PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. (2016)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/ppp.1895

Can Deep Groundwater Influx be Detected from the Geochemistry of Thermokarst Lakes in Arctic Alaska?

Kenneth M. Hinkel,[1,2]* *Christopher D. Arp,*[3] *Amy Townsend-Small*[1,4] *and Karen E. Frey*[5]

[1] Department of Geography, University of Cincinnati, Cincinnati, OH, USA
[2] Michigan Technological University, Geological and Mining Engineering and Sciences, Houghton, MI, USA
[3] Water and Environmental Research Center, Institute of Northern Engineering, University of Alaska Fairbanks, Fairbanks, AK, USA
[4] Department of Geology, University of Cincinnati, Cincinnati, OH, USA
[5] Graduate School of Geography, Clark University, Worcester, MA, USA

ABSTRACT

In the continuous permafrost zone, unfrozen ground may exist beneath large lakes and streams. Sub-lake taliks that extend through permafrost provide a potential conduit for subpermafrost groundwater to reach the surface, increasing dissolved ion concentrations in lake water. Twenty-eight lakes on the Arctic Coastal Plain of northern Alaska were sampled in 2013–14 to determine whether a difference in ionic concentration could be detected between lakes with and without through taliks. A thermal model originally developed by J. Ross Mackay indicated that 20 of the lakes may have a talik that penetrates the permafrost. Lake water samples were analysed for a variety of ions and geochemical properties. Generally, there was little interannual variation in ion concentration, pH and specific conductivity of lake water. Proximal lakes tended to have similar chemical signatures, but there were large variations across the study region. Local factors appeared largely to control lake water chemistry. Lakes with suspected through taliks did not demonstrate a hydrochemical signature distinct from nearby lakes lacking a through talik. This suggests that either: (1) there is no hydrological connection with subpermafrost groundwater due to aquicludes in the subsurface; (2) the flux of groundwater is too small to have a measurable impact on lake water chemistry; or (3) the steady-state condition for talik configuration assumed in the thermal model is not justified. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: arctic lakes; talik, thaw lakes; lake water chemistry; groundwater; permafrost

INTRODUCTION

In regions underlain by permafrost, water bodies tend to raise the mean annual temperature (MAT) of the lake or stream bed (e.g. Burn, 2005), but in the continuous permafrost zone, warming by several degrees may not elevate the MAT above 0 °C. However, if the water body is sufficiently deep that it does not freeze to the bed in winter, the MAT will be above the ice point and a talik will develop in the underlying sediments. Given sufficient time, the thermal perturbation beneath deep and large lakes or streams may penetrate the permafrost body, creating a talik that may connect the lake with subpermafrost water in the process.

The presence of a sub-lake talik may be established using several approaches. Boreholes (Burn, 2002; Lin *et al.,* 2010) and geophysical methods are effective in locating the boundary between frozen and unfrozen ground near the surface (Nolan *et al.*, 2009; Schwamborn *et al.*, 2002), but are time-consuming, expensive and less effective at greater depths beneath the lake. Alternatively, thermal equilibrium (Mackay, 1962) or dynamic numerical models may be used to evaluate the impact of a surface thermal disturbance on the subjacent ground (Ling and Zhang, 2003, 2004; West and Plug, 2008). J. Ross Mackay (1962) examined the ground temperature regime beneath lakes in the Canadian Arctic in the late 1950s in an effort to understand pingo formation. Adapting a one-dimensional model developed by Lachenbruch (1957, 1959) and using field data, Mackay was able to estimate talik configuration beneath lakes assuming steady-state thermal conditions. His benchmark paper 'Pingos of the Pleistocene Mackenzie Delta area' (1962) was the result of these efforts. Subsequently, M. Smith (1976) and Burn (2002) modified and expanded the approach to account for elongated water bodies. Burn

* Correspondence to: K. M. Hinkel, Department of Geography, University of Cincinnati, Cincinnati, OH 45221, USA. E-mail: Kenneth.Hinkel@uc.edu

Received 30 June 2015
Revised 19 January 2016
Accepted 24 January 2016

(2002) applied these methods, and field data from Todd Lake (informal name), to determine talik conditions beneath lakes on Richards Island near the western Canadian Arctic coast. Hinkel and Arp (2015) used the same methods to estimate the talik conditions of 28 lakes located in the continuous permafrost of Arctic Alaska from which the requisite morphometric and temperature data had been collected as part of the Circumarctic Lake Observation Network (CALON) project (Table 1; Figure 1). The analysis suggested that 20 of these lakes were large and deep enough to have a talik extending through the permafrost, while eight lakes had no talik or only a shallow talik beneath the lake bed.

