Journal of Hydrology 545 (2017) 327–338

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Landscape-gradient assessment of thermokarst lake hydrology using water isotope tracers

Biljana Narancic [a,*], Brent B. Wolfe [b], Reinhard Pienitz [a], Hanno Meyer [c], Daniel Lamhonwah [d]

[a] Laboratoire de paléoécologie aquatique, Centre d'études nordiques, Département de géographie, Université Laval, QC G1V 0A6, Canada
[b] Department of Geography and Environmental Studies, Wilfrid Laurier University, Waterloo, ON N2L 3C5, Canada
[c] Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research, Research Unit Potsdam, 14473 Potsdam, Germany
[d] Department of Geography and Planning, Queen's University, Kingston, ON K7L 3N6, Canada

ARTICLE INFO

Article history:
Received 19 May 2016
Received in revised form 11 November 2016
Accepted 14 November 2016
Available online 24 November 2016
This manuscript was handled by Tim R. McVicar, Editor-in-Chief, with the assistance of Joshua Larsen, Associate Editor

Keywords:
Nunavik
Thermokarst lakes
Water isotope tracers
Permafrost
Water balance
Maritime climate

ABSTRACT

Thermokarst lakes are widespread in arctic and subarctic regions. In subarctic Québec (Nunavik), they have grown in number and size since the mid-20th century. Recent studies have identified that these lakes are important sources of greenhouse gases. This is mainly due to the supply of catchment-derived dissolved organic carbon that generates anoxic conditions leading to methane production. To assess the potential role of climate-driven changes in hydrological processes to influence greenhouse-gas emissions, we utilized water isotope tracers to characterize the water balance of thermokarst lakes in Nunavik during three consecutive mid- to late summer sampling campaigns (2012–2014). Lake distribution stretches from shrub-tundra overlying discontinuous permafrost in the north to spruce-lichen woodland with sporadic permafrost in the south. Calculation of lake-specific input water isotope compositions (δ_I) and lake-specific evaporation-to-inflow (E/I) ratios based on an isotope-mass balance model reveal a narrow hydrological gradient regardless of diversity in regional landscape characteristics. Nearly all lakes sampled were predominantly fed by rainfall and/or permafrost meltwater, which suppressed the effects of evaporative loss. Only a few lakes in one of the southern sampling locations, which overly highly degraded sporadic permafrost terrain, appear to be susceptible to evaporative lake-level drawdown. We attribute this lake hydrological resiliency to the strong maritime climate in coastal regions of Nunavik. Predicted climate-driven increases in precipitation and permafrost degradation will likely contribute to persistence and expansion of thermokarst lakes throughout the region. If coupled with an increase in terrestrial carbon inputs to thermokarst lakes from surface runoff, conditions favorable for mineralization and emission of methane, these water bodies may become even more important sources of greenhouse gases.

1. Introduction

Numerous shallow thermokarst or 'thaw' lakes develop as a result of rapid permafrost degradation throughout the Arctic and subarctic regions of northern North America (Allard and Séguin, 1987; Payette et al., 2004; Bouchard et al., 2013) and Eurasia (Agafonov et al., 2004). The prerequisite for their formation is the presence and thaw of ground ice. When the depth of seasonal thawing (active layer) exceeds the depth at which ice-rich permafrost occurs, thawing of the perennial frozen layers (permafrost) begins followed by local ground subsidence and water collects in a depression (Pienitz et al., 2008). The latent heat of the water body may further thaw the underlying ground ice, leading to subsidence and deepening of the lake basin.

