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Snow retention for increased water supply of shallow Arctic lakes

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ABSTRACT

Throughout the year, water availability in the Arctic is marginal because of the cold climate, presence of permafrost, and low precipitation. Recent resource development and improvements in living conditions of the expanding population have placed additional stresses on the annual local water supply of communities and industry located in this region. This study implemented a snow control practice to enhance snowdrift growth as a local water source at a shallow Arctic lake located on Alaska's Coastal Plain, 50 km south of Prudhoe Bay, USA. A 130 m long and 3 m tall snow fence was placed next to a lake for the winters of 2009–2010 and 2010–2011. This snow fence retained large quantities of snow transported by wind during the winter, forming a sizable snowdrift. In this region of the Arctic, lakes receive most of their water from seasonal snowpack melt in late May and early June, with subsequent drying of the lakes after snowmelt. The artificially created snowdrift at the experimental lake contributed meltwater until early July during both summers of the study period and effectively offset summer lake drying. At summer's end, the additional lake volume from the fence snowdrift was 21% and 29% in 2010 and 2011, respectively. While techniques such as snow fences can be used to address existing needs for enhanced water supplies, they can also serve as a tool for assessing lake response to a future climate scenario in which summers are warmer and both evaporation and winter precipitation increase.

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1. Introduction

Water availability in the Arctic shifts dramatically between seasons, with an abundance of water in spring and scarce supply in winter. Constant local water supply in the polar regions can be difficult to maintain because of the long periods of continuous freezing temperatures and the presence of snow cover and permafrost (McFadden and Collins, 1978; Slaughter et al., 1975). Prolonged freezing air temperatures last from October to May in the Alaskan Arctic (Olsson et al., 2002). During this time, most of the ground surface is covered by snow and surface waters are covered by ice. Air temperatures might rise above freezing and affect snowpack conditions, but before May, energy is insufficient to overcome the snowpack's cold content and generate surface water runoff. In addition to the cold climate, large parts of the Arctic receive little precipitation, less than 250 mm annually, which makes this region a polar desert (Woo and Young, 2014). About half of the annual precipitation is stored as seasonal snow cover and then released to the drainage network during snowmelt, typically in middle May through early June. These environmental factors cause challenges that affect the local water supply, including: (1) short open-water season in rivers and lakes, (2) low annual precipitation, (3) limited access to groundwater resources constrained by continuous permafrost, and (4) high operating costs of water distribution systems (see Slaughter et al., 1975).

Arctic communities and industry largely depend on the local water supply for domestic purposes, maintenance of existing infrastructure, and oil and gas exploration and industry activities. This project was funded to address environmental questions associated with allocation of water resources for the construction of ice roads and ice pads. An ice pad is a temporary ice structure built in wintertime for the purpose of having a work area for exploratory drilling on the tundra with minimal environmental impact. Ice roads provide the means by which supplies, materials, equipment, and machinery are transported to remote exploration sites, otherwise inaccessible by conventional roads. A traditional water source for ice road construction is water withdrawal from lakes (Hinzman et al., 2006), as local streams and rivers have very low or a complete lack of winter flow.

The distinctive hydrological regime of Arctic lakes, caused by the presence of seasonal ice cover and permafrost, exerts an influence on lake water availability in winter (Arp et al., 2012; Duguay et al., 2003). Lakes are covered with ice from October to June, and often no water recharge of lakes occurs until snowmelt in early June. The shallow active layer has limited storage, which minimizes suprapermafrost groundwater contributions to lake systems. Most lakes in permafrost environments have a thaw bulb (talik) of unfrozen ground directly beneath them. Subpermafrost groundwater can contribute water to the larger lakes via open taliks that penetrate permafrost completely, like Teshekpuk Lake (Kane et al., 2013). There is no subpermafrost water contribution to the majority of smaller lakes, as they have closed taliks. After

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snowmelt, water volumes in the lakes decrease throughout the summer, when water loss due to evaporation is considerably greater than water gained from rainfall (Bowling et al., 2003; Mendez et al., 1998). This balance switches in August, when air temperature drops, evaporation decreases, and rain (or snow) is more likely to occur. Some of the summer surface storage deficit in the active layer and surface water bodies (lakes, ponds, wetlands) is recharged during this time (Bowling et al., 2003). However, if the surface storage deficit is not replenished (for example, precipitation in the fall is low and near-surface soils are dry), lake recharge is directly affected, and water availability for the following winter is reduced. For example, an extremely dry summer and fall occurred in 2007. During that year, the Kuparuk River at Deadhorse, Alaska had its lowest end-of-summer flow since 1971, when the U.S. Geological Survey initiated streamflow gauging at this site (Kane et al., 2008). The impact of the 2007 drought on the surface storage deficit was evident during the 2008 snowmelt runoff and annual water yield (Arp et al., 2012).

One of the ways to address the consequences of drought and drought-like conditions is to augment a lake's water supply with snow fences and snowdrifts (i.e., Jairell and Schmidt, 1990; Tabler, 1968). In watershed hydrology, natural snowdrifts have a profound effect on energy and mass balance at certain spatial scales (Clark et al., 2011; Davison et al., 2006; Grayson and Blöschl, 2001; Woo and Young, 2014; Young et al., 2013). Over time, snowdrifts and snow fences have proven to be effective tools for harvesting water. More than a century ago, an Alaskan newspaper—*Seward Weekly Gateway*—described the successful use of snow fences by Seward miners in 1909 (Seward Weekly Gateway, 1909). In the 1970s and 1980s, both in Wyoming and in some Alaska Arctic villages, significant progress was made in increasing local water supplies by using snow fences (Jairell and Schmidt, 1990; McFadden and Collins, 1978; Sturges, 1992; Tabler, 1968). Recently, snow fences were used in Afghanistan to increase water yield for irrigation (Thompson et al., 2009).

