ABSTRACT

INTRODUCTION

Thermokarst lakes cover nearly 25% of the landscape in ice-rich, permafrost lowlands of Arctic Alaska (Hinkel *et al.*, 2005), Siberia (Grosse *et al.*, 2005), and Canada (Mackay, 1988; Marsh *et al.*, 2009). Thus, they play a key role in hydrology, permafrost, carbon, and habitat dynamics in the continuous permafrost zone (Grosse *et al.*, 2013). Thermokarst lakes form as a result of permafrost degradation and ground subsidence, and expand through thermal and mechanical erosion (Jorgenson and Shur, 2007; Grosse *et al.*, 2013). They may persist for several thousand years, yet are susceptible to drainage (Mackay, 1992). Their formation, expansion, and drainage have actively reshaped ice-rich permafrost lowlands since the onset of the Holocene (Mackay, 1992; Hinkel *et al.*, 2003; Jones *et al.*, 2012). The conversion of these aquatic ecosystems to terrestrial or wetland ecosystems is thought to be very rapid, as a result of catastrophic drainage (Mackay, 1981).

Drained thermokarst lake basins may presently occupy as much as 50% to 75% of the ice-rich permafrost landscape in Arctic lowlands (Hinkel *et al.*, 2003, 2005; Grosse *et al.*, 2005; Jones *et al.*, 2012). Remote sensing analyses of the continuous permafrost zone indicate that roughly 1 to 2 lakes may drain annually in several Arctic regions (Mackay, 1988; Hinkel *et al.*, 2007; Marsh *et al.*, 2009; Jones *et al.*, 2011). Lake drainage in the continuous permafrost zone is thought to occur laterally and result from a number of different geomorphic and hydrologic processes. Factors that likely initiate drainage include (1) tapping of lakes by rivers, streams, adjacent lakes, or the sea; (2) headward gully erosion; (3) anthropogenic disturbance; (4) thaw slump formation; and (5) bank over-topping resulting from elevated water levels following heavy precipitation events and/or snow-damming of outlets (Mackay, 1988; Brewer et al., 1993; Mackay, 1992; Weller and Derksen, 1979; Hinkel *et al.*, 2007; Wolfe and Turner, 2008; Marsh *et al.*, 2009; Jones et al., 2011; Grosse *et al.*, 2013).

Mackay (1988) noted that elevated lake water levels and diversion of water through interconnected ice-wedge systems likely played a major role in the occurrence of

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catastrophic drainage events. Mackay (1992) indicated that these conditions were most likely to occur during the snowmelt period and thus lakes would likely tend to drain during early summer. An observation of a catastrophic drainage event in the late 1980s in northern Alaska by an Inupiaq Elder indicated that a lake likely drained during this early season period because abundant lake ice was observed in the lake prior to it overtopping its bank and catastrophically draining (Hinkel *et al*., 2007). Wolfe and Turner (2008) reported the partial drainage of a thermokarst lake in the Old Crow Flats, sometime between 06 June and 23 July 2007, that likely resulted from near record precipitation between March and May that increased the lake water level and triggered erosion of a drainage outlet (Turner *et al*., 2010; Turner *et al*., 2014). Brewer *et al*. (1993) noted the sudden, natural drainage of a thermokarst lake in northern Alaska in 1989 due to elevated lake water levels and over-topping of the lake along an ice-wedge trough, but in this case the lake drained later in the summer, presumably as a result of heavy late-summer rains. Marsh *et al*. (2009) also reported on the catastrophic drainage of a lake in late summer and suggested that deeper than normal active layers, thaw slump formation, and moderately high lake levels were the primary drivers of catastrophic lake drainage in the western Canadian Arctic. Although these observations are important for characterizing the mechanisms and controls on catastrophic drainage events, they all lacked *in situ* observations in the lake leading up to and during the drainage event, and so they provide little environmental context.

Previously, the most detailed observations from a catastrophic drainage event come from an experiment to study permafrost aggradation below Lake Illisarvik on Richards Island in western Arctic Canada by J.R. Mackay (1981, 1992, 1997). Mackay (1981) excavated a 25 m long ditch down to the frost table in late June 1978, from the sea coast to within 20 m of the pre-drainage lake margin. Water was pumped from the lake and down the artificial ditch, creating a 1.5 m deep channel. The ditch margin was allowed to thaw in July and then deepened in August to a depth of 4 m at the coast and tapering up to a depth of 1.5 m within a few meters of the pre-drainage lake margin. On 12 and 13 August 1978, the remaining distance between the lake and the artificial channel was ditched and channelized, and the lake drainage was initiated. Within 4 hours the lake level had dropped more than 1 m and within 10 hours the lake level had dropped by 2 m, after which measurements of lake level decline were hindered by a soft lake bottom (Mackay, 1981; Mackay, 1997). Peak discharge during the drainage event was estimated by Marsh and Nuemann (2001) to be 36 m^3/s. This human-induced drainage experiment provided the first evidence that catastrophic drainage events are capable of producing peak discharges that exceed snowmelt-generated peak flows of the spring freshet in Arctic headwater basins (Marsh and Neumann, 2001; Marsh *et al*., 2008). However, because the ultimate goal of this experiment focused on the growth of permafrost in the unfrozen lake sediments following drainage (Mackay, 1997) and not necessarily the drainage itself, the degree to which this human-induced lake drainage reflected the duration and magnitude of a natural drainage event remained uncertain.