Permafrost landscapes cover more than 50% of Canada including 30% of subarctic Québec (Nunavik; Bouchard et al., 2011). Rapid degradation of permafrost since the mid-20th century along the eastern coast of Hudson Bay has contributed to an increase in the number of shallow thermokarst lakes (Payette et al., 2004). Thermokarst lakes constitute an important landscape feature and recent studies have documented the global implications of these aquatic ecosystems as a potential source of greenhouse gases, especially methane (Laurion et al., 2010; Comte et al., 2015; Crevecoeur et al., 2015; Deshpande et al., 2015; Przytulska et al., 2015). They are rich in dissolved organic carbon (DOC), most of which originates from thawing permafrost. Laurion et al. (2010) found that some lakes demonstrate strong thermal stratification due to high DOC concentrations. As a result, most of the lakes have

* Corresponding author.
E-mail address: biljana.narancic.1@ulaval.ca (B. Narancic).

http://dx.doi.org/10.1016/j.jhydrol.2016.11.028
0022-1694/

anoxic bottom waters despite their shallow depth (<5 m). This chemical gradient of oxygen, with an upper oxic and bottom anoxic layer, represents an ideal environment for anaerobic processes such as methane production (Laurion et al., 2010; Deshpande et al., 2015; Matveev et al., 2016). During water column mixing, methane is released to the atmosphere. Consequently, thermokarst lakes (and their influence on atmospheric methane concentrations) are expected to play a major role in future climate change (Wik et al., 2016).

Based on the Canadian Regional Climate Model (CRCM), Nunavik is expected to experience 3 °C warming in winter air temperature and 1.5 °C warming in summer air temperature, along with a 25% increase in total annual precipitation by 2050 (Brown et al., 2012). Changes in temperature and precipitation, combined with permafrost thaw, may increase soil-derived DOC supply via runoff and enhanced hydrological connectivity, possibly further promoting stratification and greenhouse-gas production in thermokarst lakes. Hydrological changes induced by climate change might have additional influence on limnological properties and biogeochemical cycling of these lakes, yet little is known about the hydrological processes that influence thermokarst lake water balance conditions in this region. Recent isotope-based studies from the western Hudson Bay Lowlands (Wolfe et al., 2011; Bouchard et al., 2013), Old Crow Flats (Tondu et al., 2013; Turner et al., 2010, 2014), Yukon Flats (Anderson et al., 2013) and northern Alberta (Gibson et al., 2015, 2016a) concluded that shallow thermokarst lakes are hydrologically dynamic systems yielding a great diversity of lake water balance conditions, variably influenced by hydrological processes (snowmelt, rainfall, permafrost meltwater, evaporation) and catchment features (vegetation, topography; Table 1). The stable isotope mass balance approach has also been used to characterize the influence of hydrological processes on non-thermokarst northern lakes (Gibson and Reid, 2014; Gibson et al., 2015, 2016b) and on lakes elsewhere (Steinman et al., 2013; Jones et al., 2016).

In this study, our aim is to identify and quantify the diversity of hydrological processes that control thermokarst lake water balances in Nunavik. Our approach was to sample lakes with different physical characteristics (color, depth, size, catchment vegetation) across vast landscape gradients from subarctic to arctic environments during a three-year sampling campaign (2012–2014) to capture the range of hydrological conditions. The main objectives of the study were to apply an isotope-mass balance model to: (1) determine lake-specific input water isotope compositions (δ_I) to identify the roles of primary source waters (e.g., rainfall, snowmelt and permafrost meltwater); and (2) calculate lake-specific evaporation-to-inflow (E/I) ratios to evaluate the influence of vapor loss. Results obtained provide the basis to anticipate hydrological responses and their influence on greenhouse gas behavior of thermokarst lakes to rapidly changing climate at the regional scale.

