Modeling Groundwater Upwelling as a Control on River Ice Thickness

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ABSTRACT

The Tanana River flows through Interior Alaska, a region characterized by discontinuous permafrost. Studies link degrading permafrost to increased winter river discharge due to increasing groundwater input. In winter, Interior Alaska rivers are exclusively fed by groundwater, which serves as an external source of heat. In fact, some portions of rivers fed by groundwater maintain thin ice throughout the winter, or remain altogether ice-free, despite very cold air temperatures. These ice conditions represent a significant danger to winter travellers that use rivers for wintertime travel, particularly in this largely roadless area. We developed a deterministic model to explore how fluctuations in groundwater discharge control ice thickness on the Tanana River. The model allows us to examine how local changes in groundwater characteristics affect ice dynamics by addressing two questions: What are the dominant factors controlling seasonal ice dynamics on the Tanana River? What are the rates of change in ice thickness resulting from observed and projected changes in these factors? Ice melt is amplified by increased hydraulic gradient, increased groundwater upwelling, increased air temperature, increased groundwater temperature, or increased snow depth. A warming climate in regions with discontinuous permafrost is expected to increase groundwater input into rivers, decrease the temperature gradient between the atmosphere and the ice/water interface, and increase snow depths. All these changes contribute to decreased ice thickness and thus more hazardous conditions for winter travellers. The model illustrates the physical mechanisms, which corroborates reports from Alaskans that ice conditions have become more dangerous in the spring, and further suggests that permafrost degradation could contribute to the degradation of river ice in a warming climate.

KEYWORDS

Groundwater; heat transfer; permafrost; ice; river; surface water

1. INTRODUCTION

Historically, many villages and towns in Alaska were founded along waterways that provided relatively easy access throughout most of the year. During Alaska winters, frozen river systems are frequently used as transportation networks by people using snow machines, dog sleds, cross-country skis, snowshoes, and in some places even as ice roads. Frozen rivers can be navigated easily because there are few barriers or obstructions to inhibit travellers. We worked with several non-academic, local collaborators who have had extensive experience traveling on Alaska rivers in all seasons. Their observations on the Tanana River mirror those found by Herman-Mercer et al. (2011), who reported that rural Alaskans have observed that thin ice is becoming more common on the Yukon River in recent winters. These areas are dangerous for winter travellers in Alaska who regularly use rivers for wintertime travel.

In collaboration with rural Alaskans, we explore how changes in hydrology will affect residents of Interior Alaska by examining the thermal balance between groundwater discharge and winter air temperatures in areas that have dangerous ice conditions in the Tanana River of Alaska. We initiated field studies in locations identified by local residents as having thin or no ice in most years. We developed a numeric model that allowed us to explore the relationship between seasonal groundwater flows and ice thickness under changing environmental conditions by examining three primary research questions: (1) What physical factors have the greatest influence on seasonal dynamics between river ice thickness and groundwater upwelling on the Tanana River? (2) How do variations in environmental conditions change the capacity of groundwater to melt river ice? (3) How might environmental conditions in a warmer climate affect river ice thickness on the Tanana River?

Heat provided by groundwater upwelling can degrade river ice from below. Under certain conditions, the groundwater heat flux exceeds atmospheric heat losses, and dangerous ice conditions can be maintained for extended periods despite very cold air temperatures. In recent decades, there have been reports that thin ice and open water may be more prevalent on Interior Alaska rivers in winter (Campbell & Althoff 2013; Herman-Mercer et al. 2011). These conditions can be caused by a number of factors including fast-moving turbulent water, warm air temperatures, external heat sources (power plant or sewage emissions), or groundwater upwelling in shallow areas. In this paper, we examine how changes in groundwater hydrology may affect river ice dynamics.

Ice-rich permafrost is an effective barrier to water transport and recharge (Burt & Williams 1976; Horiguchi & Miller 1980; Kane & Stein 1983), but warming temperatures have caused permafrost degradation across the Arctic (Hinzman et al. 2005; Jorgenson et al. 2001; Serreze et al. 2000). Permafrost degradation has been described as a potential mechanism for increased hydrologic connectivity between surface and groundwater systems observed through drainage of lakes (Yoshikawa & Hinzman 2003); increased daily summer and winter minimum flows (Smith et al. 2007); and increases in winter river baseflow (Walvoord & Striegl 2007). During winter conditions in Alaska, ice-covered rivers are fed entirely by groundwater; therefore, increased winter baseflow is indicative of increased groundwater input.