On the Alaskan North Slope, a relatively thin layer of frozen Quatrnary marine, fluvial and aeolian sediments overlies Tertiary and Cretaceous sedimentary rock. The thick, continuous permafrost includes the overlying mantle and the underlying sandstone, shale and carbonate rocks. Thus, taliks extend beneath lakes through unfrozen sediments and into the underlying bedrock. In porous sedimentary units lacking aquicludes, the surface water may be hydrologically connected to the subpermafrost water at depth. Deming *et al.* (1992, 1996) analysed high-resolution temperature logs of 21 deep boreholes in the region, and found that thermal gradients were inversely correlated with elevation, varying from 22 °C/km in the foothills of the Brooks Range to 53 °C/km on the outer coastal plain. Estimated near-surface heat flow showed a similar pattern, with the flow at the coast three times greater than that observed in the foothills. Significant east-west variation in subsurface temperature and heat flow was also apparent (Deming *et al.*, 1996, their Figure 10). These spatial patterns led Deming *et al*. (1996) to infer that gravity-driven groundwater flow at depth perturbs the thermal field across the 300 km expanse of the North Slope. In their model, groundwater is recharged in the Brooks Range and flows northward through permeable strata beneath the permafrost; the estimated Darcy velocity is of the order of 0.1 m/yr. Deming *et al*. (1996) postulated that through taliks beneath large lakes and rivers provide flow pathways to the surface, although they suggested that the bulk of the discharge occurs offshore, north of the coastal plain.

Previous studies from the discontinuous permafrost zone have demonstrated coupling between surface and subpermafrost groundwater, with rapid lake-level lowering or drainage occurring via through taliks (Smith *et al.*, 2005; Yoshikawa and Hinzman, 2003). Assuming porous and permeable bedrock and sufficient hydraulic head for

Table 1 Location and basic characteristics of lakes discussed in this study. *Note*: The right-hand column indicates the estimated depth (m) to the top of the permafrost using the method of Mackay (1962) and Burn (2002), as reported in Hinkel and Arp (2015).

Lake	Lat (N)	Long (W)	Area (ha)	Depth (m)	Surficial sediments	Depth to permafrost (m)
Brw-100	71.24163	156.77391	183.8	2.3	Silt/sand	Through talik
Brw-103	71.12312	156.31664	179.8	1.9	Silt/sand	Through talik
Brw-107	71.27396	156.49700	125.0	1.9	Silt/sand	Through talik
Ikp-001	70.78966	154.45043	68.7	2.7	Silt	Through talik
Ikp-002	70.81512	154.42441	14.8	0.5	silt	< 1
Ikp-003	70.79303	154.51704	11.2	2.7	silt	18
Lmr-400	70.75409	156.72044	252.3	1.5	sand	Through talik
Lmr-402	70.72825	156.84290	356.0	1.0	sand	Through talik
Tes-001	70.76625	153.56248	979.9	2.5	silt	Through talik
Tes-002	70.78914	153.47001	265.3	0.8	silt	< 1
Tes-003	70.86790	153.77329	356.7	0.9	silt	< 1
Tes-005	70.75189	153.86877	34.0	0.6	silt	< 1
Tes-006	70.70613	153.92424	110.1	2.2	silt	Through talik
Atq-200	70.45475	156.94790	271.3	2.5	sand	Through talik
Atq-202	70.28790	156.98490	148.8	2.4	sand	Through talik
Atq-207	70.32911	156.59154	353.6	3.5	sand	Through talik
FC-9819	70.26970	151.35505	100.5	1.8	sand	Through talik
FC-9820	70.26666	151.38647	128.5	1.1	sand	Through talik
FC-9925	70.24689	151.47762	87.4	0.4	sand	< 1
FC-0066	70.14686	151.76467	104.5	2.4	sand	Through talik
Ini-001	69.99615	153.07007	66.4	4.4	sand	Through talik
Ini-002	69.99998	153.03666	1.3	0.8	sand	< 1
Ini-003	69.95922	152.95072	417.3	2.2	sand	Through talik
Ini-005	70.01843	153.18606	4.9	2.1	sand	12
Ini-006	70.21893	153.17164	361.7	4.3	sand	Through talik
Rdc-300	69.96079	156.54585	63.8	6.0	silt	Through talik
Rdc-308	69.98635	156.42445	78.7	2.2	silt	Through talik
Rdc-311	69.99614	156.68912	76.9	7.0	silt	Through talik