2. Study region

The study region is located on the eastern coast of Hudson Bay, Canada, and comprises four distinctive sites (Fig. 1). The two northern sites are located near the Umiujaq village: Nastapoka River valley (NAS; 56°55.423′N, 76°22.750′W) and Sheldrake River valley (BGR; 56°36.652′N, 76°12.912′W). Two southern sites are located near the village of Whapmagoostui-Kuujjuarapik (W-K): Kwakwabtanikapistikw River valley (KWK; 55°19.853′ N, 77°30.166′ W) and Sasapimakwananisikw River valley (SAS; 55°13.228′, N 77°42.444′ W). The bedrock geology of the area includes Precambrian granites and gneisses overlain by Quaternary glacial, glaciofluvial and marine deposits. The region was submerged by the postglacial Tyrrell Sea until ca. 6000 cal. BP following the last regional deglaciation ca. 8000 cal. BP (Pienitz et al., 1991; Saulnier-Talbot et al., 2007) that left thick deposits of marine silts and clays in valleys. These poorly-drained valley floors covered with marine clay induced the development of wetlands with peat plateaus supporting trees and shrubs (ca. 5000 cal. BP). Climate cooling during the Neoglacial period (~3200 BP) led to a decrease in peat accumulation and drying of the soil surface due to growth of ground ice (Allard and Séguin, 1987). During the cold and dry climate of the Little Ice Age, permafrost reached its maximum extent (~500 BP; Allard and Séguin, 1987; Calmels et al., 2008). Presence of permafrost is easily assessed in this landscape as it forms mounds of organic-rich palsas and mineral lithalsas that coexist within a few tens of meters of each other. Climate warming during recent decades has led to increasingly rapid thawing of permafrost mounds and transformation of the landscape into a mosaic of colorful shallow thermokarst lakes (Payette et al., 2004; Fig. 2). The color variability originates from permafrost thaw in surrounding soils and ranges from white to green in lakes with high concentrations of suspended fine clay particles, to brown and black in lakes rich in DOC (Laurion et al., 2010; Comte et al., 2015; Crevecoeur et al., 2015; Przytulska et al., 2015).

The study lakes are distributed along a north–south latitudinal, vegetation and permafrost gradient (Figs. 1 and 2). Lakes in the northern sites, NAS and BGR, are situated in the transitional boreal/arctic tundra zone dominated by shrub tundra vegetation and scattered forest overlying discontinuous permafrost and marine silts of low permeability. The arctic tundra zone has almost no trees; sheltered locations contain mainly *Betula glandulosa* shrubs. The dominant vegetation in the boreal-subarctic zone includes spruce trees (*Picea mariana, P. glauca*), tall shrubs (*Betula glandulosa, Salix planifolia*), mosses (*Sphagnum* spp.) and herbaceous plants (*Carex* spp). At the time of field work, sampled lakes at BGR were distinctly colored and unlikely to have been influenced recently by the nearby river (Fig. 2). The southern KWK and SAS are situated in the boreal-subarctic zone within spruce-lichen woodland overlying sporadic permafrost. Lakes at KWK are located on postglacial marine clay soils of low permeability covered with dense forest and shrub vegetation where local permafrost is at an advanced stage of degradation (Bouchard et al., 2011). The elevation of the lakes at KWK are well above the nearby creek shown in Fig. 2. Lakes at SAS are located in peatlands within rapidly degrading permafrost mounds (Bhiry and Robert, 2006). The landscape is relatively flat at SAS and BGR, whereas slight topographic relief exists at NAS and KWK sites owing to rocky hills and steep trenches. Low permeability of fine-grained substrate, presence of permafrost and generally low relief likely restrict hydrological surface and subsurface connectivity between lakes.

The climate is influenced by the proximity of Hudson Bay. The farthest inland site (BGR) is located approximately 20 km from Hudson Bay. Once the bay freezes, the climate becomes dry continental with low temperatures (Dec-Feb = −19.5 °C mean) and when ice retreats, maritime conditions with frequent dense fogs occur in the summer (Jun-Aug = 9.5 °C mean). Mean annual temperature and total precipitation for the three-year sampling period were above the 55-year regional long-term means (Table 2). There were some seasonal differences with more rainfall in 2014 than during the previous two years whereas snowfall was less than the long-term mean during 2012 and similar to the 2013 and 2014 means. The summer relative humidity for 2012–2014 ranged from 77.2 to 80.4%, close to the 55-year regional mean (80%; Environment Canada, 2015).