Despite the prevalence of thermokarst lakes and drained thermokarst lake basins in the Arctic, detailed observations of the environmental conditions preceding a natural catastrophic drainage as well as *in situ* observations on the duration and magnitude of a natural drainage event have previously not been recorded. In this study, we describe the preceding conditions, timing, and processes associated with a natural thermokarst lake drainage event in northern Alaska during the early summer of 2014. We place these observations in the context of lake drainage events and climatic conditions occurring in the study region since 1955. Our observations from a natural, thermokarst lake drainage event may provide useful information for predicting future catastrophic lake drainage events and their broader impacts.

STUDY AREA

The Arctic Coastal Plain of northern Alaska contains the second largest lake-district in the state (Arp and Jones, 2009). Lakes in the northern portion of this region, the younger outer coastal plain (Hinkel *et al*., 2005), are classified as “true” thermokarst lakes (Jorgenson and Shur, 2007). The permafrost is ice-rich, with an estimated volumetric ground-ice content that exceeds 80% for both primary landscape surfaces and drained lake basins (Kanevskiy *et al*., 2013). Excess ice content in the ground is typically restricted to the upper few meters of permafrost (Sellmann *et al*., 1975; Kanevskiy *et al*., 2013) and thus the majority of the lakes on the younger outer coastal plain range from 1 to 3 m in depth (Hinkel *et al*., 2012). Previous estimates from the region indicate that lake surface area comprises 22.6% of the landscape and drained lake basins account for an additional 46.6% of the landscape (Hinkel *et al*., 2005). The mosaic of lakes and drained lake basins indicates that active landscape processes associated with permafrost degradation and aggradation have operated throughout the Holocene (Hinkel *et al*., 2003; Jorgenson and Shur, 2007).

Lake 195 (L195), the lake that catastrophically drained in 2014, is located approximately 170 km southeast of Barrow, on the younger outer coastal plain of northern Alaska (Figure 1). This thermokarst lake expanded at a rate of 0.5 m/yr between 1979 and 2002, preferentially at the northern and southern margins (~1 m/yr) (Arp *et al*., 2011). The segment of Arctic coastline adjacent to L195 has also experienced an increase in erosion rates since the early 2000s (Jones *et al*., 2009a, 2009b). Thus, the lake was thought to have a high likelihood for drainage and we hypothesized that it would drain by the year 2020 as a result of tapping by coastal erosion (Arp *et al*., 2010). Prior to drainage it had a surface area of ~80 ha, a maximum water depth of 1.4 m, a mean water depth of 1.1 m, and an estimated water