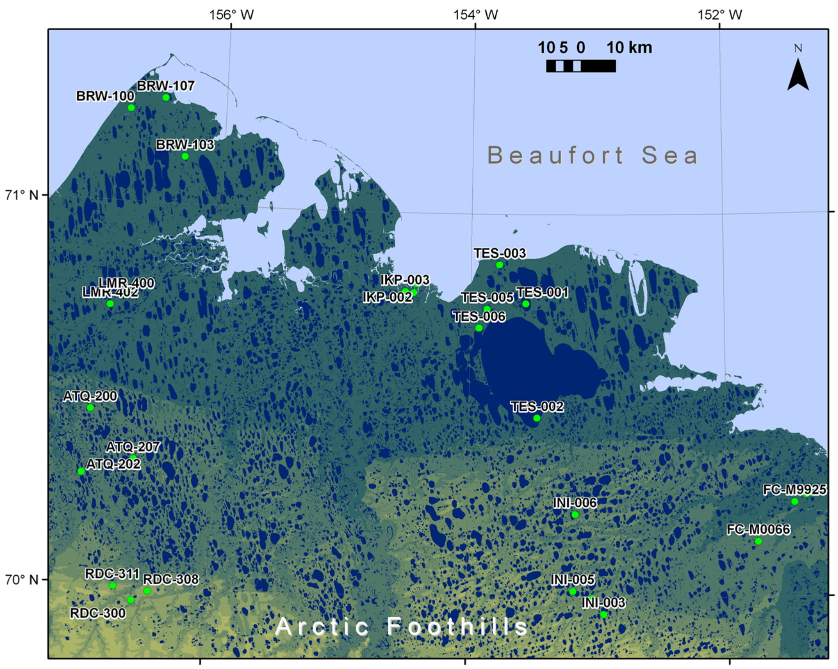

Figure 1 The North Slope of Arctic Alaska indicating lakes sampled in this study. The mosaic is derived from several Landsat Thematic Mapper and Enhanced Thematic Mapper scenes obtained in 2001 and 2005. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

artesian flow, we suggest that lakes linked to subpermafrost groundwater via a talik may receive an upward influx of ion-rich groundwater, as has been observed with stream flow (Frey *et al.*, 2007). Lake water levels are primarily maintained by relatively pure meteoric water in the form of rain and snowmelt, with some input of meltwater from the thawing ground in summer. Given that slow-moving groundwater beneath the North Slope has resided in the subsurface for over 10^6 years, it presumably has a higher solute concentration than surface water. We hypothesise that lakes with a subpermafrost groundwater contribution should therefore have higher concentrations of mineral ions in solution. Summer evaporation will tend to increase the concentration of solute in lakes, since evaporation is a fractionating process. Even if the volume contributed by groundwater is relatively small, the solute concentration of lakes receiving groundwater should be greater than nearby lakes lacking a through talik. Standard chemical metrics such as pH, conductivity and ion concentrations might provide evidence of a subpermafrost groundwater contribution.

