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# Thermokarst lake, hydrological flow and water balance indicators of permafrost change in Western Siberia

Johanna Mård Karlsson *, Steve W. Lyon [1], Georgia Destouni [2]

*Department of Physical Geography & Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden*
*Bert Bolin Centre for Climate Research, Stockholm University, SE-106 91 Stockholm, Sweden*

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SUMMARY

Permafrost, mainly of discontinuous type, that underlies the tundra and taiga landscapes of the Nadym and Pur river basins in northwestern Siberia has been warming during the recent decades. A mosaic of thermokarst lakes and wetlands dominates this area. In this study we tested the hypothesis chain that permafrost thawing changes thermokarst lake area and number, and is then also reflected in and detectable through other associated hydrological changes. Based on indications from previous studies, the other hydrological changes in a basin were expected to be decreasing intra-annual runoff variability (quantified by decreasing maximum and increasing minimum runoff) and systematically decreasing water storage. To test this hypothesis chain, we mapped thermokarst lake changes using remote sensing analysis and analyzed both climate (temperature and precipitation) and water flow and balance changes using available monthly data records. This was done for the whole Nadym and Pur river basins and a smaller sub-basin of the former (denoted 7129) with comparable data availability as the whole river basins. The results for the 7129 sub-basin show all the indicators (thermokarst lake and other hydrological) changing consistently, as could be expected in response to permafrost thawing that alters the connections between surface and subsurface waters, and leads to overall decreases in water (including ground ice) storage within a basin. Over the Nadym and Pur basins, the relative area influenced by similar permafrost thawing and associated lake and hydrological effects appears (yet) too small to be clearly and systematically reflected in the basin-average indicators for these large basins.



## 1. Introduction

Recent warming in the Arctic has triggered changes in the cryosphere, including warming and degradation of permafrost, and deepening of the active layer above permafrost (Serreze et al., 2000; Hinzman et al., 2005; Romanovsky et al., 2010). Observed changes in some characteristics of hydrological discharge dynamics (Lyon et al., 2009; Lyon and Destouni, 2010), and in soil moisture, drainage patterns and surface runoff (Prowse et al., 2006) have further been interpreted as hydrological reflections of the changes in permafrost and active layer thickness. Changes in permafrost and active layer depth directly affect the subsurface water storage and as such can be expected to also affect river discharge (Kane, 1997; Yang et al., 2002; Yoshikawa and Hinzman, 2003). Previous studies have indicated a decreasing trend in intra-annual runoff variability as a hydrological signal of permafrost degradation, due to increasing active layer thickness and deeper and longer flow pathways to surface water discharge (Ye et al., 2009; Frampton et al., 2011). Basins with permafrost have also been found to exhibit higher peak flow and lower base flow compared to non-permafrost basins (Woo, 1986; Kane, 1997; Yang et al., 2002; Smith et al., 2007; Ye et al., 2009). Furthermore, Frey and McClelland (2009) and Rowland et al. (2010) have shown that permafrost degradation may cause a transition from a surface water-dominated to a groundwater-dominated hydrological system.

Thermokarst lakes are also dependent on permafrost, and changes in thermokarst lake size and number have been reported for ice-rich discontinuous and continuous permafrost regions (Bosikov, 1998; Yoshikawa and Hinzman, 2003; Agafanov et al., 2004; Brouchkov et al., 2004; Smith et al., 2005; Riordan et al., 2006; Kirpotin et al., 2008; Plug et al., 2008; Marsh et al., 2009; Grosse et al., 2010; Carroll et al., 2011; Jones et al., 2011). Thermokarst lakes form where melting of ground-ice and surface settlement initiate ponding (Marsh et al., 2009), and are generally sensitive to changes in climate. Lake surface area may change due to several different processes, including (a) changes in precipitation (Plug et al., 2008), (b) changes in evapotranspiration

* Corresponding author at: Department of Physical Geography & Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden. Tel.: +46 (0)8 674 7569; fax: +46 (0)8 16 4818.

*E-mail addresses:* johanna.maard@natgeo.su.se (J.M. Karlsson), steve.lyon@natgeo.su.se (S.W. Lyon), georgia.destouni@natgeo.su.se (G. Destouni).

[1] Tel.: +46 (0)8 16 4888; fax: +46 (0)8 16 4818.

[2] Tel.: +46 (0)8 16 4785; fax: +46 (0)8 16 4818.

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(Riordan et al., 2006), (c) lateral drainage caused by shoreline erosion due to permafrost thaw (Marsh et al., 2009; Yoshikawa and Hinzman, 2003; Smith et al., 2005; Jones et al., 2011), or (d) internal drainage if underlying permafrost thaws and open taliks appear (Smith et al., 2005). Thermokarst lake changes that have mainly involved decreasing lake surface area (although to varying degrees of severity) have been observed in Siberia (Smith et al., 2005; Kirpotin et al., 2008), Alaska (Yoshikawa and Hinzman, 2003; Riordan et al., 2006; Hinkel et al., 2007; Jones et al., 2011), western Canada (Marsh et al., 2009), and in Scandinavia (Sannel and Kuhry, 2011).