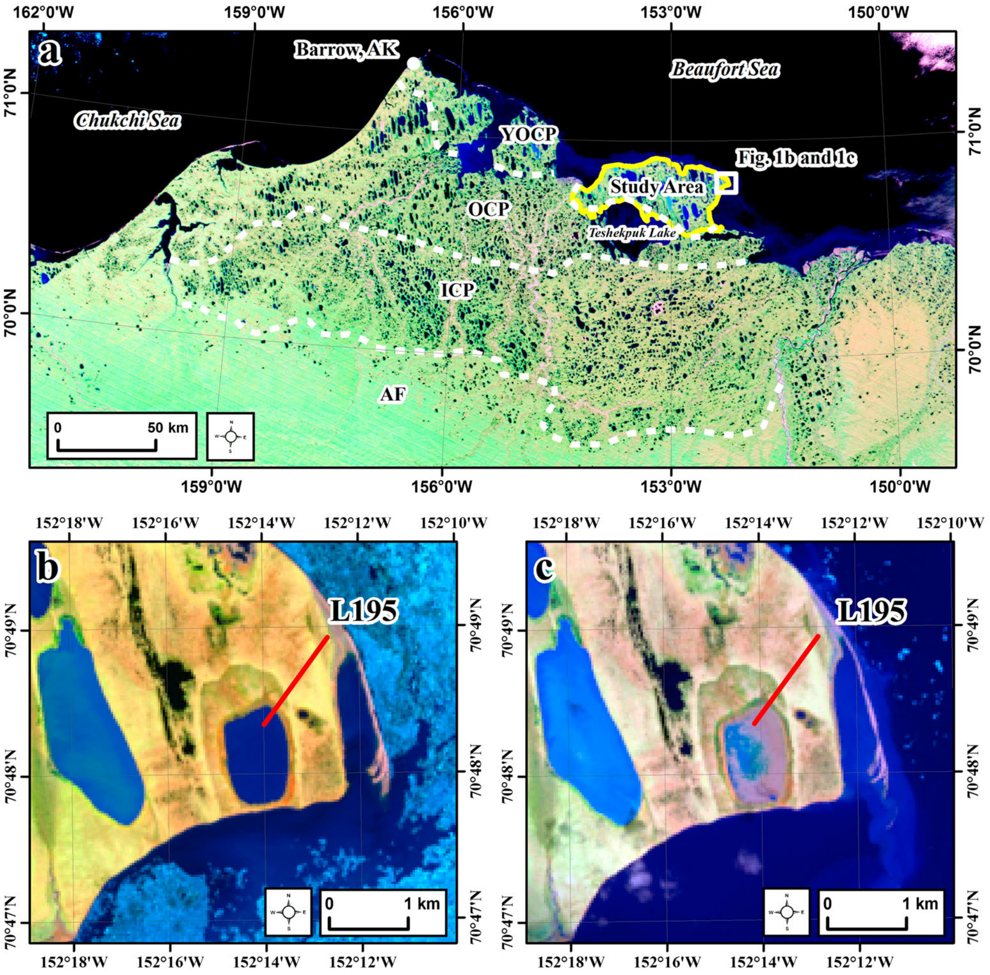

Figure 1 (a) MODIS satellite image showing a portion of the Arctic Coastal Plain of northern Alaska and key landscape divisions indicated with a dashed white line: YOCP is younger outer coastal plain, OCP is outer coastal plain, ICP is inner coastal plain, and AF is the Arctic foothills (modified from Hinkel *et al.*, 2005). The study area is outlined with the yellow polygon and the white box indicates the location of L195. Landsat OLI image pair from (b) 12 July 2013 and (c) 15 July 2014 showing the drainage of L195. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp.

volume of 871,990 m^3. L195 is also considered critical habitat for molting Black Brant (*Branta bernicla nigricans*) as this migratory Arctic goose has shifted its habitat to coastal influenced lakes since the 1970s (Flint *et al*., 2008).

METHODS

In situ Observations

In anticipation of the drainage of L195, we established a lake data buoy in July 2009 that measured water level and water temperature data at a 2-hr interval. The 2-hour interval was set based on the expectation that the lake would drain around the year 2020 as a result of tapping by coastal erosion and thus within the memory limitations of the data logger. Hobo U20-001-01 data loggers recorded pressure and temperature of the lake bed. Atmospheric pressure was also recorded with a Hobo-U20-001-01 data logger. This was used to convert the lake bed data logger measurements to a water level measurement (+/- 0.5 cm).

A meteorological station that measures air temperature, wind speed and direction, precipitation, snow depth, soil moisture, ground temperature, surface pressure and solar radiation was established within 10 km of L195 in August 2007 (Urban and Clow, 2014). The observations from the weather station provided information on the environmental conditions preceding the catastrophic lake drainage event. We utilized air temperature data measured with a Campbell Scientific CSI model 107 thermistor probe, rainfall data measured with a Texas Electronics TE 525 rain gauge positioned 60 cm above the ground within an ETI Instrument Systems Lexan altershield, and snow depth data measured with a CSI model SR50 ultrasonic distance sensor mounted 2.5 m above the ground surface.

Lake basin geometry was surveyed after the drainage event, on 14 August 2014, using a Differential GPS system with a vertical accuracy of 1-2 cm. Additional data points were added in a GIS environment based on common basin geometries from other outer coastal plain lakes (Hinkel *et al.*, 2012) and a bathymetric map was created using a triangulated irregular network (TIN) point to raster transformation. Change in lake volume during the drainage event was calculated using the Grid-Volume tool in Surfer 10™ relative to recorded changes in lake depth measured by the water level logger. Lake outlet discharge was estimated to equal change in storage during our 2 hour measurement interval and as a result our observed peak discharge is likely to be lower than the true peak discharge. Thus, the peak instantaneous discharge was estimated based on a linear regression of peak discharge values observed at 2 hour and lower recording intervals (i.e. 4, 6, and 8 hours) and approximated at the zero intercept.

Remotely Sensed Imagery Analysis

Lakes, drained lake basins, and other landscape features in the study area (Figure 1) were mapped using a cloud-free, Landsat TM image acquired on 21 August 2010. The image was clipped to the younger outer coastal plain north of Teshekpuk Lake. Extant lakes were automatically classified using Landsat TM band 5 and an object-oriented classification technique (Frohn *et al.*, 2005). The remainder of the image space was classified as land and individual drained lake basins were manually delineated in a GIS using the Landsat TM image band combination 5-4-3 (Jones et al., 2012) as well as a 5 m resolution IfSAR-derived digital terrain model (Wang *et al.*, 2012). All data are reported to a minimum mapping unit of 10 ha and the drained lake basin dataset was updated to include the drainage of L195 in 2014.

Lakes evident in U.S. Geological Survey topographic map sheets provided the baseline for determining lake drainage events in the study region since 1955. Cloud-free Landsat imagery available for the study region, beginning in 1977 and then every six to eight years since, was assessed to determine lake drainage events between 1955 and 1977, 1978 and 1985, 1986 and 1992, 1993 and 2000, 2001 and 2007, and 2008 to 2014. Lake surface area was also derived from Landsat imagery for L195 on an annual basis between 2007 and 2013.

Long-term and Short-Term Climate Data Analysis

In order to place the L195 drainage event in the context of preceding weather and climate conditions, we analyzed air temperature, snow depth, and rainfall data collected at a meteorological station located 10 km from the lake (Urban and Clow, 2014). Since L195 drained in early July, following a period of abnormally wet and cold weather that we hypothesized had initiated this catastrophic drainage event, we summarized the average air temperature and total rainfall from 1 June to 15 July 2014. This was compared to the same early summer period going back to 2008, when rainfall data were first collected from this station. Late winter snow depth (1 May) from this station was converted to a snow-water equivalent, assuming a snow density of 0.20 g/cm^3 and 50% loss to sublimation, providing an estimate of snowmelt runoff (Arp *et al.* 2011). Snow-water runoff was then combined with total rainfall over this period to represent early season recharge to L195 between 2008 and 2014.