The Tanana Flats, which lies to the south of the Tanana River downstream of Fairbanks, has a high groundwater table and is reported to have experienced extensive permafrost degradation since the 1700s (Jorgenson et al. 2001). Much of the Tanana River neighboring the Flats appears to be fed by groundwater upwelling. Assuming that observations of our local collaborators and Herman-Mercer et al. (2011) are correct, the increased observations of thin ice and open water on the Tanana are hypothesized to be caused by increased winter groundwater flow caused by permafrost degradation intensified by a warming climate.

2. METHODS

We modeled the thermal balance between groundwater discharge and ice-free areas in the Tanana River near Fairbanks, Alaska, USA, a region that is characterized by discontinuous permafrost (Jorgenson et al. 2008). Our study area was located in Hot Cake Slough on the Tanana River, which is located in the Bonanza Creek Long-Term Ecological Research (LTER) area approximately 9 miles southwest of Fairbanks (64°43′26″N, 148°7′22″W). This region is bordered by the Tanana Flats to the south, an area with a high water table largely fed by groundwater.

Our objective was to better understand how groundwater upwelling influences river ice thickness and how the potential ice melt rate (by groundwater) is affected by changing various environmental parameters (hydraulic conductivity, upwelling rate, ice thickness, snow depth, air temperature, and water depth). Thus, we developed a conceptual model (Figure 1) that illustrates how groundwater controls river ice thickness under specific conditions. Based upon this conceptual model, we created a numerical model using MATLAB (version 2011b) to estimate the potential ice melt rate by groundwater under static environmental conditions (assumes constant air temperature, wind velocity, snow depth, snow density, upwelling rate, groundwater temperature, and water column temperature).

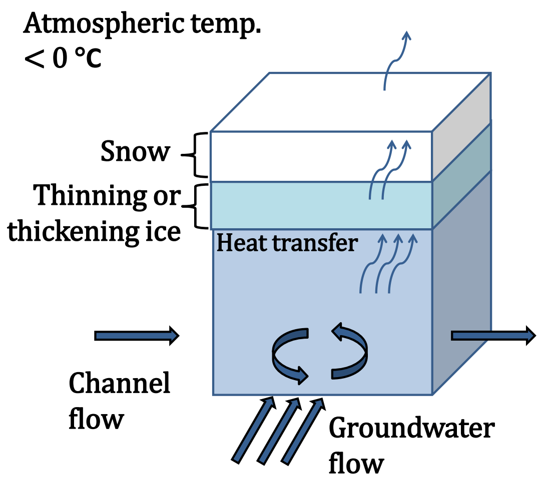

Figure 1: Conceptual model of heat transfer and changing ice conditions.

The conceptual model (Figure 1) shows a system where water flows laterally into and out of a control volume cell, while groundwater flows into the cell vertically. The cell is capped by a top layer of ice and snow with a specified initial thickness (d_{ice} and d_{snow}, respectively). The atmosphere above the ice and snow is set to a constant temperature (T_{air}) and wind velocity (V_{wind}). The boundary between the ice and the water is assumed to be 0°C, and heat is conducted from the water to the atmosphere (through the snow and ice) when the air temperature is less than 0°C.

The initial inflows and outflow have a specified volumetric flow rate (Q) and temperature (T), and a calculated volumetric heat content [H, relative to the freezing point of water (T_{melt})], which are subscripted by source in the equations [inflow (in), groundwater (GW), or outflow (out)]. H_{in}, H_{GW}, and H_{out} are calculated using Eq. (1), which references the density of water (ρ_{H_2O}) and the specific heat capacity of water (C_{p,H_2O}).

$$H = \rho_{H2O}\, C_{p,H2O} Q\, (T - T_{melt}) \tag{1}$$

The groundwater inflow is assumed to be thoroughly mixed with the lateral inflow. The temperature of the lateral outflow is assumed the same as the lateral inflow, but the volumetric flow out of the cell is equal to the sum of the lateral and groundwater inflows. The total sum of heat available to be conducted through the ice and snow (H_{loss}) or to melt ice (H_{melt}) is calculated according to Eq. (2).

$$H_{melt} = H_{in} + H_{GW} - H_{out} - H_{loss} \tag{2}$$

The heat lost through conduction through the ice, snow, and air boundary layer is partially dependent upon the thickness and thermal conductivity of the ice and snow (k_{ice}, k_{snow}, respectively) and the wind velocity according to the relationships denoted in Eq. (3). The k_{snow} was calculated from field measurements of snow density using equations presented by (Sturm et al. 1997), and the thermal transmittance of the boundary layer component is estimated using an approach discussed in Starosolszky (1968).