Here, we examine both naturally occurring and artificially created snowdrifts to quantitatively assess the response of a lake to seasonal precipitation storage within the lake's watershed. This study is twofold: the first part focuses on the characteristics of snowdrifts at selected locations, precipitation storage capacity of snowdrifts, and rate of snowdrift melt; the second part quantifies the change in lake water levels and volumes during the open-water season in response to water contribution from an artificially created snowdrift.

2. Study area

Lakes, ponds, and wetlands are extensively distributed throughout the Arctic. Lakes account for 15–40% of the circumpolar Arctic Coastal Plain (ACP) (Duguay et al., 2003) and for at least 25% of Alaska's ACP (Arp et al., 2012; Sturm and Liston, 2003). The majority of Alaska's ACP lakes are shallow with a low ratio of lake volume to lake surface area (Arp and Jones, 2009; Sellmann et al., 1975).

In selecting a research site, we focused on lakes accessible from the Dalton Highway (Fig. 1). Beyond the highway's terminus at Deadhorse are private roads managed by oil companies, with use restricted to authorized vehicles only. We selected two lakes 30 miles south of Deadhorse near Franklin Bluffs (Fig. 1). One lake is a gravel pit (also referred to as the experimental lake); it serves as a water source for maintaining the nearby Dalton Highway. The second lake is a natural lake (referred to as the control lake), representative of shallow thermokarst ACP lakes.

Low-gradient terrain prevails at the study area. Generally, the elevation gradually increases from the coastline toward the foothills of the northern Brooks Range, which borders Alaska's ACP to the south and east. The flat coastal landscape features some steep cliffs at riverbanks and lakes that can be as high as 5 to 10 m. Higher terrain occurs at White Hills and Franklin Bluffs (Fig. 1). The entire region is underlain with continuous permafrost that reaches a maximum thickness of 600 m near Prudhoe Bay (Osterkamp and Payne, 1981). The active layer is typically 50 to 90 cm and varies considerably due to vegetation, soil moisture, soil type, aspect, slope, etc., with extensive surficial organic soils overlying mineral soils (Slaughter and Kane, 1979). This region has low-growing tundra vegetation. Sedge tussocks, dwarf (<0.5 m) deciduous shrubs, and occasional large (2–7 m high) deciduous shrubs prevail along floodplains, water tracks, and other drainages (Tape et al., 2006).

3. Methods and data

A suite of field measurements, including snow surveys, weather, and hydrologic data, was collected at the experimental lake for one spring and one summer before the snow fence was installed. These measurements, taken in spring and summer 2009, represent baseline conditions. The same suite of measurements was collected for two more years after a 130 m long and 3 m tall snow fence was placed next to the experimental lake in September 2009 (Fig. 2). Data collected at the control lake served as a reference to the natural hydrological regime during this two-year experiment. Overall, field data collection lasted from April 2009 to September 2011.

3.1. Snow survey

Detailed snow depth information was collected for each lake and from nearby tundra using a MagnaProbe (Sturm and Holmgren, 1999). The sampling extent covered both the lake surface and the surrounding tundra because snow properties differ depending on the underlying material (lake ice versus tundra vegetation). The sampling strategy included detailed snow depth measurements approximately every 2 m in a rectangular grid, transects, and random patterns. The automated snow depth probe (MagnaProbe) recorded both the snow depth and the geographical position of the each snow depth measurement. Collected snow depth measurements were interpolated using the nearest-neighbor technique in a regular grid with a 10 m cell size. The resulting gridded dataset was then used for snow depth and snow volume analysis. Snow volume (V_s) was calculated using

$$V_s = \sum_{i=1}^{n} h_{s_i} A_i \tag{1}$$

where h_{s_i} is the snow depth at ith grid cell (m), and A_i is the area of the grid cell (m^2). Periodic snow density measurements on the lake surface and on the tundra accompanied the snow depth measurements (Table 1). Snow density was measured with a fiberglass tube (Adirondack) that had an inside area of 35.7 cm^2 and was equipped with metal teeth on the lower end to cut through dense snow layers.

To evaluate seasonal snow accumulation during the three years of this experiment in terms of long-term average maximum and minimum snow water equivalent (SWE), we used the snow-research dataset collected by UAF/WERC faculty, staff, and students from 1999 to 2014 (Stuefer et al., 2013). This longer record includes SWE calculated from 50 snow depths and 5 snow densities using Eq. (2).

$$\mathrm{SWE} = h_s \frac{\rho_s}{\rho_w} \left(\frac{10 \quad \mathrm{mm}}{1 \quad \mathrm{cm}} \right) \tag{2}$$

where SWE is snow water equivalent (mm), h_s is the average snow depth (cm), ρ_s is the average bulk snow density (kg/m^3), and ρ_w is water density (1000 kg/m^3).

3.2. Snow fence and snowdrift

A Wyoming-type snow fence 3 m tall and 130 m long was constructed in September 2009 (Tabler, 2003). The snow fence was large enough to create a snowdrift that would capture a volume of snow comparable to