Recent warming reverses forty-year decline in catastrophic lake drainage and hastens gradual lake drainage across northern Alaska

Mark J Lara, Yaping Chen and Benjamin M Jones

1 Department of Plant Biology, University of Illinois, Urbana, IL 61801, United States of America
2 Department of Geography, University of Illinois, Urbana, IL 61801, United States of America
3 Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, AK 99701, United States of America

* Author to whom any correspondence should be addressed.
E-mail: mjara@illinois.edu

Keywords: lake drainage, climate change, Arctic, permafrost, talik, thermokarst

Abstract

Lakes represent as much as ∼25% of the total land surface area in lowland permafrost regions. Though decreasing lake area has become a widespread phenomenon in permafrost regions, our ability to forecast future patterns of lake drainage spanning gradients of space and time remain limited. Here, we modeled the drivers of gradual (steady declining lake area) and catastrophic (temporally abrupt decrease in lake area) lake drainage using 45 years of Landsat observations (i.e. 1975–2019) across 32 690 lakes spanning climate and environmental gradients across northern Alaska. We mapped lake area using supervised support vector machine classifiers and object based image analyses using five-year Landsat image composites spanning 388 968 km². Drivers of lake drainage were determined with boosted regression tree models, using both static (e.g. lake morphology, proximity to drainage gradient) and dynamic predictor variables (e.g. temperature, precipitation, wildfire). Over the past 45 years, gradual drainage decreased lake area between 10% and 16%, but rates varied over time as the 1990s recorded the highest rates of gradual lake area losses associated with warm periods. Interestingly, the number of catastrophically drained lakes progressively decreased at a rate of ∼37% decade⁻¹ from 1975–1979 (102–273 lakes draining year⁻¹) to 2010–2014 (3–8 lakes draining year⁻¹). However this 40 year negative trend was reversed during the most recent time-period (2015–2019), with observations of catastrophic drainage among the highest on record (i.e. 100–250 lakes draining year⁻¹), the majority of which occurred in northwestern Alaska. Gradual drainage processes were driven by lake morphology, summer air and lake temperature, snow cover, active layer depth, and the thermokarst lake settlement index ($R^2_{adj} = 0.42$, CV = 0.35, $p < 0.0001$), whereas, catastrophic drainage was driven by the thawing season length, total precipitation, permafrost thickness, and lake temperature ($R^2_{adj} = 0.75$, CV = 0.67, $p < 0.0001$). Models forecast a continued decline in lake area across northern Alaska by 15%–21% by 2050. However these estimates are conservative, as the anticipated amplitude of future climate change were well-beyond historical variability and thus insufficient to forecast abrupt ‘catastrophic’ drainage processes. Results highlight the urgency to understand the potential ecological responses and feedbacks linked with ongoing Arctic landscape reorganization.

1. Introduction

Lakes are widespread across northern latitudes (Smith et al 2007, Grosse et al 2013). These often shallow water bodies initially formed during warm periods of the Pleistocene-Holocene transition, as the ground surface subsided with the thawing of ice-rich permafrost and melting of buried glacial ice (Rampton 1988, Walter et al 2007). Although such permafrost degradation processes have been
responsible for their creation, the same processes have been implicated in their destruction (Nitze et al. 2020, Jones et al. 2020a, Lara and Chipman 2021). Although lake drainage is a natural process (Billings and Peterson 1980, Mackay 1988, Hinkel et al. 2003, Yoshikawa and Hinzman 2003, Marsh et al. 2009), anthropogenic climate change has recently triggered widespread patterns of lake drainage across Arctic and subarctic permafrost regions (Carroll and Loboda 2017, Nitze et al. 2018, 2020, Veremeeva et al. 2021).

Though there is a general consensus that the trajectory of northern lake area is decreasing, spatial and temporal patterns of lake area change have been highly dynamic (i.e. increasing, decreasing, or stable). For example, lake area has been relatively stable on the Arctic Coastal Plain of northern Alaska, decreasing <1% since 1985 (Hinkel et al. 2007, Jones et al. 2009, 2020a), similar to observations on the Tuktoyaktuk Coastlands in northwestern Canada (Plug et al. 2008, Marsh et al. 2009). In the Old Crow Flats of the northern Yukon Territories, lake area increased 1.6% between 1951–1972 and decreased 5% between 1972–2001 (Labrecque et al. 2009), with drainage further intensifying through 2010 (Lantz and Turner 2015). In addition, lake area decreased across Canada between 2000 and 2009, but rates of lake area loss were greatest at high-latitudes (Carroll et al. 2011). In western Siberia, lakes decreased 11% between 1978 and 1998 (Smith et al. 2005), while others reported no change (Karlsson et al. 2013). Lake area declined by 7% between 1972 and 2015 in the Kotzebue Sound Lowlands of northwestern Alaska (Lindgren et al. 2021), in line with the 15% decline reported between 1950 and 2007 in the northern Seward Peninsula (Jones et al. 2011). However, recent observations of lake drainage in northwestern Alaska have been ten times higher than historical drainage rates (Swanson 2019, Nitze et al. 2020). Understanding the underlying causes, mechanisms, and drivers of such spatiotemporal patterns and variability in lake dynamics is key to anticipating the consequences of future landscape evolution.

Temporal patterns of lake change are hypothesized to regionally vary with gradients in climate, topography, surficial geology, landscape history, permafrost conditions, and associated interactions. For example, lake drainage has been linked to extreme precipitation events, which can elevate lake water levels, increasing lateral ice-wedge degradation (Mackay 1988, Marsh et al. 2009, Jones et al. 2020a). Whereas high snowfall events can create ice dams, promote drainage channel formation (Jones and Arp 2015), and subsequent outburst floods (Arp et al. 2020a). Warmer winter air temperatures have also been shown to increase the likelihood of gully formation (Jones et al. 2020a), while thinning lake ice promotes the growth of permafrost penetrating taliks (Sardu et al. 2014, Arp et al. 2016). Widespread talik growth has also been implicated in the recent anomalous lake drainage activity in northwestern Alaska (Swanson 2019, Nitze et al. 2020), potentially triggered by a combination of warmer winter temperatures and higher than normal snowfall. In addition, local topographic variability can influence drainage pathways as thermokarst lakes gradually expand towards these drainage gradients (Jones et al. 2011). Quaternary history is also a strong determinant of lake drainage, as it is relatively common phenomenon in lakes developed in ice-rich yedoma permafrost but rare in lakes developed in ice-poor permafrost terrains (Larsen et al. 2017, Swanson 2019, Lara and Chipman 2021). Due to the array of complex climate-geophysical interactions that influence patterns of lake drainage across permafrost and glacial environments, our ability to forecast future lake change and associated carbon and energy dynamics has been severely limited.

