Predicting the future hydrology of western Canadian Arctic watersheds dominated by thermokarst lakes

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Abstract

Across extensive areas of the Arctic, watersheds have a myriad of lakes that cover up to 50% of the total surface area and can be linked together in complex streamflow networks. Warming of ice-rich permafrost has significant impacts on the interactions between surface water, shallow surface water, lakes, and streamflow. Most of these lakes formed from the melting of massive ground ice over the past millennia and are termed thermokarst lakes. Thermokarst lakes are susceptible to rapid, or catastrophic, drainage due to permafrost degradation, especially where ice-wedge polygons occur in low-lying areas adjacent to these lakes. These drainage events are increasing as of recent, for reasons unknown, and can create extreme floods that are a risk to people and infrastructure located downstream, and the destruction of fish habitat. To answer key questions related to this apparent crossing of a key tipping point in the viability of these lakes, this is a review of the new projects we have initiated at the Trail Valley Creek research station, north of Inuvik, NT, to investigate the controls on thermokarst lake drainage. We will use a combination of field observations, satellite data, remote sensing, and ultra high-resolution modelling focused on thermokarst lakes, ice-wedge polygons, and the impact of beaver activities, to answer key questions related to the history of lake drainage over the last 70 years and consider the future viability of these lakes. Insights gained from this study will help support climate change mitigation efforts for northern communities and ecosystems.

1 Introduction

Recent changes in the Arctic are having an impact on the interactions between surface water, supra-permafrost water, lakes and streamflow, particularly as ongoing climate warming continues to thaw ice-rich permafrost (Box et al. 2019). This recent and continuing thawing of permafrost poses a threat to ecosystems, infrastructure, and indigenous communities in the Canadian Arctic (Hjort et al. 2018; Krogh and Pomeroy 2021) and will change the water and carbon balance in the region (Burke et al. 2017; Anderson et al. 2020).

Arctic watersheds have a myriad of lakes that range from seasonally flooded wetlands to shallow or deep lakes and are important for controlling streamflow, aquatic habitat and supplying local water for northern communities (Marsh et al. 2009; Webb et al. 2022). In ice-rich permafrost, many of these lakes are formed, or enlarged, by the thawing and draining of meltwater during warm periods, which leads to land subsidence and creates topographic depressions that may be infilled by water (Marsh et al. 2009; Woo 2012). For these types of lakes, termed thermokarst lakes, the lake water surface elevation is sensitive to changes in lake water balance/lake level, increased groundwater outflow as the permafrost thaws, or by the erosion and/or melting of the shoreline by thermokarst processes, which can happen at annual or decadal periods (Kokelj et al. 2009; Marsh et al. 2009; Pohl et al. 2009).

Thermokarst lakes are susceptible to rapid, or catastrophic, drainage due to the warming of the permafrost, especially where ice-wedge polygons occur in low-lying areas adjacent to these lakes (Marsh et al. 2009; Jones et al. 2023). Thermokarst lake drainage, not coinciding with the original lake outlet, could be due to melting of ground ice currently holding in lakes. Mackay (1988, 1992) suggests at least two common scenarios for rapid lake drainage, both dependent on high lake levels (due to snowmelt or after heavy rainfall events), which leads to water flowing over or through ice-wedge networks. The first is when the lake level is high, commonly in the spring, lake water will enter through interconnecting winter ice-wedge cracks (i.e., thermal contraction cracks), allowing for tunnel flow, where the wedge ice can melt, leading to rapid drainage. A second possibility is when water from the high lake level overflows ice-wedge troughs and the sustained flow thaws the wedge ice from the top down. These drainage events can create extreme floods that are a risk to people and infrastructure located downstream, and the destruction of fish habitat (Marsh and Neumann 2001; Marsh et al. 2009).

Over the last 8,000 years, thermokarst lakes in the western Canadian Arctic have been draining at a rate of approximately one lake per year (Mackay 1988). Marsh et al. (2009) showed that between 1950 and 2000, the rate of lake drainage had decreased by one third. As the climate continues to warm and permafrost thaws, a tipping point would be reached where the rate of drainage would increase dramatically. Recent work by Kariyawasam and Marsh (2022) found that the rate of lake drainage has almost tripled between 2004 and 2019. Similar trends of lake drainage were found in the permafrost regions of Northern Alaska by Lara et al. (2021). Reasons for this recent increased rapid lake drainage are not well known, as only a few thermokarst lake drainage events have been studied (Mackay 1974; Jones et al. 2023), which raises significant concerns.