In addition, we used meteorological data recorded at Barrow (National Weather Service, Station ID 700260 27502) to place the early summer conditions into a longer term context and to compare this record to other lake drainage events north of Teshekpuk Lake since 1955. Data from this station, located 170 km northwest of L195, were also summarized by average air temperature from 1 June to 15 July for the period 1955 to 2014. Total precipitation (snowfall and rainfall) was also summarized over the same period. The climate data from Barrow were then analyzed according to the time periods that bracketed lake drainage events in the study area north of Teshekpuk Lake. Barrow, which is also on the younger outer coastal plain, is considered to have very similar climatology as the area north of Teshekpuk Lake (Arp *et al.* 2011), though day to day weather patterns can vary between these locations.

RESULTS

During the early summer of 2014 we observed a natural, catastrophic thermokarst lake drainage event using a data logger deployed in a lake that we anticipated would drain during the next decade. These observations were coupled with observations from a nearby meteorological station providing information on the environmental conditions that preceded the drainage event. The 2014 lake drainage event was then placed in the context of lake drainage events and early summer weather conditions in the region since 1955.

2014 Catastrophic Lake Drainage Event

Analysis of Landsat OLI imagery shows that L195 drained between 12 July 2013 (Figure 1b) and 15 July 2014 (Figure 1c). Annual Landsat-based observations between 2007 and 2013 reveal a fluctuating, yet increasing surface area for L195 prior to drainage (Figure 2a). Measurements from the lake data buoy shows that L195 began to drain on 05 July 2014 and almost entirely emptied by 07 July 2014, with 75% of the water volume loss occurring in the first ten hours (Figure 2b). Unusually intense early summer rainfall events were recorded on 21 and 22 June before complete ice-out, as well as several smaller events in the week preceding drainage (Figure 2b). Water level data show a slight increase in the depth of L195 following ice-off, corresponding to these precipitation events. From 01 June to 15 July 2014, 31.5 mm of rainfall were recorded, which was over four times higher than the average rainfall recorded for the period between 2008 and 2013 (6.2 mm). In addition, the combination of rainfall and estimated snowmelt runoff indicates that the early summer water input to the lake in 2014 was more than twice that of the 2008-2013 average (Figure 2a).

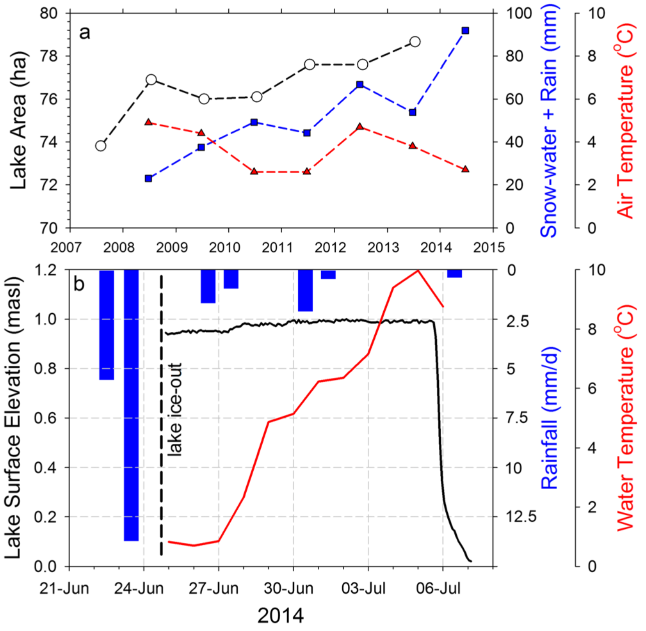

Figure 2 Hydroclimatic conditions prior to the catastrophic drainage of L195. (a) Lake area derived from mid-summer Landsat data between 2007 and 2013 (open circles and dashed line) plotted along with estimated early summer (1 June to 15 July) snowmelt runoff and rainfall (blue squares and dashed line) and air temperature (red triangles and dashed line) from 2008 to 2014. (b) Changes in lake surface elevation leading up to and during the drainage event (black line), lake ice-out (black dashed line) lake water temperature following ice-off (red line), and rainfall events (blue bars) between 21 June and 07 July 2014. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp.

The wetter than normal early summer conditions in 2014 likely resulted in bank overtopping, which promoted thermal and mechanical erosion along an ice-wedge network and the drainage of L195 (Figure 3). Erosion and melting of ice during the drainage event formed a thermo-erosional gully that was 9 m wide, 2 m deep, and 70 m long. It is likely that this gully was completely eroded during the drainage event because we visited the site within ten days of drainage and again 40 days after drainage and documented no noticeable changes to the gully. Based on these measurements and the estimated water volume of 871,990 m^3 prior to drainage, we estimate that the drainage resulted in a measured peak flow of 25.0 m^3/s and an estimated, peak instantaneous discharge of 29.4 m^3/s, or 17.5% higher than was recorded (Figure 4). Although the drainage event lasted for 36 hours, 75% of the lake discharge occurred in the first ten hours.