Here we advance knowledge of the spatial and temporal drivers of both gradual and catastrophic lake drainage in northern and northwestern Alaska. We follow lake drainage terminology as defined by Grosse et al. (2013), where gradual drainage is the progressive decrease in lake area over time as a result of evaporation, deepening of thaw bulb, gully formation, or talik formation. Catastrophic drainage is defined as the rapid lake drainage within several days to weeks as a result of external (i.e. thermal or mechanical erosion of the permafrost via coastal erosion, river tapping, lake overflow) or internal factors (i.e. thermal erosion of lake banks or talik formation). We analyze the spatiotemporal patterns of 32690 high-latitude lakes between 1975 and 2019, determine the drivers of change, and forecast lake drainage through 2050. We use supervised support vector machine (SVM) classifiers in eight seamless Landsat image composites created every five years using Google Earth Engine (GEE) to extract lake surface water extents. An object-based image analysis (OBIA) masked all waterbodies and generated the lake drainage product for driver attribution analysis. Boosted regression tree (BRT) models were used to determine the primary drivers of gradual and catastrophic lake drainage, respectively. Results improve our ability to anticipate landscape evolutionary trajectories in warmer and wetter permafrost ecosystems.

2. Methods

2.1. Study region
Our study domain includes six Arctic and subarctic ecoregions spanning 388 968 km² of shrub-tussock upland tundra in northern and northwestern Alaska (Figure 1). Ecoregions include Arctic tundra (Brooks Foothills, Brooks Range), Bering tundra (Kotzebue Sound Lowlands, Seward Peninsula) and the Intermontane boreal (Davidson Mountains, Kobuk Ridges and Valleys). Continuous permafrost (>90% of the landscape underlain...
by permafrost) dominates our study region, though discontinuous permafrost (50%–90% of the landscape underlain by permafrost) is found on the southern margin of the Seward Peninsula. Mean annual air temperature ranges from $-1.9$ °C to $-10.5$ °C and annual total precipitation from 190 to 719 mm (CRU, [www.cru.uea.ac.uk](http://www.cru.uea.ac.uk)) across the study regions. In addition, annual temperature and precipitation vary across ecoregions: Seward Peninsula ($-3.5 \pm 0.6$ °C, 417 ± 82 mm), Kobuk Ridges and Valleys ($-3.4 \pm 0.8$ °C, 424 ± 61 mm), Kotzebue Sound Lowlands ($-4.1 \pm 0.3$ °C, 351 ± 37 mm), Davidson Mountains ($-5.1 \pm 1.0$ °C, 252 ± 43 mm), Brooks Range ($-6.3 \pm 1.6$ °C, 476 ± 108 mm) and the Brooks Foothills ($-8.8 \pm 1.3$ °C, 344 ± 79 mm). See Lara and Chipman ([2021](#)), for detailed site and ecoregion descriptions.

### 2.2. Image processing

Forty-five years (i.e. 1975–2019) of Landsat observations were used to map the spatiotemporal patterns of lake drainage in northern Alaska. All Landsat data was pre-processed by the United States Geological Survey and downloaded by GEE in a radiometrically, atmospherically, and geometrically terrain-corrected state. We used Landsat surface reflectance products acquired from the Multispectral Scanner (MSS), Terrestrial Mapper (TM), Enhanced Terrestrial Mapper Plus (ETM+), and Operational Land Imager (OLI) sensors to compute eight image mosaics for the ice-free period (15 June 15 to 1 September) at five-year time-periods (figure 2). We extracted the following spectral bands from all sensors: blue (0.45–0.52 µm), green (0.52–0.60 µm), red (0.63–0.69 µm), near-infrared (0.77–0.90 µm), and short-wave infrared 1 (1.55–1.75 µm; actual wavelengths slightly vary between sensors), with the exception of the blue band in the MSS. Clouds and shadows were masked using the Fmask algorithm and short-wave infrared thresholds (e.g. Lara et al [2019](#)). Median pixel values were selected to generate each five-year image composite, ensuring any remaining fog, haze, and high diffused clouds were filtered from the dataset (figure 2). However, during time-periods 1990–94 and 1995–99 we replaced an average of ~5% of the study domain with imagery from the preceding time-periods due to poor data coverage or data quality.

### 2.3. Decadal lake drainage

Supervised SVM algorithms were trained on 353 reference sites in GEE to extract waterbodies from each five-year image composite. To represent the full spectral range of land cover features and improve SVM feature extraction, we selected reference sites from wet tundra ($n = 33$), dry tundra ($n = 66$), sandy barrens ($n = 24$), geologic outcrops ($n = 30$), and surface waterbodies ($n = 200$). Surface waterbodies included spectral reflectance from shallow ponds, turbid rivers, lakes of varying origin (e.g. thermokarst, glacial, maar), and coastal water. All reference sites were specifically selected to represent waterbodies and terrain features that did not change over the 45 year observation period (figure 2).

Surface water classifications for each five-year image composite was exported to an object based image analysis (eCognition version 9.1) for lake extraction and decadal lake drainage product creation. Following protocols described in Lara et al ([2018a](#), [2018b](#), [2019](#)), we masked ponds, streams, rivers, and coastal water using spectral and morphological (i.e. roundness) metrics. Lakes were differentiated from ponds using surface area thresholds.
Figure 2. Schematic representation of the data processing workflow used to map and model gradual and catastrophic lake drainage. Processing within GEE, eCognition, and R are indicated by background colors: white, blue, and grey, respectively.