This recent increasing trend has been attributed to increases in mean annual air temperature and precipitation, lengthening of the thaw season, and increasing near-

https://doi.org/10.52381/ICOP2024.199.1

surface permafrost ground temperature that will destabilize ice-rich permafrost soils (Swanson 2019; Nitze et al. 2020; Lara et al. 2021). The presence of beaver activity in low Arctic tundra regions of Alaska and Canada has implications for surface water changes and ice-rich permafrost degradation (Jones et al. 2020) and is responsible for some rapid lake drainage events (Jones et al. 2023; Tape et al. 2018, 2022).

With recent warming and changes occurring in the Arctic, we expect these lakes will continue to change dramatically in the future, but due to our lack of knowledge of the controlling processes and the lack of data on their current state, we do not have an understanding of how these lakes are currently changing or how they will change in the future. Thermokarst lakes drainage is increasing as of recent for reasons unknown, which are a risk to people and infrastructure located downstream, and the destruction of fish habitat. To answer key questions related to this apparent crossing of a key tipping point in the viability of these thermokarst lakes, new projects, using a combination of field observations, satellite data, remote sensing, and ultra high-resolution modelling, will examine permafrost degradation and monitor changes to the surface and subsurface hydrology, and thermal regimes in ice-wedge polygons, and investigate the impact of beavers on lake levels, in order to consider the future viability of these lakes.

2 Trail Valley Creek Research Observatory

The Trail Valley Creek (TVC) research observatory, approximately 50 km north of Inuvik, NT, is located in the taiga-tundra transition zone and underlain by ice-rich continuous permafrost (Figure 1). As a long-term research facility, it provides +30 years of available climate, lake and permafrost observations supporting the studying of controlling processes and ongoing changes in the region. In and around the TVC watershed, there are two Environment Canada and Climate Change hydrometric gauges: one on TVC, where the watershed contains 16 lakes that cover <1% of the basin area; and at Hans Creek, a neighbouring watershed, which contains 293 lakes that cover 10% of the basin area. These hydrometric stations have provided streamflow measurements since 1979. The nearby Inuvik-Tuktoyaktuk highway (ITH) provides easy access in tundra region and the research site. The TVC research observatory has enhanced instrumentation such as precipitation radar, cosmic ray sensors for snow and soil moisture, and a network of eddy covariance systems in place. In addition, five lakes are currently monitored in the TVC watershed for water levels, evaporation, and discharge. This paper is a review of the new projects implemented at the TVC research observatory, that are focused on the drainage of thermokarst lakes and how these events relate to ice-wedge polygons, and the impact of beavers on lake levels.

3 Monitoring Thermokarst Lakes

With the western Canadian Arctic having many thermokarst lakes that cover a large percentage of the total land surface, there is limited monitoring of thermokarst lake size and water surface elevation, with only a few studies having mapped these lakes (Marsh et al. 2009; Cooley et al. 2019). Additionally, lake-hydrology models used in past studies for this region have a limited capacity to simulate changes in permafrost lake area, occurrence, or water surface elevation (Pohl et al. 2009, Bowling and Lettenmaier 2010).

With the focus on thermokarst lakes within the Trail Valley Creek and Hans Creek basins, we will develop, test, and apply an integrated system of ground-based observations, satellite remote sensing, and enhanced hydrological models, to monitor changes in lake area and water elevation across the sensitive permafrost terrain. An extensive lake observation network across the study region is currently in place, with observations of water surface elevation and outlet discharge, to quantify the variability in lake conditions. Processes controlling lake water balance for single lakes will be examined and applied to further develop a lake-hydrology model for simulating water balance and water surface elevation.