Landscape Features and Drainage Events Since 1955

Thermokarst lakes (22.5%) and drained thermokarst lake basins (61.8%) currently account for ~84% of the landscape area on the younger outer coastal plain north of Teshekpuk Lake (Figure 5). Between 1955 and 2014, nine lakes completely or partially drained (>25% loss in lake surface area) or 0.17 lakes drained per year. Of these nine lakes, four drained between 1955 and 1977, two between 1977 and 1985, one between 1985 and 1992, one between 1992 and 2000, none between 2000 and 2007, and one between 2007 and 2014. This corresponds to a drainage rate of 0.18, 0.25, 0.14, 0.13, 0, and 0.14 lakes per year, respectively.

Lakes drained into three different settings. Two of the lakes drained directly into the sea, five drained into adjacent lakes, and two drained into river systems. It appears that one of the lakes was tapped by the lateral expansion of Teshekpuk Lake (Weller and Derksen, 1979), one directly by coastal erosion, whereas the other seven appear to have drained through a thermo-erosional gully that presumably developed as a result of water spilling out of the lake. The average length of seven thermo-erosional drainage gullies was 160 m but ranged from 30 m to 500 m.

Long-Term Climatic Conditions

The weather station at Barrow provides the best long-term regional dataset available during the observation period (1955 to present). Analysis of early summer air temperature and precipitation data (01 June to 15 July), within the time periods constrained by the U.S. Geological Survey topographic map and the Landsat imagery used in the study, shows varying patterns of precipitation relative to air temperature (Figure 6). Early summer air temperatures in 2014 were cool (1.9°C) compared with the 1955 to 2013 average (2.4°C). Total precipitation at Barrow during 2014 was 39.9 mm, the sixth highest amount recorded over the last 59 years, and twice the average between 1955 and 2013. During 2013, the year before L195 drained, total precipitation was 34.3 mm, which was also wetter than normal, but was considerably warmer (4.7°C) relative to the long-term mean (Figure 6).

DISCUSSION

Field Observations of Drainage Events

Although catastrophic lake drainage events are cited as a common Arctic landscape process, *in situ* observations of the timing and discharge associated with a natural drainage have previously not existed. Mackay (1981, 1997) induced and directly observed the catastrophic drainage of Lake Illsarvik in 1978 by excavating an artificial drainage channel in ice-rich permafrost. This experiment provided the first direct data on the duration and magnitude of a catastrophic thermokarst lake drainage event in the Arctic. Subsequently, Marsh and Neumann (2001) constrained the duration of a natural lake drainage from a downstream gauging station. Their data indicate that the event likely lasted 16 hours; however, due to instrument failure the magnitude of the event was not captured. Our observations of a natural drainage event indicate that for an 80 ha lake with a water volume

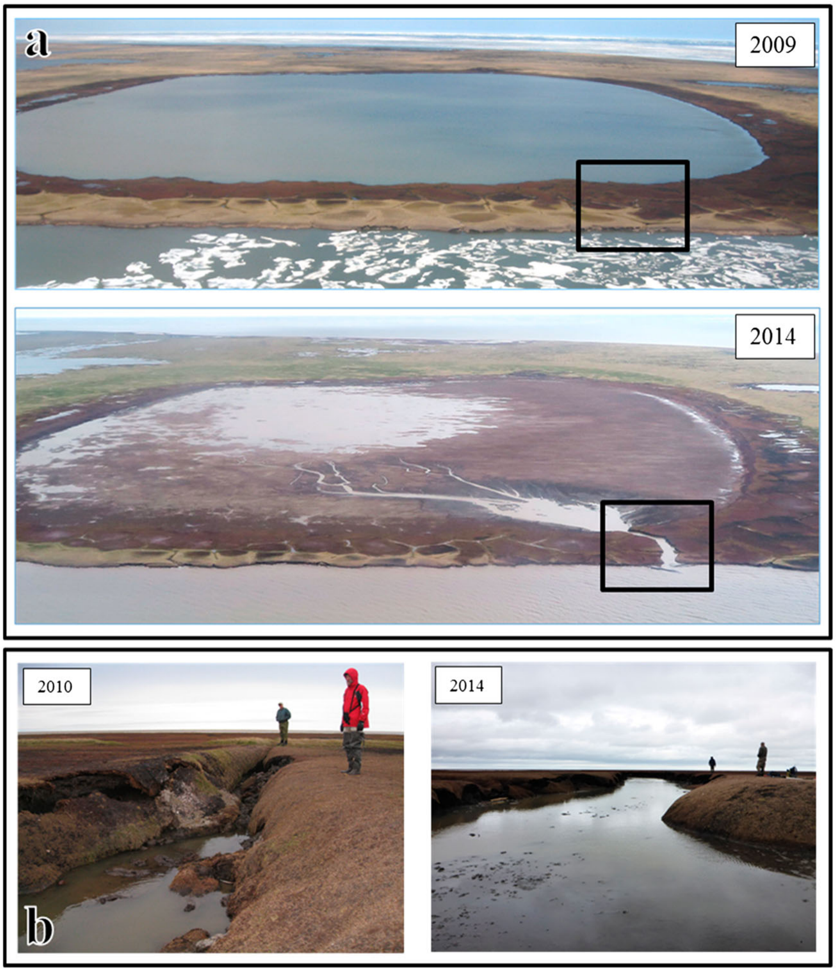

Figure 3 (a) Oblique aerial photographs of L195 in 2009 (top) prior to drainage and in 2014 (bottom) following drainage. (b) Ground photographs of a thermo-erosional gully (black boxes in Figure 3a) in 2010 (left) prior to drainage and again in 2014 (right) following the catastrophic drainage of L195. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