(i.e. ponds <1 ha), resulting in 32,690 lakes considered in this assessment. However, due to the different mechanisms likely driving lake expansion versus drainage (Jones et al., 2011, 2020a, Shur et al., 2012, Roach et al., 2013, Lara et al., 2019, Veremeeva et al., 2021), and the small but quantifiable contribution of lake expansion to total lake area change (Smith 2005, Nitze et al., 2020), we controlled for lake expansion by restricting the outward growth of lakes beyond the initial 1975–1979 lake boundaries. We computed the lake-specific change in area and percent over time, relative to these 1975–1979 lake boundaries. Therefore, the overall patterns of lake change presented here, represent a slight overestimation of the actual lake area declines observed over time. In addition, unlike typical surface water change analysis, this approach cannot discriminate between the formation of ‘new’ remnant ponds or lakes within the initial lake boundary following drainage, which is reported to be responsible for the increase in number of lakes in northwestern Alaska as lake area decreases (Jones et al., 2011, Lindgren et al., 2021). Despite differences in the spatial resolution between Landsat MSS (~60 m) and TM, ETM+, and OLI (30 m), lake change studies have used a variety of approaches to integrate MSS data into time-series analysis. Some of these include resampling imagery to a common spatial resolution (Smith 2005, Karlsson et al., 2013), restricting interpretation to larger lakes (Smith 2005, Hinkel et al., 2007, Plug et al., 2008, Karlsson et al., 2013), or completely bypassing this issue (Royer et al., 2012, Lantz and Turner, 2015, Lindgren et al., 2021) as the surface water mapping uncertainties between Landsat sensors is likely negligible. Nevertheless, we developed a post-classification method to inherit lake change data from the MSS 1975–1979 scenes, but maintain the 30 m spatial resolution of the TM scenes. To accomplish this task, we selected the earliest available TM lake classification (i.e. 1985–1989) and used an object based growth function to extend the 1985–1989 TM lake boundary into the overlapping 1975–1979 MSS lake boundary. If lake area increased between TM and MSS time-periods, the growth function expanded the 1985–89 TM lake area into the 1975–1979 MSS lake extent, keeping the initial 30 m spatial resolution from the TM, but inheriting the lake drainage data from the 1975–1979 time-period. If lake area change did not increase between TM and MSS time-period, the 1985–1989 lake boundary was not updated. The newly updated 30 m spatial resolution 1975–1979 lake boundaries were used.
to detect patterns of lake drainage across time (figures 2 and 3).

2.4. Driver attribution analysis
Although catastrophic drainage is defined as the rapid reduction in lake area within several days to weeks (Mackay 1988, Jones and Arp 2015), we identify the occurrence of catastrophic drainage in Landsat observations as the abrupt decline in lake area by 30%, 45%, or 60% of the total lake area, relative to the prior observed lake area extent (e.g. difference between the 1995–1999 and 2000–2004 image composites). Three drainage thresholds were selected to define catastrophically drained lakes as the quantitative definition of gradual versus catastrophic lake drainage is not well defined in the literature, and to eliminate any potential misinterpretation of driver attribution associated with quantitative definitions. However for simplicity, only 30% and 60% thresholds are presented throughout the manuscript, and results from the 45% threshold are presented within supplemental materials 1 and 2 (available online at stacks.iop.org/ERL/16/124019/mmedia). We model the drivers of catastrophic drainage using data from the time-period of drainage (table 1). If a lake catastrophically drained, it was recorded and removed from the proceeding dataset to avoid double counting of drainage events. All lakes that did not catastrophically drain were categorized as gradually draining lakes, where we modeled the drivers of long-term lake-specific change rates (i.e. including stable and gradually draining lakes).

Driver attribution analysis was implemented using a BRT model for each drainage type (i.e. gradual and catastrophic) and threshold (30%, 45%, and 60%). We used 35 static (i.e. temporally non-changing parameter) and dynamic (i.e. temporally changing parameter) morphologic, topographic, environmental, disturbance, and climate related parameters to model lake drainage (table 1). With the exception of lake-specific morphological metrics, all spatial data were extracted using 500 m lake buffers. Morphological metrics lake perimeter, area, edge-to-area ratio, roundness, and distance to drainage gradients (adjacent lake or river), were computed within the OBIA (e.g. Lara et al 2018a), while the thermokarst lake settlement index (TSI) was calculated using the Arctic digital elevation model (DEM), following Lara and Chipman (2021). Topographical metrics, topographic position index, topographic wetness index, elevation, slope, and aspect were also computed using the Arctic DEM (Danielson and Gesch 2011). Environmental metrics, day of thaw (DOT), day of freeze (DOF), length of thawing season (number of days between DOT and DOF), and snowfall equivalent (SWE) were derived from the Scenarios Network of Alaska and Arctic Planning (SNAP) (CRU 4.0; Harris et al 2014), while permafrost temperature (MAGT), ground surface temperature (MAST), active layer thickness (ALT), and minimum permafrost thickness (Pthick) were modeled by Geophysical Institute Permafrost Laboratory model (Luo et al 2014). Near surface permafrost probability (PermProb) was obtained from Pastick et al (2015) and Vegetation cover (Veg) referred to the latest National Land Cover Dataset (NLCD) Land Cover Map (Homer et al 2015). Disturbance metrics year since fire (YSF), Fire Severity (Severity), and Fire
Table 1. Parameters used as predictor variables in boosted regression tree models of catastrophic and gradual lake drainage.

| Category             | Parameter                        | Acronym | Unit   | Dynamic/Static |
|----------------------|----------------------------------|---------|--------|----------------|
| Morphological        | Lake perimeter                   | Perimeter | m     | S              |
|                      | Lake area                        | Area    | ha     | S              |
|                      | Edge to area ratio               | EtoA    | Unitless | S              |
|                      | Lake classification              | Class   | Categorical | S              |
|                      | Roundness                        | Round   | Unitless | S              |
|                      | Distance to nearest lake         | Dist_L  | m      | S              |
|                      | Distance to nearest river        | Dist_R  | m      | S              |
|                      | Thermokarst lake settlement index| TSI     | Unitless | S              |
| Topographical        | Topographic position index       | TPI     | Unitless | S              |
|                      | Topographic wetness index        | TWI     | Unitless | S              |
|                      | Elevation                        | Elev    | m.a.s.l. | S              |
|                      | Slope                            | Slope   | Degrees | S              |
|                      | Surficial geology                | Geology | Categorical | S              |
|                      | Aspect                           | Aspect  | Degrees | S              |
| Environmental        | Thawing season                   | ThawDays| Days    | D: decadal     |
|                      | Day of thaw                      | DOT     | Days    | D: decadal     |
|                      | Day of freeze                    | DOF     | Days    | D: decadal     |
|                      | Permafrost temperature (1 m)     | MAGT    | °C     | D: annual      |
|                      | Mean ground surface temperature  | MAST    | °C     | D: annual      |
|                      | Active layer thickness           | ALT     | m      | D: annual      |
|                      | Minimum permafrost thickness     | Pthick  | m      | D: annual      |
|                      | Near surface permafrost probability| PermProb | %  | S              |
|                      | Vegetation cover                 | Veg     | Categorical | S              |
| Disturbance          | Year since fire                  | YSF     | Count   | D: annual      |
|                      | Fire severity                    | Severity | Categorical | S              |
|                      | Fire occurrence                  | FireOccur | Yes/No | S              |
| Climate              | Mean summer (JJAS) air temperature| MSAT   | °C     | D: monthly     |
|                      | Mean annual air temperature      | MAAT    | °C     | D: monthly     |
|                      | Summer total precipitation       | TSP     | mm     | D: monthly     |
|                      | Annual total precipitation       | TAP     | mm     | D: monthly     |
|                      | Summer total insolation          | TSR     | w/m²   | D: monthly     |
|                      | Annual total insolation          | TAR     | w/m²   | D: monthly     |
|                      | Snowfall equivalent              | SWE     | Unitless | D: decadal   |
|                      | Snow cover days                  | SD      | Day     | D: decadal     |
|                      | Lake skin temperature            | LakeT   | °C     | S              |

