0	0	0	0	0	19
1993	5	5	4	2	0	0	2	0	0	0	3	5	26
1994	18	28	31	30	31	4	0	0	0	4	9	31	186
1995	31	28	31	30	17	0	0	0	0	0	0	2	139
1996	3	3	0	0	0	0	0	0	0	2	2	4	14
1997	8	0	0	0	0	0	0	0	2	0	4	0	14
1998	2	2	0	0	0	0	0	0	0	0	2	2	8
1999	2	2	0	0	0	0	0	0	0	1	0	16	21
2000	31	29	31	30	17	0	0	0	0	0	2	2	142
2001	0	0	0	0	0	0	0	0	0	2	15	14	31
2002	19	17	11	13	14	0	0	0	0	0	14	16	104
2003	26	25	26	30	31	29	0	0	0	2	9	2	180
2004	0	0	0	8	31	8	1	0	0	2	0	25	75
2005	31	16	0	0	0	0	0	0	0	0	2	13	62
2006	31	2	0	0	0	0	0	0	2	0	6	7	48
2007	6	4	0	0	0	0	0	0	0	4	9	10	33
2008	2	7	4	0	0	0	0	0	0	0	0	0	13
2009	4	9	3	0	0	0	0	0	0	0	0	0	16
2010	0	2	0	0	0	0	0	0	0	0	0	4	6
2011	6	6	0	0	0	0	0	0	0	0	2	2	16
2012	1	4	1	0	0	0	0	0	0	0	4	3	13

Table A2 (continued). Days of Missing Data by Year and Month at the Noatak RAWs.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
2013	0	0	0	0	0	0	0	0	0	0	0	6	6
2014	0	0	0	0	0	0	0	0	0	0	4	2	6
2015	4	2	4	0	0	0	0	0	0	2	18	31	61
2016	30	23	0	2	20	30	31	11	0	0	0	8	155
2017	4	0	4	0	0	0	0	0	0	2	2	0	12
2018	2	2	4	0	12	10	0	0	0	0	2	6	38
2019	2	4	0	0	0	0	0	0	2	31	30	31	100
2020	31	29	31	30	14	1	31	4	0	15	30	31	247
2021	31	28	31	30	31	30	31	31	30	31	30	31	365
2022	31	28	31	30	31	30	31	31	30	31	30	31	365
2023	31	28	31	30	31	30	31	31	30	31	30	31	365

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 189/192779, February 2024

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1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525