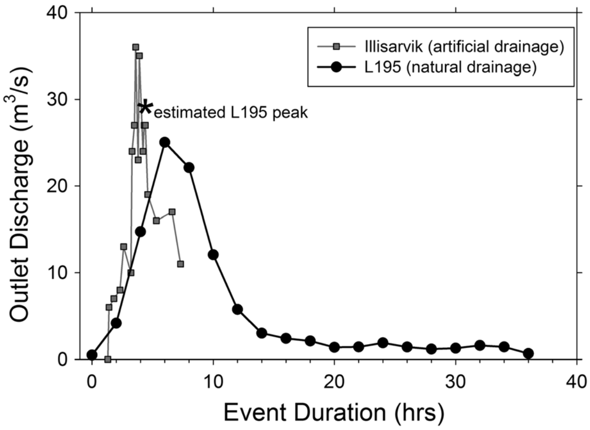

Figure 4 Observed outlet discharge generated by the natural drainage of L195 (black circles and line) and the outlet discharge generated by artificial drainage of Lake Illisarvik (grey squares and line) (Mackay, 1997; Marsh and Neumann, 2001). Asterisk indicates the estimated, peak instantaneous discharge associated with the L195 drainage.

of 871,990 m^3, that drainage can indeed be catastrophic, with the majority of it occurring in the first ten hours.

The observation network indicates that the cooler and wetter than normal early summer conditions in 2014 were likely responsible for the drainage of L195. The drainage was likely a result of bank overtopping and thermo-erosion along a course of interconnected ice wedges from the lake margin to the sea. Mackay (1988) indicated that thermo-erosion along an ice-wedge network due to lake bank overtopping was one of the most likely pathways controlling catastrophic lake drainage events. Since the drainage of L195 occurred in the early summer, limited seepage was likely occurring through the active layer prior to drainage, which could have allowed the lake to fill and spill over and erode the drainage pathway. However, we cannot rule out the possibility of subsurface thermal erosion and resulting ice-wedge tunneling as playing a role in the drainage of L195 (Marsh *et al.*, 2009).

Our findings support the notion of Mackay (1992) that early summer weather conditions likely have a major influence on catastrophic lake drainage events. Our sensor

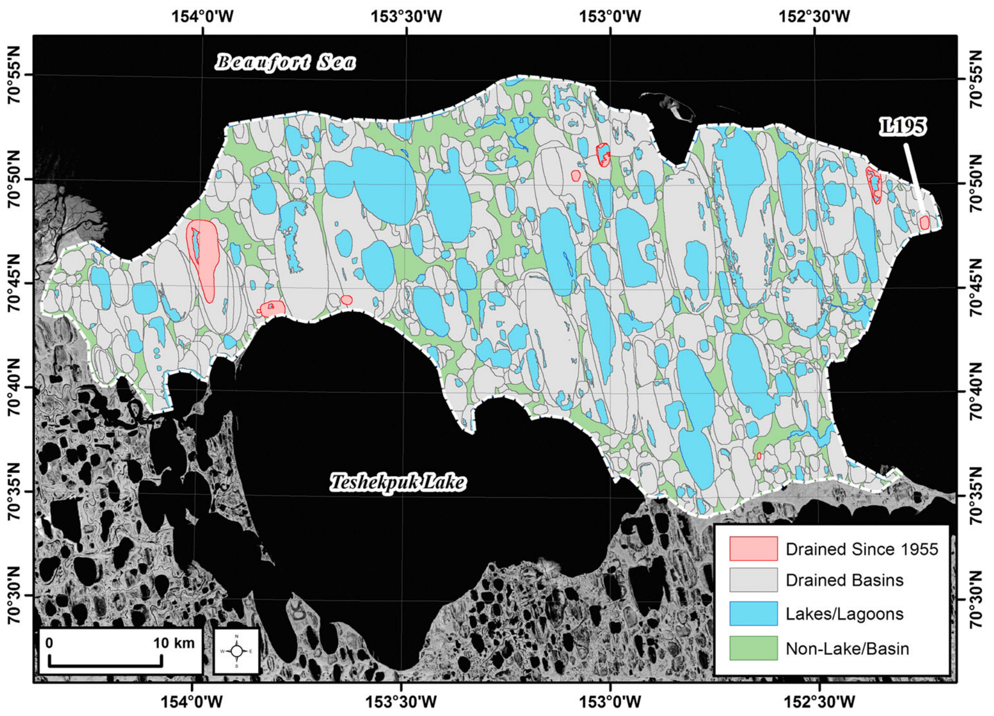

Figure 5 Landscape features derived from a Landsat TM image acquired on 20 August 2010 and updated with a Landsat OLI image acquired on 15 July 2014. Lakes that drained since 1955 are shown in red, older drained basins in grey, extant lakes in blue, and other terrain features in green. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