Occurrence (FireOccur; i.e. burned or unburned, since 1950) were developed by the Bureau of Land Management fire history dataset (www.blm.gov/programs/fire-and-aviation) and the Monitoring Trends in Burn Severity project (www.mtbs.gov/). All climate metrics were derived from SNAP data (CRU 4.0, Harris et al 2014), with the exception of lake skin temperature (LakeT), which was estimated from six years (2014–2019) of Thermal Landsat imagery (Huang et al 2017).

BRT algorithms were trained and validated using all lake drainage data (e.g. Elith et al 2008). We used all candidate predictors to fit the model (table 1), and removed all non-significant parameters (relative influence <5%) in a step-wise fashion to avoid overfitting following the principle of maximum parsimony and minimizing cross-dependent and cross-correlative variables. The regularization parameters of the model were tested before being fixed at the optimal bag fraction of 0.75, learning rate of 0.0001, and tree complexity of 8, which resulted in the number of trees >5000. Model performance was evaluated using a k-fold cross-validation procedure (ten-folds), where lake drainage data was randomly divided into ten subsets (training/testing) to estimate the average accuracy of the model after each fold. All BRT model development was performed in R v3.6.1 (with package 'gbm'; e.g. Greenwell et al 2020).

3. Results

Forty-five years of Landsat observations were used to generate a seamless 30 m spatial resolution lake drainage map product of 32 690 lakes spanning six ecoregions in northern Alaska (figure 3). This product characterized the timing of lake area change between 1975 and 2019, and was used to differentiate gradual from catastrophic drainage patterns and processes.

3.1. Spatiotemporal patterns of lake drainage

Cumulative lake area (i.e. including both gradual and catastrophic drainage) declined $-14.4\%$ across all ecoregions. The ecoregions with the highest and lowest lake area declines between 1975 and 2019 occurred in the Kobuk Ridges and Valleys ($-16.2\%$)
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Figure 4. Cumulative lake drainage (i.e. sum of catastrophic and gradual drainage; panel (A)) and percent change in lake area (panel (B)) between 1975 and 2019 across six ecoregions of northern and northwestern Alaska. Due to the absence of Landsat observations between 1980–84, drainage rates for '1975–79–1980–84' and '1980–84–1985–89' were recomputed by dividing the lake area change between 1975–79 and 1985–89 by two (panel (B)). The 'All Ecoregions' category represents the mean lake change by ecoregion and time-period.

...and the Brooks Range (−10.0%), respectively. The overall mean lake drainage rate across all ecoregions was approximately −3.6% decade$^{-1}$, but rates varied by ecoregion and over time (figure 3). Drainage rates from northern to southern ecoregions ranged from the Brooks Foothills (−3.6% decade$^{-1}$), Brooks Range (−2.6% decade$^{-1}$), Davidson Mountains (−3.4% decade$^{-1}$), Kobuk Ridges and Valleys (−4.1% decade$^{-1}$), Kotzebue Sound Lowlands (−3.8% decade$^{-1}$), and the Seward Peninsula (−3.2% decade$^{-1}$). The temporal variability in lake drainage rates was apparent as only about 7% of the cumulative lake drainage over time occurred between the first 15 years of observation (i.e. 1975–1989), whereas nearly half of all drainage occurred within the 1990s (figure 4).

Gradual lake drainage dominated the overall proportion of lake area change across time and space (figure 5), as it was responsible for between 94.0% and 97.6% of all lake area loss (range dependent on 30%–60% drainage threshold definitions). In contrast, catastrophic drainage processes were responsible for only between 2.4% and 6.0%. Interestingly, the proportion of lakes to experience gradual versus catastrophic drainage were not static over time, as the proportion of lakes to experience gradual drainage increased between 1.8% and 1.1% decade$^{-1}$ as catastrophic drainage proportionately decreased (figure 4). For example, during the earliest time-period (1975–1979), catastrophic drainage represented as much as 10.0%–4.5% (range associated with 30% and 60% threshold definition) of all lake area loss, but linearly decreased over time, representing only 3.0%–0.5% of all drained lake area during the most recent time-period (2015–2019).

In line with the decreasing proportion of catastrophic drainage, the number of catastrophically drained lakes precipitously declined from 273 to 103 lakes draining year$^{-1}$ during 1975–1979 to 8 to 3 lakes draining year$^{-1}$ during 2010–2014 (figure 6). However this 40 year negative trend was reversed during the most recent time-period (2015–19), with observations of catastrophic drainage among the highest rates on record (i.e. 100–250 lakes draining year$^{-1}$). Our wall-to-wall mapping of lake drainage consistently identified such hotspots within northwestern ecoregions (i.e. Kotzebue Sound Lowlands and the Kobuk Ridges and Valleys), whereas coldspots were observed in mountainous ecoregions within the Brooks Range and Davidson Mountains (figure 7).