Five thermokarst lakes are currently being monitored in the Trail Valley Creek basin for water levels, evaporation, and discharge. Two of these five lakes, Big Bear and Little Bear lakes (BBL and LBL) are currently instrumented to monitor water temperature, surface elevation and outflow (Figure 1). This project will use the existing data for these lakes from the last 5 years, and continue the collection of current and new observations, which will include runoff from surrounding watershed into the lakes, lake level, lake evaporation using eddy covariance, and lake outflow to document all aspects of the lake water balance. This will allow us to detect changes and advance the development of predictive watershed/lake models to further understand the drivers and trajectory of changes to thermokarst lakes.

3 Ice-Wedge Polygon Site

Ice-rich permafrost regions contain ice-wedge polygon terrain that form when frozen ground cracks due to thermal contraction and fill with meltwater that freezes to form a vein of ice (Mackay 1974). Repeated cracking over hundreds or thousands of years can lead to the development of large ice-wedges spanning several meters across (French 1974). Polygonal terrain can contain high, intermediate, or low-centred polygons, where the troughs in between provide favourable locations for infiltration, water storage and flow (Woo 2012). Troughs are modified and enlarged by thermo-erosion of the wedge ice, the collapse of side walls, and by erosion due to running water. Troughs can link up to form a gully system that conveys the flow to a stream or fans out to inundate depressions downslope (Woo 2012). With Arctic warming, ice-wedge degradation increases, creating deep ponded troughs and the destruction of low-centred polygon rims, to create high-centred polygons that could develop into a well-established drainage network of troughs (Woo 2012).

With instruments recently installed at an ice-wedge polygon site, just northeast of the TVC research observatory (Figure 1), we will use a combination of field sampling, drones, and a high-resolution hydrological model to examine permafrost degradation and monitor changes to the surface and subsurface hydrology and thermal regimes. During the