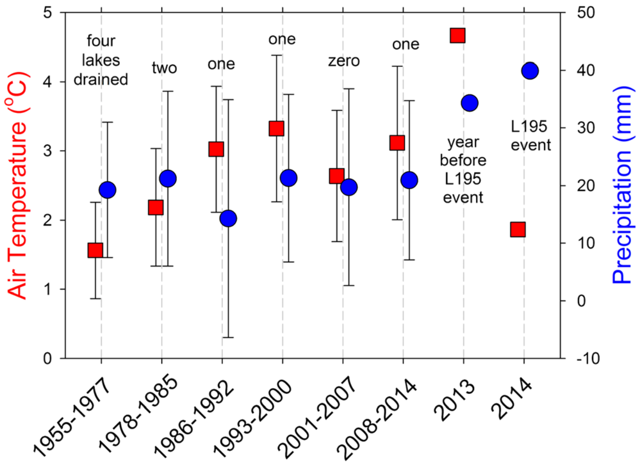

Figure 6 Mean early summer (01 June to 15 July) air temperature and precipitation derived from the Barrow, AK, climate station between 1955 and 2014 summarized by the time periods used to bracket lake drainage events in the study area. The early summer of 2014 experienced 92% greater precipitation relative to the record we analyzed going back to 1955. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

observations documenting the drainage of L195, along with local knowledge observations from an Inupiaq Elder (Hinkel *et al.*, 2007), and aerial reconnaissance and field observations at Lake Zelma in the Old Crow Flats (Wolfe and Turner, 2008), further support this notion of early summer conditions being critical to the catastrophic drainage of thermokarst lakes. However, the observations of Brewer *et al.* (1993) and Marsh *et al.* (2009) highlight the importance of late summer conditions as driving some catastrophic lake drainage events. Better constraining the seasonality associated with catastrophic lake drainage events will be important for predicting the response of these systems to future environmental change in the Arctic.

Remotely Sensing Lake Drainage Events

Reconstructing lake drainage events between 1955 and 2014, based on analysis of U.S. Geological Survey topographic maps and Landsat imagery, identified nine lake drainage events in the 1,750 km^2 study area (Figure 5). While retrospective analyses of remotely sensed data lack the detailed observations that we were able to describe prior to and during the drainage of L195, there appear to be patterns associated with early season weather conditions and lake drainage events (Figure 6). Lakes may have a higher tendency to drain when relatively cool early summer air temperatures and enhanced early summer precipitation prevail, similar to the conditions observed during 2014 and the associated drainage of L195.

Hinkel *et al.* (2007) identified three lake drainage events for this area between 1977 and 2000, providing a drainage rate of 0.13 lakes per year. By extending the period of record back to 1955 as well as forward to 2014 we have identified an additional six lake drainage events, with five of these occurring prior to 1977. This seemingly indicates a reduction in the drainage rate of lakes in the study area over the past ~60 years. Marsh *et al*. (2009) documented thermokarst lake drainage events in the western Canadian Arctic between 1950 and 1973, 1973 and 1985, and 1985 and 2000 and reported a decrease in the drainage rate of lakes from 1.13 to 0.83 to 0.33 lakes per year, respectively; they hypothesized that this decrease was linked to changes in climate during this period. Other studies documenting lake drainage events over time have reported steady (Jones *et al*., 2011) to increasing (Grosse *et al*., 2009; Lantz and Turner, 2015) patterns, highlighting the need for more concentrated and detailed field observations and data collection to determine the processes controlling catastrophic lake drainage events around the Arctic.

Our landscape-scale assessment of drained lake basins north of Teshekpuk Lake revealed ~15% greater coverage than previously mapped for the study area (Hinkel *et al*., 2005). This difference is not related to an increase in the number of lake drainage events since the early 2000s. Instead, it can be explained by the manual digitization of multiple overlapping drained basins that the automated techniques described in Frohn *et al*. (2005) struggled with, a cloud-free Landsat image (cloud cover was an issue in the imagery used by Frohn *et al*. (2005)), and the use of a high-resolution digital terrain model for distinguishing the perimeters of these sometimes subtle landscape features.

Peak Discharge Associated with Drainage Events

The observed peak discharge of 25.0 m^3/s and the estimated peak instantaneous discharge of 29.4 m^3/s associated with the catastrophic drainage of L195 are similar to the 36 m^3/s peak discharge measured at the much smaller (340,000 m^3) Lake Illisarvik (Marsh and Nuemann, 2001; Mackay, 1997). Marsh and Nuemann (2001) also provided estimates of peak discharge for a lake with an estimated volume of 112,500 m^3 that catastrophically drained in 1989. Based on a record from a downstream hydrograph, this drainage occurred over a 16 hour period, with an estimated peak discharge of 29 m^3/s likely occurring 6 hours after the onset of drainage (Marsh and Nuemann, 2001). Thus, these three observations from lakes that vary in surface area and volume indicate peak discharge floods that range from 25 to 36 m^3/s for catastrophic drainage events. However, lakes and drained lake basins can be several orders of magnitude larger than these three examples (Figure 5). Thus, the catastrophic floods generated during future lake drainage events from larger or deeper lakes or during past lake drainage events require further analysis (Marsh *et al*., 2008). Nonetheless, the fact that 50-75% of the landscape area in several Arctic lowland regions (Hinkel *et al*., 2003; Grosse *et al*., 2005; Hinkel *et al*., 2005; Jones *et al*., 2012) represents drained lake basins means that these events have likely had a dramatic influence on downstream ecosystems and erosion of the landscape, and pose a potential threat to infrastructure (Marsh *et al*., 2009).