3.2. Spatiotemporal drivers of lake drainage

Despite differences in our quantitative definitions of gradual and catastrophic drainage (i.e. 30%, 45%, and 60%), BRT models consistently identified the drivers of change to differ by drainage process, suggesting drainage definitions had little influence on our overall results. Gradual lake drainage models for 30 ($n = 29,020$ lakes), 45 ($n = 31,244$ lakes), and 60% ($n = 32,329$ lakes) drainage thresholds explained 42%, 39%, and 39% of the overall variance in lake drainage in northern Alaska, respectively. All gradual drainage models identified the same six drivers: the edge-to-area ratio (E:A), mean summer air temperature (MSAT), lake skin temperature (LakeT), snow cover days (SD), ALT, and the TSI. The ten-fold cross validation procedure indicated model validation error was low (10-CV = 0.35–0.30, $P < 0.001$; supplemental material 1) as locally indicated by observed versus predicted gradual drainage between 1975 and 2019 (supplemental material 3).

Catastrophic lake drainage models for 30 ($n = 29,020$ undrained, 6101 drained lakes), 45...
Figure 5. The proportional contribution of lake area loss from gradual (A) and (B) and catastrophic drainage processes (C) and (D) across ecoregions of northern and northwestern Alaska. The bold black line represents the mean for all ecoregions for each time-period, whereas the dotted black line represents the mean across time-periods. Left and right columns represent lake drainage definitions, considering 30% and 60% catastrophic drainage thresholds, respectively (see section 2).

Figure 6. Annual number of catastrophic drainage events by ecoregion between 1975 and 2019. Panel (A) and (B) represent lake drainage definitions, considering 30% and 60% catastrophic drainage thresholds, respectively (see section 2).

\( n = 31,244 \) undrained, 3877 drained lakes), and 60\% \( (n = 32,329 \) undrained, 2792 drained lakes) drainage thresholds explained between 75, 75\%–76\% of the overall variance in catastrophic drainage events, respectively, over time. All catastrophic drainage models also identified the same four drivers: the length of the thawing season \( \text{ThawDays} \), total annual precipitation, minimum permafrost thickness \( \text{Pthick} \), and LakeT. Similar to gradual lake drainage, the ten-fold cross validation procedure indicated low model validation error \( (10-\text{CV} = 0.67–0.63, P < 0.001; \text{supplemental material 2}) \) as locally indicated by observed versus predicted catastrophic drainage between 1975 and 2019 (supplemental material 3).

Due to the skill of BRT lake drainage models, we forecast the potential lake drainage across northern Alaska over the next 30 years (figure 8). Models project gradual lake drainage to continue to decrease in lake area between 19\% and 23\% across our study domain by 2050. However, this pattern differed by ecoregion, as cumulative gradual lake
drainage decreased in the Brooks Foothills (−21.5% to −17.5%), Brooks Range (−20.5% to −17.3%), Davidson Mountains (−31.3% to −24.5%), Kobuk Ridges and Valleys (−33.9% to −24.9%), Kotzebue Sound Lowlands (−18.2% to −14.9%), and the Seward Peninsula (−21.7% to −14.9%) dependent on radiative concentration pathway (RCP) and drainage threshold definition (supplemental material 1, 3). Despite good overall model performance of catastrophic drainage (i.e. low bias and low variance), the model was unable to account for the climate variability projected by 2050. BRT models markedly over-projected the frequency of catastrophic drainage events by projecting between 68.4% and 90.0% of all lakes to catastrophically drain in the study region by 2050. Due to limited historical observations beyond 157 ThawDays, the model was highly sensitive to values beyond this range, as all northwestern ecoregions approached the 157 ThawDays threshold by 2050 (supplemental material 4), whereas the Kobuk Ridges and Valleys exceeded this threshold as early as 2020. Therefore, we did not further scrutinize these lake drainage predictions.

4. Discussion

4.1. Spatiotemporal patterns of lake drainage

Using nearly a half-century of Landsat observations (1975–2019), we identified a 14.4% (~3.6% decade\(^{-1}\)) decrease in lake area, spanning the upland and lowland tundra region of northern and northwestern Alaska. Catastrophically drained lakes were a relatively uncommon form of lake drainage, accounting for 2.4%–6.0% of annual lake area losses. The disproportionately higher prevalence of gradual drainage was likely due to the broader influence regional climate change had on all lakes (via evaporation versus recharge). Increased gradual drainage rates across northern Alaska during the 1990s (figure 4(B)) were nearly identical to that observed on the Old Crow Flats in the northwestern Yukon, which attributed amplified drainage to regional water deficits between 1988 and 2001, associated with the Pacific Decadal and Arctic Oscillations (Labrecque et al. 2009). Additionally, we observe the number of catastrophically drained lakes to decrease between 1975–1979 and 2010–2014, similar to Jones et al. (2020) and Marsh et al. (2009). However, this forty-year negative trend was reversed during the most recent time-period (i.e. 2015–2019) as the number of catastrophic drainage events was among highest on record (figure 6). These lake drainage observations may be even more notable as we also identify a negative trend in the proportion of gradual versus catastrophic drainage throughout all time-periods (figure 5), suggesting the most recent time period (2015–2019) was an extremely high lake drainage epoch for both gradual and catastrophic drainage. We hypothesize
this was due to the progressive thawing and elimination of lakes with thin stabilizing permafrost as the climate warmed and winter snow cover increased (Nitze et al 2020). At the start of the anomalous warming periods during the 1980s and 1990s, lakes with relatively thin stabilizing ground ice are more likely to be punctured and lost to the groundwater by the progressive thaw subsidence and lake deepening. Therefore, over time the most sensitive lakes will have been lost quickly after the climate began to change, resulting in the observed decreasing trends in catastrophic drainage rates.

Interestingly, the recent high number of lake drainage events (i.e. 2015–2019) were all recorded in northwestern ecoregions in the Kotzebue Sound Lowlands, Kobuk Ridges and Valleys, and the Seward Peninsula (figure 6). This observation confirms recent patterns of lake area losses reported within the Kotzebue Sound Lowlands (Nitze et al 2020), the Noatak National Preserve (Swanson 2019), and the Seward Peninsula (Lindgren et al 2021). In addition to the identified proximate drivers of lake drainage, the high drainage rates in this region may be ultimately influenced by the northward shifting continuous to discontinuous permafrost boundary (Nitze et al 2018, Lindgren et al 2021) with regional warming (Jafarov et al 2012).