$$H_{loss} = \frac{T_{melt} - T_{air}}{\frac{d_{ice}}{k_{ice}} + \frac{d_{snow}}{k_{snow}} + \frac{1}{10 + V_{wind}}} \tag{3}$$

The potential ice melt ($\dot{d}_{melt}$) rate is calculated from the H_{melt} in combination with the latent heat of fusion for water (λ_{fusion}) and the density of ice (ρ_{ice}) using Eq. (4).

$$\dot{d}_{melt} = \frac{\Delta d_{ice}}{t} = \frac{H_{melt}}{\lambda_{fusion}\, \rho_{ice}} \tag{4}$$

The model modifies the ice thickness in the subsequent cell by subtracting Δd_{ice} from d_{ice} over the amount of time necessary for water to flow across the surface of the cell. After determining the ice thickness in the subsequent cell, the model calculates the potential rate of ice melt for that cell using the revised water flow rate and ice thickness assuming that the groundwater inflow is the same in every cell.

3. RESULTS

Model results indicate that the groundwater upwelling rate and its associated energy flux increases linearly as the hydraulic conductivity of a system increases under a constant temperature (Figure 2). At a groundwater upwelling temperature of 4.0°C, the heat flux could melt up to 17 mm/day under conditions without atmospheric heat losses, that is, if 100% of the groundwater heat was used to melt river ice (Figure 3).

Our results indicate that under field conditions with the measured upwelling rate (0.312 m^3/m^2 day), the potential ice melt is increased by increasing air temperature, hydraulic conductivity, groundwater upwelling, or snow depth. Figure 4 illustrates the linear relationship between atmospheric temperature and potential ice melt. Given our measured upwelling rate (0.312 m^3/m^2 day), at -10°C, the potential ice melt rate would be positive, but at -20°C, the potential ice melt rate is negative (indicating that there would be ice growth). This assumes that there was no accumulated water depth and a small layer of ice covering the water surface.

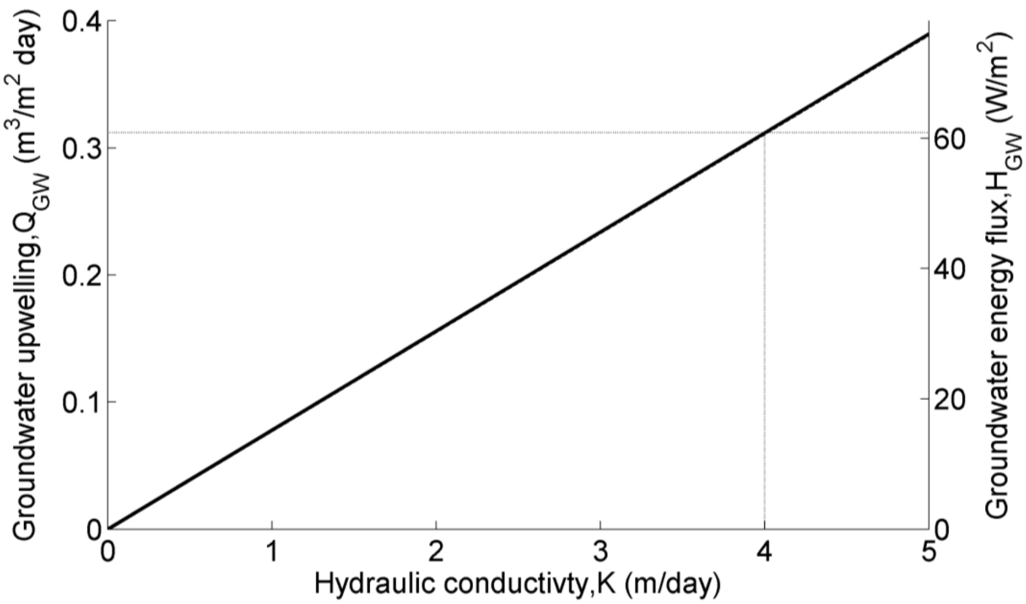

Figure 2: Hydraulic conductivity relative to the groundwater upwelling rate and its associated heat flux at a groundwater temperature of 4°C at our measured vertical hydraulic gradient.