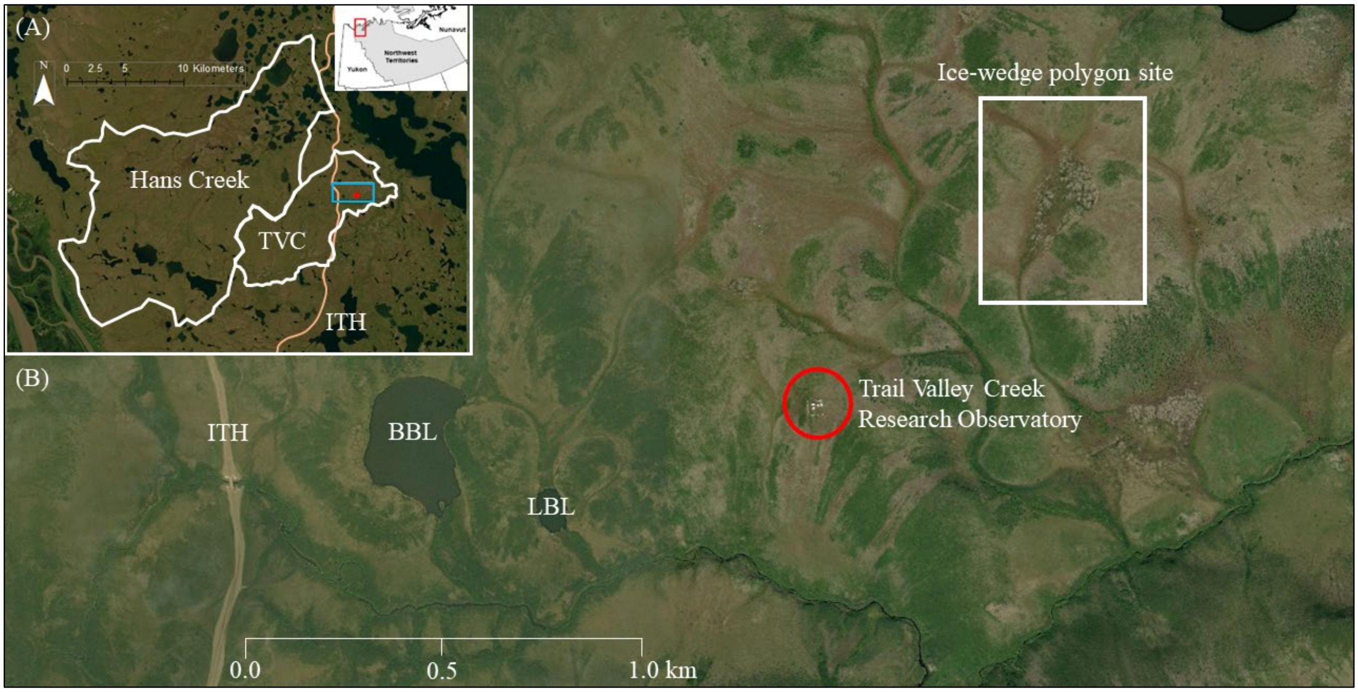

Figure 1. (A) Location of the Hans Creek and Trail Valley Creek (TVC) watersheds, and the Inuvik-Tuktoyaktuk Highway (ITH), in the Northwest Territories. Blue box is the spatial extend of the Trail Valley Creek watershed around the TVC research observatory, located by the red dot. (B) Spatial extend of the TVC watershed around the research observatory (circled in red), with the location of the ITH, Big Bear Lake (BBL), Little Bear Lake (LBL), and the ice-wedge polygon site (white box).

summer of 2022, the ice-wedge polygon site was outfitted with nine ground temperature boreholes and thirteen water level wells. Monitoring sites were installed along three transects roughly perpendicular to the calculated flow direction (Figure 2). We will conduct an analysis of the permafrost conditions along these transects with a focus on polygon centre, rim, and trough regions. The maximum ground temperature borehole depths range from 1.5 m (troughs and rims) to 3 m (centres). Groundwater wells were installed at maximum depths of 1.5 m to monitor groundwater gradients throughout the ice-wedge polygon field. Frost table depths were recorded along the transects throughout each summer.

Using this newly instrumented polygon site, we will investigate both lake and ice-wedge controls on the observed changes in thermokarst lake drainage. Specifically, we will consider two key processes: ice-wedge cracking and overtopping of ice-wedge fields. We will determine if permafrost temperatures within ice-wedge polygons increased sufficiently to minimize ice-wedge cracking over the period 1950 to present, and therefore resulted in a decrease in the rate of lake drainage due to this cracking. We will examine if there is an increase in overtopping events due to higher lake levels or deeper active layer. We will model winter ice-wedge temperatures and active layer (i.e., depth to the top of the ice-wedge) to consider the impact of climate changes on processes controlling rapid lake drainage.

Process-based models are essential tools to help understand complex hydrological processes in the Arctic. There is a need for a new generation of hydrological models that can account for spatial heterogeneity and can integrate surface and subsurface hydrology, lakes, vegetation, and permafrost. Our study will use the cryohydrogeological model GEOtop, a finite-difference numerical model, which integrates the surface/subsurface model of permafrost thermal hydrology (Endrizzi and Marsh 2010; Endrizzi et al. 2014). It has been shown to be applicable for simulating surface energy balance, hydrology, and permafrost conditions, and has been tested at a hyper-resolution scale (Endrizzi and Marsh 2010; Endrizzi et al. 2014). It uses coupled numerical solution of heat and water flow equations in soil and snow cover, which can consider frost table depth, soil moisture and runoff. We will be applying GEOtop to understand changes in permafrost temperature and therefore, ice-wedge cracking over the full study period. It will also be applied to understand increasing active layer thickness at the top of the ice-wedge polygons, therefore the increasing probability of the flow of lake water over the tops of this terrain.

Using data collected from the polygon centres, rims, and troughs, we will use GEOtop to further examine permafrost degradation and the effect of microtopography on the thermal hydrology in the system. When modelling we will consider the model initialization, dividing the subsurface into moss, peat and mineral soil layers, the trough depths (e.g., deeper troughs lead to increase snow entrapment), the lateral water fluxes (e.g., water flow from centre to trough or reversed), how the polygon rims are exposed to summer and winter climate extremes, and will compare simulated and modelled soil temperatures at different depths for each centre, rim, and trough.

Figure 2. Ice-wedge polygon site located just northeast of the Trail Valley Creek research observatory. White lines represent the three transects, which are roughly perpendicular to calculated flow direction (blue arrow), that are used as continuous monitor sites.