4.2. Modeling drivers of lake drainage

Due to evidence suggesting that the drivers and mechanisms of gradual and catastrophic lake drainage may differ (Jones et al 2011, 2020a, Shur et al 2012, Roach et al 2013, Lara et al 2019, Veremeeva et al 2021), we evaluated the drivers of both drainage processes separately. Gradual lake drainage was controlled by lake morphology and type (i.e. E:A, TSI), temperature (i.e. MSAT, LakeT), and snow-permafrost interactions (i.e. SD and ALT). We found the more irregular the shoreline and the warmer the air/water temperatures (i.e. increased evaporation), the more vulnerable the lake to gradual drainage. In addition, the identification of the thermokarst lake settlement index

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**Figure 8.** Cumulative historical and projected change in lake area associated with gradual lake drainage in northern Alaska. Temporal patterns of gradual drainage by ecoregion are displayed in panels (A) and (C), where dotted lines assume a linear trajectory from observed 2015–2019 drainage and projected 2045–2049 drainage. The spatial patterns of cumulative gradual drainage from 1975 to 2049 are mapped in panels (B) and (D), where BRT models were forced using radiative concentration pathways (RCPs) 4.5 and 8.5, respectively.
confirms the predisposition that thermokarst lakes are indeed more likely to experience lake drainage than non-thermokarst lakes of glacial or volcanic origin (Swanson 2019, Lara and Chipman 2021). Our identified drivers of catastrophic drainage well-represented the spatiotemporal patterns of drainage events (supplemental material 1–3), and correspond with previous observations (Labrecque et al 2009, Jones et al 2011, Lantz and Turner 2015, Swanson 2019, Nitze et al 2020, Lindgren et al 2021). However we identify historical patterns of catastrophic lake drainage to be regionally controlled by the length of thawing season (i.e. ThawDays), as partial dependency plots identified the magnitude of catastrophic drainage events to be closely linked to a threshold of 137 thawing days, after which the likelihood of catastrophic drainage events rapidly increased. This pattern explains the recent catastrophic drainage events in northwestern Alaska (2014–2019), as the ThawDays threshold was often locally exceeded but regionally approached in the Kobuk Ridges and Valleys (156.6 days), Kotzebue Sound Lowlands (150.4 days), and the Seward Peninsula (152.0 days). We interpret the additional drivers of catastrophic drainage, precipitation and permafrost thickness to be indirect indicators of regional landscape heterogeneity as (a) the dominate precipitation gradient across our study domain occurs from low to high elevations associated differences in lapse rates, and (b) the modeled permafrost thickness generally decreased with latitude and increased with elevation.

Equally important are the parameters that the models did not identify as regional drivers of lake drainage, such as fire metrics, proximity to drainage gradients, and increased precipitation. Although wildfire may indirectly alter the timing and extent of ALT by modifying surface energy dynamics (Michaelides et al 2019), linkages to local pond and lake drainage events are limited (e.g. Roach et al 2013, Frost et al 2019, Chen et al 2020), and also not supported by our results. In addition, the proximity to drainage gradient (i.e. distance to river, stream, or lake) has been reported to be a predominant drainage mechanism in low-relief coastal tundra ecosystems as thermokarst lakes laterally expand (Jones et al 2011, 2020a). However, models failed to identify this well-studied mechanism of drainage reported for the northern Seward Peninsula and the Arctic Coastal Plain of Alaska, suggesting the identified drivers (i.e. warming and extended thawing season) may be robust regional indicators of lake drainage, but represent an array of local mechanisms of drainage. Increased precipitation has also been linked with lake drainage as rising lake water may facilitate bank overtopping and gully or channel formation (Jones and Arp 2015, Jones et al 2020a), a phenomenon that may be exacerbated by adjacent ice-wedge degradation that create new surface hydrological flow paths for drainage (Jorgenson et al 2006, Liljedahl et al 2016). However we did not identify precipitation change as a dominant driver of lake drainage (gradual or catastrophic), which was in line with Swanson (2019) as he reported high rates of lake drainage following record high temperatures during periods of declining precipitation across northwestern Alaska.

4.3. Forecasting lake drainage

By 2050, models project gradual lake drainage to continue to decrease lake area between 19% and 23% across our study domain (figure 8). Hotspots of lake drainage are found in the intermontane boreal eco-regions (i.e. Kobuk Ridges and Valleys and the Davidson mountains; ~34% lake area losses), as they are projected to experience among the greatest warming in MSAT and associated vertical permafrost thaw (i.e. ALT; supplemental material 4). However, it remains unclear how these climate-driven patterns in future lake loss may be further compounded by catastrophic drainage. Assuming the decreasing trend in the proportion of catastrophic versus gradual drainage will continue (figure 5), the contribution of catastrophic drainage to overall lake area losses approach zero by 2020–24 (30% drainage threshold) or 2030–34 (60% drainage threshold) across upland and lowland tundra of Alaska, suggesting gradual drainage processes will govern nearly all lake drainage by 2050. In contrast, our catastrophic drainage model artificially triggered an enormous (i.e. 65% of all lakes) wave of catastrophically drained lakes across the region. Despite our spatially and temporally robust lake drainage dataset spanning climate, environmental, topographic, and disturbance gradients, which generated models that well-represented past catastrophic drainage dynamics (supplemental material 2, 3), our observations remained insufficient to predict how abrupt thermokarst-driven lake dynamics will change over the next 30 years. This highlights the challenges of predicting abrupt permafrost degradation processes with limited knowledge of ground ice distribution and without explicit linkages with local mechanisms of drainage. To improve forecasts of thermokarst-driven lake drainage processes, future research should aim to characterize and model the various mechanisms and pathways of talik formation, sub-surface tunnel development, gully or drainage channel formation, bank-overtopping, lake expansion, and associated interactions with adjacent land cover properties (Yoshikawa and Hinzman 2003, Shur et al 2012, Jones and Arp 2015, Arp et al 2016, Liljedahl et al 2016, Jones et al 2020a, 2020b), as they are likely to accelerate as Arctic and sub-Arctic regions become warmer and wetter (Liu et al 2012, Bintanja and Selten 2014, Arp et al 2020b, Jones et al 2022).
5. Conclusion

We leveraged the entire Landsat image archive (MSS, TM, ETM+, OLI) to create wall-to-wall lake drainage maps for six northern and northwestern ecoregions of Alaska. The frequency of lake drainage observations enabled the identification of the likely drivers of change, which differed between drainage processes. The drivers of gradual and catastrophic drainage corresponded with climate-driven versus thermokarst-driven parameters, respectively. We found gradual lake drainage to intensify over the 45 year Landsat time-series as increased temperatures (i.e. MSAT and LakeT) and potentially surface water deficient (e.g. Labrecque et al 2009) reduced overall lake area, which is likely to continue through 2050. By leveraging early Landsat observations we captured intense periods of catastrophic lake drainage events that (a) linearly decreased for forty years, but was reversed by one the highest number of catastrophic drainage periods on record (i.e. 2015–2019), and (b) corresponded with periods of amplified summer warming and lengthening of the thawing season. Although the inclusion of a larger breadth of lake drainage observations and climate and environmental variability undoubtedly improved model performance, this historical variability was still insufficient for sophisticated machine learning models to forecast catastrophic drainage. Collectively, these results bridge many previous observations of high-latitude lake drainage and provide new insights into (a) how permafrost ecosystems are changing, and (b) why they are changing, however further research into the biogeophysical consequences of such transitions from water-to-land (e.g. Walter Anthony et al 2018), should be prioritized.