The objective of this study is to test this hypothesis using geochemical data derived from water samples collected from 28 thaw lakes in northern Alaska as part of the CALON project. The water chemistry of these lakes was evaluated to assess the possibility that some lakes receive a contribution of subpermafrost groundwater that has a measurable impact on the hydrochemistry. If this approach is viable, it would provide a relatively quick and inexpensive way of identifying lakes with through taliks.

STUDY AREA

The North Slope of Arctic Alaska is similar to Mackay's study area, with tundra underlain by continuous permafrost up to 600 m thick (Lachenbruch *et al.*, 1982). Elevation gradually declines northward from 1500 m in the foothills of the east-west trending Brooks Range to sea level at the coast. The area is characterised by thousands of lakes, many of which have a thermokarst origin and are actively expanding.

Near the Arctic Ocean, the Arctic Coastal Plain is a flat, low-relief region with large oriented thermokarst lakes developed in ice-rich marine silt and sand. The region grades southward into higher, hillier terrain with aeolian sand at the surface, where the lakes are numerous and oriented, but not as large as those near the coast; lake basins tend to be deeper and often have prominent littoral terraces (Hinkel *et al.*, 2005, 2012). Further inland, and at higher elevations, a belt of ice-rich loess deposits (yedoma) forms a higher-relief terrain of lower lake density and lake basins with occasional deep pools. In the southern part of the study area, at elevations above 120–200 m, the Arctic foothills have surface materials largely of glacial till containing kettle lakes.

Basic characteristics of the 28 lakes included in this study are given in Table 1, with the listing arranged by decreasing latitude. The lakes range in size from about 1 to nearly 1000 ha and have variable depths. The dominant surficial sediment is also indicated, along with the estimated depth to the permafrost table as determined by Hinkel and Arp (2015).

METHODOLOGY

If there is a hydrological connection between large, deep lakes and subpermafrost groundwater, it may be detectable in the lake water chemistry. Compared to surface waters, groundwater should have a different anion and/or cation concentration, or have a different electrolytic conductivity or pH. The National Science Foundation (NSF)-sponsored CALON project is designed to determine basic physical, biological and geochemical characteristics from a representative sample of lakes collected across the north-south geomorphic and climatic gradients. Two north-south transects separated by several hundred kilometres were established on the Alaskan North Slope to monitor lakes for geochemical and thermal effects (Figure 1). A total of eight nodes were established along these transects, and six representative lakes from each node have been monitored since 2012. The lakes were selected to cover a range of lake size and depth.

Water samples have been collected from the lakes in the CALON study area in April and August each year. The samples were analysed for ionic concentrations of: chloride (Cl^-, mg/L), sulfate (SO_4^{2-},mg/L), nitrate (NO_3^-,mg/L), phosphate (PO_4^{3-}, mg/L), sodium (Na^+, mg/L), ammonium (NH_4^+, mg/L), potassium (K^+, mg/L), magnesium (Mg^{2+}, mg/L), calcium (Ca^{2+}, mg/L) and bicarbonate (HCO_3^-, mg/L). Samples were filtered in the field through 0.45 micron nylon syringe filters and frozen immediately. Ionic concentrations were measured via ion chromatography, where analyses had an accuracy and precision within ± 5 per cent. Inferred alkalinity (Alk_{inf}) was calculated by charge balance. Owing to the high concentrations of dissolved organic carbon (DOC) in these waters, we assumed Alk_{inf} to be composed of both carbonate alkalinity and organic anions. As a first approximation, we estimated the organic anion concentration of each sample from its pH and DOC concentration (Thurman, 1985). We attributed the remainder of Alk_{inf} to carbonate alkalinity, which we assumed to be HCO_3^- based on the circumneutrality of the waters. Samples for chlorophyll-*a* measurements were filtered through 0.7 micron Whatman (GE Healthcare Life Sciences, Maidstone, Kent, England) GF/F filters and stored frozen until analysis with a Turner Designs (San Jose, California, USA) Trilogy Laboratory fluorometer. Samples for DOC were filtered in the field through the same filters and stored frozen until analysis with a Shimadzu Scientific (Instruments, Columbia, Maryland, USA) TOC/TN analyser. Specific conductivity (µS cm^{-1}) and pH were measured *in situ* with a Yellow Springs Instruments, (Yellow Springs, Ohio, USA) 6600 multi-parameter water quality sonde. For this analysis, only water samples collected in summer are used; samples collected beneath the ice in April are not useful since they reflect the impact of closed-system freezing on solute concentration. All geochemical analyses are presented in Supplementary Table 1.