4 Beaver Impact Research

Beaver activity in this tundra region offers an opportunity to study the interactions between beavers, permafrost, and thermokarst lake dynamics (Jones et al. 2020) and how they relate to the increased growing season length and an increase in shrub cover (Tape et al. 2006, 2018). Increased winter snowfall and increasing winter air temperature is likely increasing the over-wintering habitat potential for beavers (Arp et al. 2018). Shorter winters reduce the duration that beavers must remain in their lodges. Finally, change in native subsistence and hunting lifestyles in the region and the reduction in the desire of beaver pelts and underfur (Tape et al. 2018).

Streamflow and lake levels in low tundra regions are prone to changes due to beaver activities (Woo and Waddington 1990). Jones et al. (2020) have shown that beavers can cause lake expansion and drainage, thaw slump initiation and permafrost degradation. Stream and river channels are more stable prior to beaver activity, whereas once introduced into the basin, there is pond formation, evolution and channel modification or diversion (Tape et al. 2018). Dammed basins tend to lose more water to evaporation, with the lake outflow suppressed and an increase in basin water storage.

Beaver activities have been found to contribute to rapid lake drainage (Tape et al. 2018, 2022). Jones et al. (2020) found that beavers were the primary driver of surface water area increases in Northern Alaska, but their engineering activities had caused the drainage of some thermokarst lakes. Jones et al. (2023) found the presence of a beaver in a lake just days before the drainage of a thermokarst lake on the Baldwin Peninsula. Shrubs that were chewed on the shore indicates that the beaver may have played a role in the lake drainage event. Marsh et al. (2009) surveyed select areas in 2004 to determine if these areas were due to drained lakes. When the area was resurveyed in 2007, two small partially drained lakes were noted near Noell Lake. These lakes had beaver dams at the outlet and were breached, resulting in partial lake drainage. Kariyawasam and Marsh (2022) monitored a thermokarst lake site in August 2019 and discovered a rise and sudden collapse in lake level due to a beaver dam. Jones et al. (2023) hypothesize that beaver activity by burrowing into the banks of a thermokarst lake could promote underground tunnel flow and the erosion of ice-wedges, contributing further to the increase rate of Arctic lake drainage, thus becoming a new thermokarst lake drainage mechanism to be considered.

With a combination of digital imagery and field sampling, we will identify and locate beaver dams and beaver activity around the TVC region, using the protocol for mapping beaver lodges, and dams based on beaver dam classifications by Woo and Waddington (1990). Water level recorders were installed at selected lakes across the region to record surface water elevation, while Water Survey of Canada discharge measurements and manual discharge measurements are obtained for select sites. A variety of remote sensing methods to map changes in snow, vegetation, beaver locations, and lake properties will be used. This study will quantify beaver impacts on water storage and discharge through observations of stream and lake properties with and without active beaver populations and dams. We will assess how water storage from beaver dams will impact streamflow and address the role of beavers in limiting discharge during drought and their impacts on incised streams. We will consider impacts on lake or pond area, lake water storage volume, lake/stream flows and water temperature.

5 Summary

Vast number of lakes across the western Canadian Arctic are in areas of ice-rich permafrost. As climate is rapidly changing, important controls on thermokarst lakes are also changing, making them prone to rapid drainage and being transformed into drained lake basins. Observed and expected changes include permafrost thaw, influence of beaver activities, changes to evaporation rates, lake levels, lake ice depth and duration of ice cover, changes in precipitation, snow accumulation and melt timing. These anticipated changes will have significant impacts on ecosystems and northern communities.

The Trail Valley Creek research observatory, underlain by ice-rich continuous permafrost, has various ice-wedge polygon sites located near and across the tundra-taiga ecotone. As a long-term research facility, it provides over 30 years of available climate, lake, and permafrost observations supporting the studying of controlling processes and ongoing changes in the region. These new projects at TVC will be a synthesis of monitoring snow, ground temperature, and permafrost conditions, with modelling efforts focused on the drainage of thermokarst lakes and how these events relate to ice-wedge polygons, and the impact of beavers on lake levels. We will apply high-resolution mathematical models of permafrost-lake-hydrology systems to investigate the crossing of an apparent tipping point in thermokarst lake drainage and consider the future viability of these thermokarst lakes.

6 Acknowledgements

Funding for these projects was supported by ArcticNet. The authors acknowledge that this study was conducted in the Inuvialuit Settlement Region in the western Canadian Arctic. The authors wish to acknowledge the advice and comments provided by the reviewers of this paper.

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