In this study we test the hypothesis chain that permafrost thawing alters thermokarst lake size and number, while also yielding other characteristic and detectable associated hydrological changes. Based on indications from previous studies (Yang et al., 2002; Muskett and Romanovsky, 2011; Frampton et al., 2011), main other hydrological changes are then expected to be decreasing intra-annual runoff variability (quantified by decreasing maximum and increasing minimum flow) and decreasing water storage in affected drainage basins. More specifically, the water stored in a basin includes all water that enters but does not leave the basin in a given annual cycle and can include various stores, such as surface water (river, lakes, and wetlands), soil moisture and ground ice, and shallow and deep groundwater. In arctic and subarctic landscapes, changes in water storage may be attributed to different internal basin alterations and interconnected processes (Bosson et al., 2012). These include permafrost degradation that can change water connectivity across the landscape, for example, due to the development of open taliks that influence the distribution of subsurface flow paths and can allow surface waters to drain and/or connect differently to groundwater, or to changes in flow interactions of intra-permafrost groundwater (i.e., groundwater in between and that resulting from thawing of ice-rich permafrost layers). These interconnected changes can further alter both how water is distributed and how much water is stored within a drainage basin (Muskett and Romanovsky, 2011; Woo, 2012).

To test this hypothesis chain, we investigate changes in thermokarst lake area and number within the Nadym and Pur river basins (48,000 km$^2$ and 95,100 km$^2$, respectively) and a small subbasin of the former (denoted 7129, with an area of 1200 km$^2$) in Western Siberia. These basins are chosen for the investigation because a previous study by Smith et al. (2005) showed decline in total lake abundance and inundation area between 1973 and 1998 based on satellite images, and hypothesized that these lake changes were due to permafrost thawing. In this paper, we use Landsat images to assess changes in thermokarst lake distribution, and available monthly precipitation, temperature and discharge data records to assess changes in the basin-scale annual precipitation–runoff and water balance relations over an extended time period relative to the previous regional lake study. Specifically, the present study involves lake distribution evaluation at three time-slices, from 1973, through 1987–1988, to 2007–2009, along with basin-scale evaluation of available hydrological parameters over this time period. With this data we demonstrate that change in lake abundance and inundation area alone is not sufficient to draw conclusions with regard to thawing of permafrost.

## 2. Study area

The Nadym and Pur river basins (Fig. 1) in the northwestern Siberian lowlands are characterized by a low relief, ranging between 0 and 200 masl. The basins are situated between the Ob basin in the west and the Yenisei basin to the east, and they both drain into the Arctic Ocean through the Kara Sea. The study area comprises tundra, forest-tundra and taiga, whereof forest-tundra is the dominant vegetation type and contains tundra vegetation with interspersed stands of birch, spruce and larch (Frey and Smith, 2007). Lacustrine–alluvial sand deposits with lenses of loamy sand and silty loam represent the region's lithological composition (An and Devyatkin, 1998). The region also contains peatlands with mosses, grasses, sedges and shrubs, where up to 5 m thick peat deposits and peat bog soils are predominant in the central part of the interfluves.

A vast mosaic of thermokarst lakes and wetlands dominates the landscape where the underlying permafrost, from continuous to sporadic, generally extends to depths of 100–300 m (An and Devyatkin, 1998). The permafrost distribution for the three basins are diverse, with the Nadym basin including 92% discontinuous permafrost and 8% sporadic permafrost, the Pur basin including 3% continuous permafrost, 77% discontinuous permafrost and 20% sporadic permafrost, and the 7129 sub-basin including 100% discontinuous permafrost. The Nadym and Pur river basins are, compared to the larger river systems in Russia, considered to be natural systems with no human water flow regulation, and the two basins have similar runoff regimes with relatively high discharge during the summer and low discharge during the winter (Fig. 2), and without glacial melt water contributions to these discharges.

Warming of surface air temperature has caused warming and thawing of the permafrost in the region since the 1970s, with a temperature increase of approximately 0.4 °C per decade at 10 m depth in the Nadym region and 0.45–0.6 °C per decade at 8–10 m depth in the Pur region (Romanovsky et al., 2010). A steady increase of active layer thickness is apparent in the Nadym region, which also corresponds to the increase in surface air temperature (Melnikov et al., 2004). The regional permafrost is further considered to be unstable with temperature just below 0 °C (An and Devyatkin, 1998), and both degradation and talik formations have been observed in the study area (Romanovsky et al., 2010).

## 3. Methods

### 3.1. Thermokarst lake change analysis

Sensors operating in the visible-infrared, such as Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+), have proven useful for monitoring open water extent due to their relatively high spatial and temporal resolution. Use of remote sensing data is also a cost-effective alternative to collecting ground-based data, which can facilitate frequent monitoring of change in remote areas at large scales, and can reveal complex spatial variations that cannot be readily elucidated by traditional in situ observations. For those purposes, satellite imagery from Landsat Multispectral Scanner (MSS, with 60 m resolution), and TM and ETM+ (with 30 m resolution), available at USGS Global Visualization Viewer (www.glovis.usgs.gov), were here used to map lake distribution over the Nadym and Pur river basins, and the 7129 sub-basin for three different time slices (1973, 1987–1988, and 2007–2009). Only imagery from the summer season was acquired. We aimed to use imagery from the later part of the season (July–September) to avoid the snowmelt period and seasonally inundated areas (Table 1). Multiple images within a season were also compared to investigate intra-seasonal variability. Landsat images were first calibrated to convert digital numbers to spectral radiance. Principal Component Analysis (PCA) was then used to remove noise and enhance the spectral contrast of water features in the imagery (Mather, 2004; Roger, 1996). Landsat TM and ETM+ were resampled to the lower resolution of Landsat MSS for multitemporal analysis of lake distribution.

The preprocessed and resampled Landsat images were further classified using the spectral signatures characterized for water. The calibration, PCA and the classification of water objects using