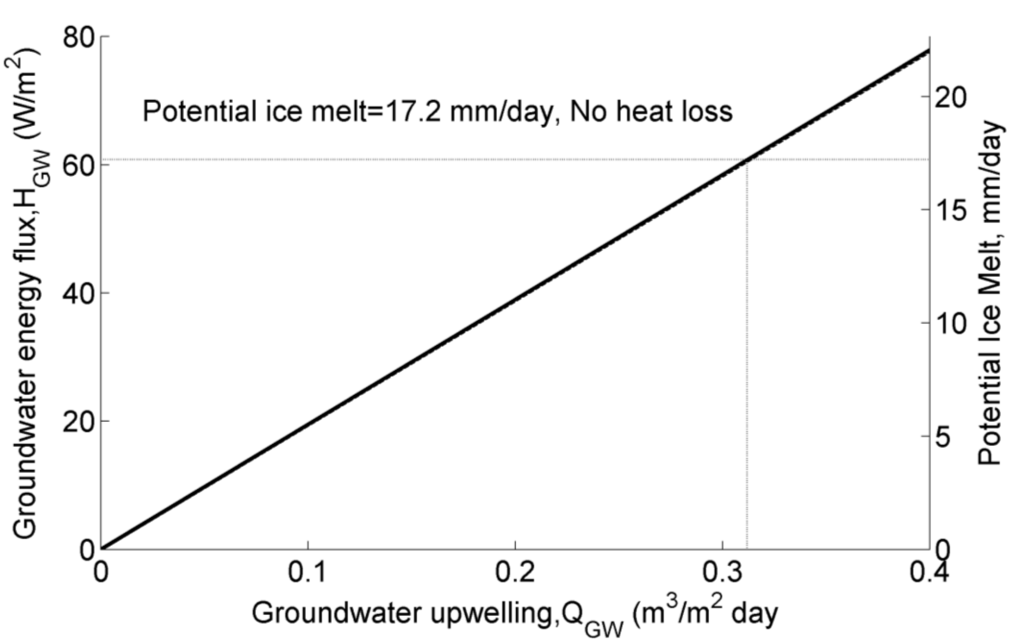

Figure 3: The potential heat flux associated with groundwater upwelling with a temperature of 4℃ and the potential ice melt rate associated with that heat flux, assuming a system with no atmospheric heat losses or gains (perfectly insulated from the atmospheric temperature).

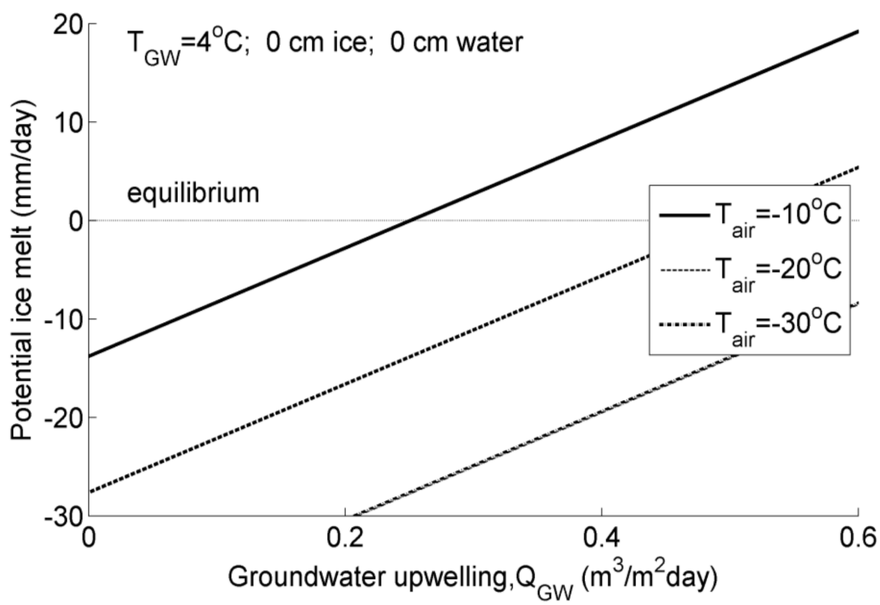

Figure 4: Groundwater upwelling effects on ice melt rates under decreasing air temperatures.

Figure 5 illustrates the modeled response to snow depth. At -27°C with no snow, the potential ice melt rate is negative (indicating conditions favoring ice growth), but with 5 cm snow at the same air temperature, the system is at thermal equilibrium with no ice growing or degrading. With 10 cm of snow, the insulating effects of the snow allow for some degradation of ice conditions (up to 5 mm/day of ice melt).