RESULTS AND DISCUSSION

Lake water specific conductivity (µS cm^{-1}), measured in each lake in August 2013 and 2014, is presented in

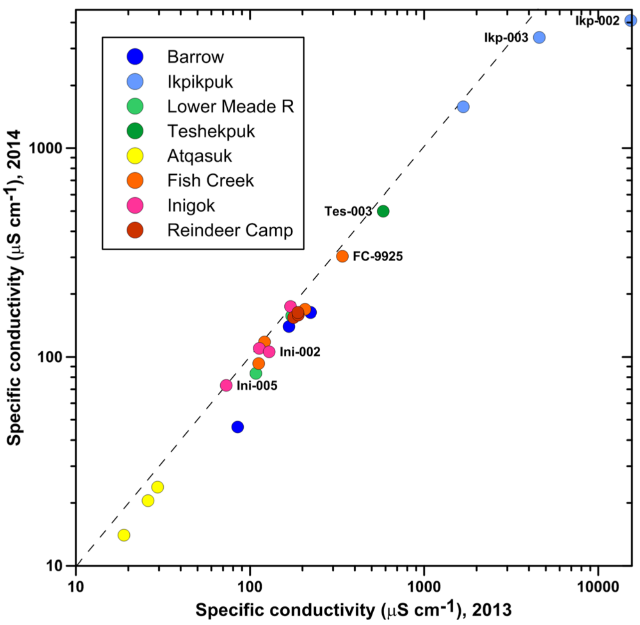

Figure 2 Specific conductivity (µS cm^{-1}) of lake water samples collected in August 2013 and 2014. The eight nodes are colour coded by latitude, with several lakes per node. Lakes lacking a through talik are labelled. Dashed line shows the 1:1 correspondence.

Figure 2. Lake nodes are colour coded and ordered by latitude, from blue in the north (Barrow on the coast) to red in the south (Reindeer Camp in the interior). Only those lakes *lacking* a through talik (Table 1) have labelled symbols.

Lake water conductivity varied over several orders of magnitude across the study area. Although slightly higher in 2013, the interannual pattern of specific conductivity was relatively consistent, as seen by the clustering along the 1:1 line. Further, conductivity values for lakes surrounding each node were quite consistent. For example, lakes near Atqasuk all had very low values, whereas the lakes on the Ikpikpuk delta were consistently very high – likely due to their proximity to the Beaufort Sea.

Figure 3a shows the pH and Alk_{inf} (µeq/L) of lake water samples collected in August 2013. It is clear that lakes within a node tend to cluster on the graph. We hypothesised that lakes lacking a subpermafrost groundwater contribution should have lower alkalinity and a more neutral pH compared to nearby lakes with a groundwater influx since the former are largely maintained by meteoric water. However, only the lakes near Inigok demonstrated this pattern. Both the Ikpikpuk delta and Fish Creek lakes without a through talik showed greater alkalinity and less neutral pH, contrary to our expectations. In short, no consistent pattern was observed, although the sample size was limited only eight lakes lacking a through talik.

This intra-nodal consistency applies to most of the biogeochemical metrics not shown graphically. The only exceptions to this nodal clustering pattern are plots of the biometrics DOC and chlorophyll-*a* (the latter shown as Supplementary Figure 1), which show significant annual differences in some lakes. Plots of Alk_{inf} (µeq/L) and Cl^-