Data availability statement

The data that support the findings of this study are openly available at the following DOI: 10.18739/A2BV79W8S.

Acknowledgments

This research was supported by the National Science Foundation’s Environmental Engineering program (EnvE-1928048 to M J L), the Office of Polar Programs, and the Office of Integrative Activities (OPP-1806213 and OIA-1929170 to B M J). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

ORCID iDs

Mark J Lara © https://orcid.org/0000-0002-4670-7031

Benjamin M Jones © https://orcid.org/0000-0002-1517-4711

References

Arp C D, Jones B M, Grosse G, Bondurant A C, Romanovsky V E, Hinkel K M and Parsekian A D 2016 Threshold sensitivity of shallow Arctic lakes and sublake permafrost to changing winter climate Geophys. Res. Lett. 43 6358–65
Arp C D, Jones B M, Hinkel K M, Kane D L, Whitman M S and Kemnitz R 2020a Recurring outburst floods from drained lakes: an emerging Arctic hazard Front. Ecol. Environ. 18 384–90
Arp C D, Whitman M S, Kemnitz R and Stuefer S L 2020b Evidence of hydrological intensification and regime change from northern Alaskan watershed runoff Geophys. Res. Lett. 47 e2020GL089186
Billings W D and Peterson K M 1980 Vegetational change and ice-wedge polygons through the thaw-lake cycle in arctic Alaska Arcit. Alp. Res. 12 413
Bintanja R and Selten F M 2014 Future increases in Arctic precipitation linked to local evaporation and ice-ice retreat Nature 509 479–82
Carroll M L and Loboda T V 2017 Multi-decadal surface water dynamics in North American tundra Remote Sens. 9 497
Chen Y, Lara M J and Hu F S 2020 A robust visible near-infrared index for fire severity mapping in Arctic tundra ecosystems ISPRS J. Photogramm. Remote Sens. 159 101–13
Danielson J J and Geish D B 2011 Global Multi-Resolution Terrain Elevation Data 2010 (GMTEDE2010) p 26
Elith J, Leathwick J R and Hastie T 2008 A working guide to boosted regression trees J. Anim. Ecol. 77 802–13
Frost G, Saperstein L B, Loehman R A, Schafer K M, Michaelides R J, Macander M and Dissing D 2019 Does tundra fire accelerate drainage of lakes in discontinuous permafrost? Evidence from the Yukon-Kuskokwim Delta, Alaska American Geophysical Union Poster
Greenwell B, Boehmke B and Cunningham J, and GBM Developers 2020 GBM: generalized boosted regression models R package version 2.1.8 (available at: https://CRAN.R-project.org/package=gbm)
Grosse G, Jones B and Arp C 2013 Thermokarst lakes, drainage, and drained basins Treatise on Geomorphology 8 525–53
Harris I, Jones P D, Osborn T J and Lister D H 2014 Updated high-resolution grids of monthly climatic observations—the CRU TS3.10 dataset Int. J. Climatol. 34 623–42
Hinkel K M, Eisner W R, Bockheim J G, Nelson F E, Peterson K M and Dai X 2003 Spatial extent, age, and carbon stocks in drained thaw lake basins on the Barrow Peninsula, Alaska Arctic, Antarct. Alp. Res. 35 291–300
Hinkel K M, Jones B M, Eisner W R, Cuomo C J, Beck R A and Frohn R 2007 Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska J. Geophys. Res. Earth Surf. 112 F02S16
Homer C, Dewitz J, Yang L, Jin S, Danielson P, Xian G, Coulston J, Herold N, Wickham J and Megown K 2015 Completion of the 2011 national land cover database for the conterminous United States—representing a decade of land cover change information Photogramm. Eng. Remote Sens. 81 345–54
Huang Y, Liu H, Hinkel K, Yu B, Beck R and Wu J 2017 Analysis of thermal structure of Arctic lakes at local and regional scales using in situ and multidate Landsat-8 data Water Resour. Res. 53 9642–58
Jafarov E E, Marchenko S S and Romanovsky V E 2012 Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset Cryosphere 6 613–24
Jones B M et al 2020a Identifying historical and future potential lake drainage events on the western Arctic coastal plain of Alaska Permafrost Periglacial Processes 31 110–27
Jones B M and Arp C D 2015 Observing a catastrophic thermokarst lake drainage in northern Alaska Permafrost Periglacial Processes 26 119–28

Front. Ecol. Environ.
Jones B M, Arp C D, Hinkel K M, Beck R A, Schmutz J A and Winston B 2009 Arctic lake physical processes and regimes with implications for winter water availability and management in the national petroleum reserve alaska Environ. Manage. 43 1071–84

Jones B M, Grosse G, Arp C D, Jones M C, Walter Anthony K M and Romanovsky V E 2011 Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska J. Geophys. Res. Biogeosci. 116 A41I4

Jones B M et al accepted Lake and drained lake basin systems in lowland permafrost regions Nat. Rev. Earth Environ. 3 2022

Jones B M, Tape K D, Clark J A, Nitze I, Grosse G and Disbrow J 2020b Increase in beaver dams controls surface water and thermokarst dynamics in an Arctic tundra region, Baldwin Peninsula, northwestern Alaska Environ. Res. Lett. 15 075005

Jorgenson M T, Shur Y L and Fullman E R 2006 Arupt increase in permafrost degradation in Arctic Alaska Geophys. Res. Lett. 33

Karlsson J M, Lyon S W and Destouni G 2013 Temporal behavior of lake size-distribution in a thawing permafrost landscape in northwestern Siberia Remote Sens. 6 621–36