Comparison of observed peak discharge measurements from L195 and Lake Illisarvik with peak discharge measurements from various ordered North Slope of Alaska river basins (Kane *et al*., 2000; Whitman *et al*., 2011; Arp *et al*., 2012) shows that peak discharge from catastrophic lake drainage events can exceed snow-melt generated peakflows for Arctic river basins that are more than two orders of magnitude larger (Figure 7). The smallest catchment that we could find with a long-term gauged station (minimum of five years of data) for comparison to L195 (~1 km^2) is Imnavait Creek (~2 km^2). This site is located in the Arctic Foothills of northern Alaska and has an average annual peakflow of 1 m^3/s (Kane *et al*., 2000). Normal peak discharge for coastal plain catchments that are more than one order of magnitude larger than L195, averaged 3.5 m^3/s (Whitman *et al*. 2011). Watersheds more than two orders of magnitude larger than L195 experience average snowmelt peak discharges between 30 and 100 m^3/s (Kane *et al*., 2000, Arp *et al*., 2012) (Figure 7), though it is recognized that extreme rainfall events can generate even higher peak flows in Arctic rivers (Kane *et al.* 2003). Thus, the event discharge generated by the drainage of L195 was of a similar magnitude as can occur from river basins more than two orders of magnitude larger. Effective flows in many low-order Arctic streams and rivers are moderated by channel-armoring bedfast ice during normal snowmelt peak flows, thus reducing erosion and sediment transport (McNamara and Kane, 2011). This comparison indicates that the one-time flood events generated by catastrophic lake drainages may be highly effective at restructuring downstream river channels and transporting large amounts of sediment. Such drainage events are presently infrequent in the study area, but the abundance of drained lake basins in the region points to this type of flood as potentially important for Arctic river systems and landscape modification over the Holocene.

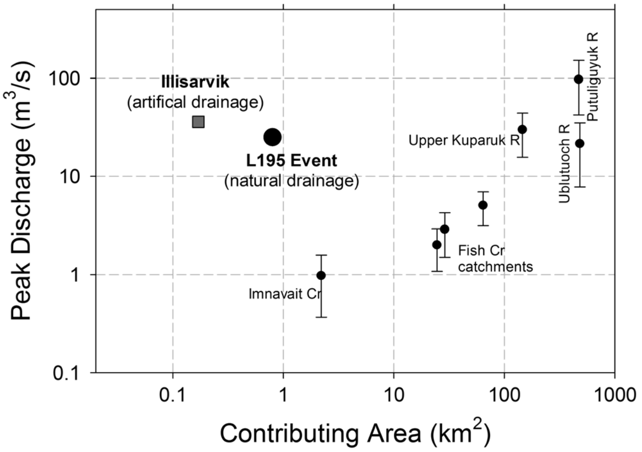

Figure 7 The observed peak discharge at L195 compared to the artificial drainage of Lake Illisarvik (Mackay, 1997; Marsh and Neumann, 2001) and normal, climatically-driven annual peak flows (mean +/- 1 standard deviation, n=5) for a range of watersheds in Arctic Alaska (Kane *et al.* 2000, Whitman *et al.* 2011; Arp *et al.* 2012).

CONCLUSION

By deploying *in situ* sensors in a thermokarst lake that we anticipated as having a high likelihood to drain, we have provided detailed information on the environmental conditions, timing, and discharge associated with a natural drainage event. The 80 ha thermokarst lake drained on 05 July 2014 over a course of 36 hours, with 75% of the 871,990 m^3 volume of water loss occurring 10 hours after the onset of drainage. Peak discharge was observed to be 25 m^3/s and the estimated, peak instantaneous discharge was 29.4 m^3/s. The lake likely drained as a result of cooler than normal air temperatures and higher than normal rainfall and snowmelt runoff during early summer. These conditions elevated the lake water level and promoted permafrost degradation through bank overtopping and thermo-erosion along an ice-wedge network. The discharge generated by this lake drainage event was of a similar magnitude to that of northern Alaska river basins whose areas are more than two orders of magnitude larger. The fact that 62% of the 1,750 km^2 area assessed during this study was mapped as drained thermokarst lake basins indicates that catastrophic drainage events have likely had a major influence on the hydrology and geomorphology of this ice-rich permafrost dominated lowland. Our findings indicate that thermokarst lakes may be primed for drainage in early summer, when cold and wet weather conditions prevail, and that drainage may result from bank overtopping and thermo-erosion along an ice-wedge network. These findings support several of the observations provided by J.R. Mackay during his many field seasons spent studying lakes and drained lake basins in the Canadian Arctic.

ACKNOWLEDGEMENTS

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