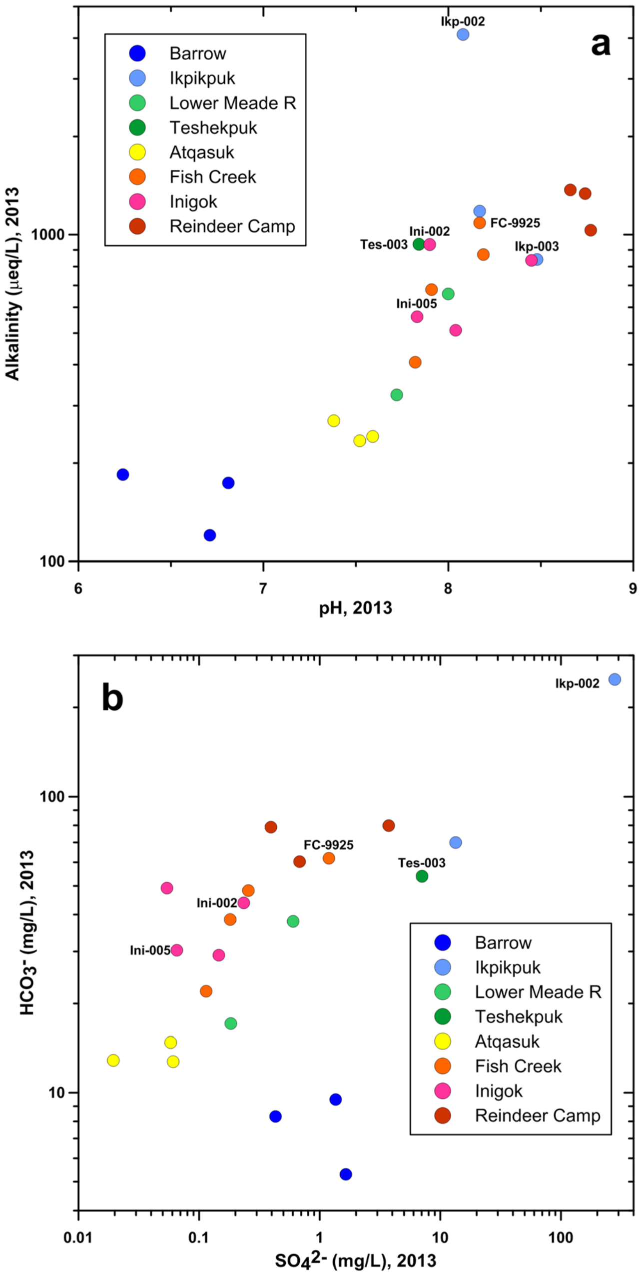

Figure 3 (a) Lake water pH and inferred alkalinity (µeq/L) for samples collected in August 2013; (b) concentration (mg/L) of sulfate (SO_4^{2-}) and bicarbonate (HCO_3^-) ions in the August 2013 lake water samples. Colour codes and labels as in Figure 2.

concentration (mg/L) obtained in August 2012 and 2013 demonstrate relative interannual consistency and clustering by node, as shown in Supplementary Figure 2 for 2013. In general, there does not appear to be any correlation to lakes with possible through taliks for either variable. However, when alkalinity and Cl^- concentration were plotted by lake latitude, there was a general increase in alkalinity southward and a general increase in Cl^- concentration northward for both years. Higher Cl^- values are likely due to the proximity of the ocean, where salt is transported as blowing snow or rain, for example, the coastal sites Ikp-002 and 003 are extreme outliers in both years. Conversely, higher alkalinity values to the south may be due to the presence of calcareous loess deposits in the yedoma deposits near the foothills. Similar plots were generated for SO_4^{2-} and HCO_3^- concentrations, but no regional pattern was discernible.

The observed intra-nodal consistency and general lack of a regional pattern imply that lake water chemistry is largely controlled by local environmental factors that vary considerably over the study area. Figure 3b shows the concentration of HCO_3^- ions in the August 2013 lake water samples. These anions would be expected in groundwater interacting for a long time period with carbonate rocks, coal or shale. Again, nodal clustering is apparent, demonstrating the importance of local factors. Sites near Reindeer Camp, Ikpikpuk delta and Teshekpuk Lake have a relatively high concentration of HCO_3^-, possibly reflecting the influence of inorganic carbon in calcareous surficial sediments. The largely siliceous sands of Atqasuk, Fish Creek and Inigok yield little SO_4^{2-}. Lakes with a through talik do not appear to be markedly different from those without, although the sample size is limited.