Labrecque S, Lacelle D, Dugay C R, Lauriol B and Hawkins J 2009 Contemporary (1951–2001) evolution of lakes in the Old Crow Basin, Northern Yukon, Canada: remote sensing, numerical modeling, and stable isotope analysis Arctic 62

Lantz T C and Turner K W 2015 Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon J. Geophys. Res. Biogeosci. 120 513–24

Lara M J, Chen Y and Jones B M 2021 Landsat derived patterns of lake drainage between 1975–2019 spanning northern Alaska Arctic Data Center urn: uuid:290dfd00-d3e7-49de-8ace-ec8e0f2c7f49

Lara M J and Chipman M L 2021 Periglacial lake origin influences the likelihood of lake drainage in northern Alaska Remote Sens. 13 852

Lara M J, Chipman M L and Hu F S 2019 Automated detection of thermooerlosion in permafrost ecosystems using temporally dense Landsat image stacks Remote Sens. Environ. 221 462–73

Lara M J, Nitze I, Grosse G and David Migueur A 2018a Data descriptor: tundra landform and vegetation productivity trend maps for the arctic coastal plain of Northern Alaska Sci. Data 5

Lara M J, Nitze I, Grosse G, Martin P and David Migueur A 2018b Reduced arctic tundra productivity linked with pondform and climate change interactions Sci. Rep. 8

Larsen A S, O’Donnell A J, Schmidt J H, Kristenson H J and Swanson D K 2017 Physical and chemical characteristics of lakes across heterogeneous landscapes in arctic and subarctic Alaska J. Geophys. Res. Biogeosci. 122 899–1008

Liijedahl A K et al 2016 Pan-Arctic ice-ledge degradation in warming permafrost and its influence on tundra hydrology Nat. Geosci. 9 312–8

Lindgren P R, Farquharson L M, Romanovsky V E and Grosse G 2021 Landsat-based lake distribution and changes in western Alaska permafrost regions between the 1970s and 2010s Environ. Res. Lett. 16 025006

Liu J, Curry J A, Wang H, Song M and Horton R M 2012 Impact of declining Arctic sea ice on winter snowfall Proc. Natl Acad. Sci. USA 109 4074–9

Luo D L, Huijun J, Marchenko S and Romanovsky V 2014 Distribution and changes of active layer thickness (ALT) and soil temperature (TTOP) in the source area of the Yellow River using the GIPIL model Sci. China Earth Sci. 57 1834–45

Mackey J R 1988 Catastrophic lake drainage, Tuktoyaktuk Peninsula area, District of Mackenzie Curr. Res. D 88-1D 83–90

Marsh P, Russell M, Polih S, Haywood H and Ondcill C 2009 Changes in thaw lake drainage in the Western Canadian Arctic from 1950 to 2000 Hydrol. Process 23 145–58

Michaelides R J, Schafer K, Zekker H A, Parsekian A, Liu L, Chen J, Natoli S, Ludvig S and Schafer S R 2019 Inference of the impact of wildfire on permafrost and active layer thickness in a discontinuous permafrost region using the remotely sensed active layer thickness (ReSALT) algorithm Environ. Res. Lett. 14 035007

Nitze I, Cooley W S, Dugay C R, Jones B M and Grosse G 2020 The catastrophic thermokarst lake drainage events of 2018 in northwestern Alaska fast-forward into the future Cryosphere 14 pp 4279–97

Nitze I, Grosse G, Jones B M, Romanovsky V E and Boike J 2018 Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic Nat. Commun. 9

Pastick N J, Jorgenson M T, Wylie B K, Nield S J, Johnson K D and Finley A D 2015 Distribution of near-surface permafrost in Alaska: estimates of present and future conditions Remote Sens. Environ. 168 301–15

Plug I J, Walls C and Scott B M 2008 Tundra lake changes from 1978 to 2001 on the Tuktoyaktuk Peninsula, western Canadian Arctic Geophys. Res. Lett. 35

Rampton V N 1988 Quaternary geology of the Tuktoyaktuk coastsland, Northwest Territories Geological Survey of Canada, Ottawa, ON, Canada, Memoir vol 423 p 126937

Roach J K, Griffith B and Verbyla D 2013 Landscape influences on climate-related lake shrinking at high latitudes Glob. Chang. Biol. 19 2276–84

Rover J, Ji L, Wylie B K and Tieszen L L 2012 Establishing water body areal extent trends in interior Alaska from multitemporal Landsat data Remote Sens. Lett. 3 595–604

Shur Y L, Kanevsky M, Jorgenson M T, Dillon M, Stephani E, Bray M and Fortier D 2012 Permafrost degradation and thaw settlement under lakes in yedoma environment Tenth International Conference On Permafrost 10 Tenth Int. Conf. Permafus. pp 383–88

Smith L C, Sheng Y and MacDonald G M 2007 A first pan-arctic assessment of the influence of glaciation, permafrost, topography and peatlands on northern hemisphere lake distribution Permafrost Periglacial Processes 18 201–8

Smith L C, Sheng Y, MacDonald G M and Hinzman L D 2005 Disappearing Arctic lakes Science 308 1429

Surdu C M, Dugay C R, Brown L C and Fernández Prieto D 2014 Response of ice cover on shallow lakes of the North Slope of Alaska to contemporary climate conditions (1950–2011): radar remote-sensing and numerical modeling data analysis Cryosphere 8 167–80

Swanson D K 2019 Thermokarst and precipitation drive changes in the area of lakes and ponds in the national parks of northwestern Alaska, 1984–2018 Arctic Antarct. Alp. Res. 51 263–79

Townshend J R G, Dimicelli C M, Loboda T and Sohllberg R A 2011 Shrinking lakes of the Arctic: spatial relationships and trajectory of change Geophys. Res. Lett. 38 L20406

Veremeeva A, Nitze I, Günther F, Grosse G and Rivkina E 2021 Geomorphological and climatic drivers of thermokarst lake area increase trend (1999–2018) in the kolyma lowland yedoma region, northeast-siberian Remote Sens. 13 178

Walter Anthony K, Schneider Von Deimling T, Nitze I, Frolking S, Emond A, Daanen R, Anthony P, Lindgren P, Jones B and Grosse G 2018 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes Nat. Commun. 9

Walter K M, Edwards M E, Grosse G, Zimov S A and Chapin F S 2007 Thermokarst lakes as a source of atmospheric CH4 during the last deglaciation Science 318 633–6

Yoshikawa K and Hinzman L D 2003 Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska Permafrost Periglacial Processes 14 151–60