In summary, none of the hydrochemical data demonstrate strong correspondence to lakes with through taliks. Lake geochemistry seems to be largely controlled by local factors, and hydrochemistry is not a good predictor of through taliks at the scale of this study. This suggests that either: (1) there is no hydrological connection due to the presence of aquicludes in the subsurface; (2) the flux of groundwater is too small to have a demonstrable impact on lake water chemistry; or (3) application of the thermal equilibrium model used to determine the existence of a through talik is inappropriate.

Future work to evaluate this approach should focus on collecting sub-lake sediment porewater from piezometers for geochemical analysis, which would be less subject to surface fluxes and natural variability in lake surface water geochemistry. Comparison of these waters to local subpermafrost groundwater collected from deep wells ideally would provide the more exact end-member ion composition to evaluate potential through-going talik connectivity. While such an analysis presents challenges for the thick continuous permafrost zone of the Alaskan North Slope, testing such an approach in the discontinuous permafrost zone where through-going taliks are common, the permafrost is relatively thin and subpermafrost wells are often available is feasible. A hydrogeological setting where vertical hydraulic gradients are known to be positive and hydraulic conductivities are relatively high would be ideal.

CONCLUSIONS

The results demonstrate that lake water chemistry varies across the study area, but is consistent interannually. Proximal lakes have similar water chemistry that, in some cases, differs markedly from lakes found in other areas of the North Slope. This suggests that local environmental factors exert a dominant influence on lake hydrochemistry, primarily controlled by surficial geology and marine influences. There may be anthropogenic effects associated with human settlements (Barrow) or resource extraction activities such as those at the Prudhoe Bay oil fields that impact lakes at a local or regional scale, but these were not addressed in this study.

It was not possible to discriminate in geochemical terms between those lakes lacking a through talik and those suspected of having a through talik and possible groundwater contribution. This may be due to the small number of sampled lakes. Two other explanations are possible. First, a talik may extend through the permafrost, but impermeable rock layers limit upward migration of groundwater to the lake bed. Shale strata are effective aquicludes that are known in the area.

Second, as noted by Hinkel and Arp (2015), the assumption of thermal equilibrium and therefore characterisation of talik geometry beneath the lakes may not be strictly applicable. Mackay (1962) assumed that following an initial surface thermal disturbance, enough time had passed for the temperature at depth to reach equilibrium. The model is driven by present-day measurements, which may not reflect thermal conditions during the time necessary to achieve such equilibrium. Verification of model results must therefore rely on borehole data or geophysical methods.

ACKNOWLEDGEMENTS

This research was support by funding from the NSF: grants AON-1107607 to KMH and ATS, AON-1107481 to CDA and AON-1107596 to KEF. We thank CH2MHill Polar Services and UIC Science for logistical support. We additionally thank Matthew Evans (Wheaton College) for contributions of ion chromatography analyses.

REFERENCES

Burn CR. 2002. Tundra lakes and permafrost, Richards Island, western Arctic coast, -Canada. *Canadian Journal of Earth Sciences* **39**: 1281–1298. DOI:10.1139/e02-035

Burn CR. 2005. Lake-bottom thermal regimes, western Arctic coast, Canada. *Permafrost and Periglacial Processes* **16**: 355–367.

Deming D, Sass JH, Lachenbruch AH, De Rito RF. 1992. Heat flow and subsurface temperature as evidence for basin-scale ground-water flow, North Slope of Alaska. *Geological Society of America Bulletin* **104**: 528–542. DOI:10.1002/ppp.542

Deming D, Sass JH, Lachenbruch AH. 1996. Heat flow and subsurface temperature, North Slope of Alaska. In Thermal Evolution of Sedimentary Basins in Alaska, Johnsson MJ, Howell DG (eds). United States Geological Survey Bulletin 2142, 21–44.

Frey KE, Siegel DI, Smith LC. 2007. Geochemistry of west Siberian streams and their potential response to permafrost degradation. *Water Resources Research* **43**W03406: DOI: 10.1029/2006WR004902

Hinkel KM, Arp C. 2015. Estimating talik depth beneath lakes in Arctic Alaska. In *Proceedings, 7th Canadian Permafrost Conference and 68th Canadian Geotechnical Conference, 20-23 September 2015, Québec City, QC.* Paper 296. Canadian Geotechnical Society: Burnaby, BC. (See Supplementary Material).

Hinkel KM, Frohn RC, Nelson FE, Eisner WR, Beck RA. 2005. Morphometric and spatial analysis of thaw lakes and drained thaw lake basins in the western Arctic Coastal Plain, Alaska. *Permafrost and Periglacial Processes* **16**: 327–341.

Hinkel KM, Sheng Y, Lenters JD, Lyons EA, Beck RA, Eisner WR, Wang J. 2012. Thermokarst lakes on the Arctic Coastal Plain of Alaska: Geomorphic controls and bathymetry. *Permafrost and Periglacial Processes* **23**: 218–230. DOI:10.1002/ppp.1744

Lachenbruch AH. 1957. Three-dimensional heat conduction beneath heated buildings. *United States Geological Survey Bulletin* **1052-B**: 51–69.

Lachenbruch AH. 1959. Periodic heat flow in a stratified medium with application to permafrost problems. *United States Geological Survey Bulletin* **1083-A**: 1–36.

Lachenbruch AH, Sass JH, Marshall BV, Moses TH Jr. 1982. Permafrost, heat flow, and the geothermal regime at Prudhoe Bay, Alaska. *Journal of Geophysical Research* **87**: 9301–9316.

Lin Z, Niu F, Xu Z, Xu J, Wang P. 2010. Thermal regime of a thermokarst lake and its influence on permafrost, Beiluhe Basin, Qinghai-Tibet Plateau. *Permafrost and Periglacial Processes* **21**: 315–324. DOI: 10.1002/ppp.692

Ling F, Zhang T. 2003. Numerical simulation of permafrost thermal regime and talik development under shallow thaw lakes on the Alaskan Arctic Coastal Plain. *Journal of Geophysical Research-Atmospheres* **108**(D16): 4511. DOI:10.1029/2002JD003014

Ling F, Zhang TJ. 2004. Modeling study of talik freeze-up and permafrost response under drained thaw lakes on the Alaskan Arctic Coastal Plain. *Journal of Geophysical Research* **109** D01111:

Mackay JR. 1962. Pingos of the Pleistocene Mackenzie Delta area. *Geographical Bulletin* **18**: 21–63.

Nolan JT, Slater LD, Parsekian A, Plug LJ, Grosse G, Walter-Anthony KM. 2009. Thaw bulb dimensions determined using electrical imaging across thermokarst lakes, Seward Peninsula, Alaska. *Eos Transactions AGU,* Fall Meeting Supplement, Abstract NS23A-1123.

Schwamborn GJ, Dix JK, Bull JM, Rachold V. 2002. High-resolution seismic and ground penetrating radar-geophysical profiling of a thermokarst lake in the western Lena Delta, Northern Siberia. *Permafrost and Periglacial Processes* **13**: 259–269.

Smith LC, Sheng Y, MacDonald GM, Hinzman LD. 2005. Disappearing Arctic Lakes. *Science* **308**: 1429. DOI:10.1126/science.1108142

Smith MW. 1976. Permafrost in the Mackenzie delta, Northwest Territories. Geological Survey of Canada, Paper 75-28.

Thurman EM. 1985. Organic Geochemistry of Natural Waters. Springer: New York; 497.

West JJ, Plug LJ. 2008. Time-dependent morphology of thaw lakes and taliks in deep and shallow ground ice. *Journal of Geophysical Research* **113**: F01009. DOI: 10.1029/2006JF000696

Yoshikawa K, Hinzman LD. 2003. Shrinking Thermokarst Ponds and Groundwater Dynamics in Discontinuous Permafrost near Council, Alaska. *Permafrost and Periglacial Processes* **14**: 151–160. DOI:10.1002/ppp.451

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site.