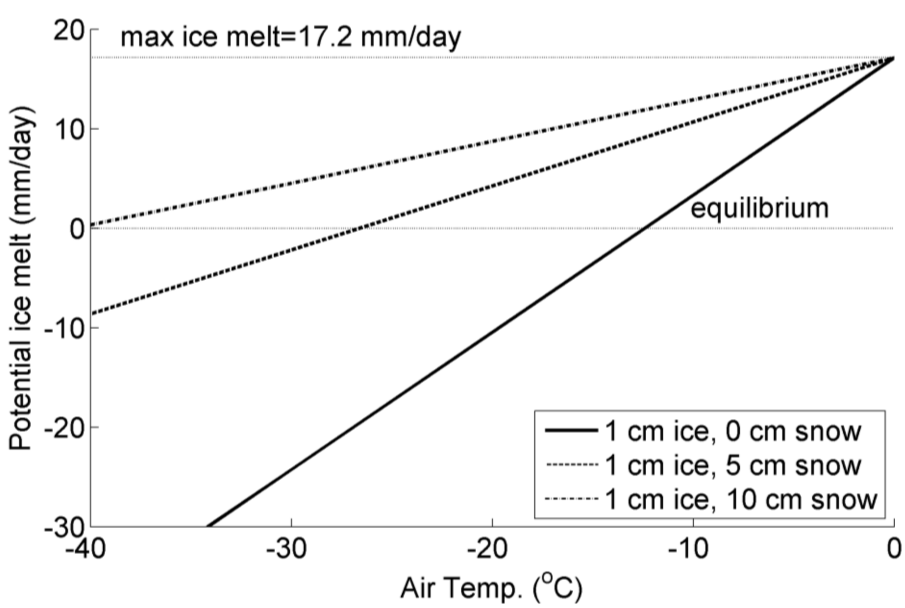

Figure 5: Potential ice melt rate at varying temperatures under different snow depths.

Figure 6 demonstrates how relatively large increases in the initial ice thickness has a relatively small effect on the potential ice melt rate when compared to similar increases in snow depth.

Under a constant snow depth, the change in potential ice melt is relatively small with even 25 cm increases in the initial ice thickness. In addition, under 20 cm or more of snow, there is a small increase in the potential ice melt rate.

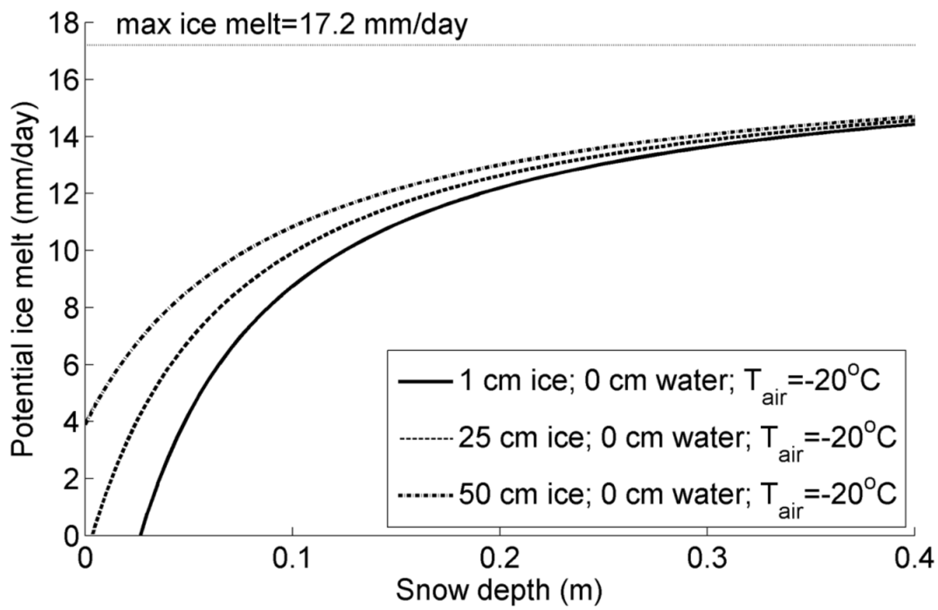

Figure 6: Potential ice melt rate at varying snow depths under three initial ice thicknesses.

4. DISCUSSION

Preliminary modeling results indicate that the wintertime groundwater–river system can be modeled and produces interesting and reasonable results. Figure 7 summarizes the model results. Increases in piezometric head (groundwater pressure) or hydraulic conductivity would increase the groundwater upwelling rate and the groundwater heat flux. The increased heat energy would lead to an increased rate of ice melt or degradation. Increases in the snow depth would increase thermal insulation over the ice and would decrease heat loss from the groundwater and river water, thus causing more heat energy to be available for degradation of the ice thickness. Increases in air temperature would decrease the temperature gradient between liquid water and the air, therefore decreasing the heat losses and increasing the ice melt rate. Finally, any increases in groundwater temperature would increase the groundwater heat flux and would increase the ice melt rate.

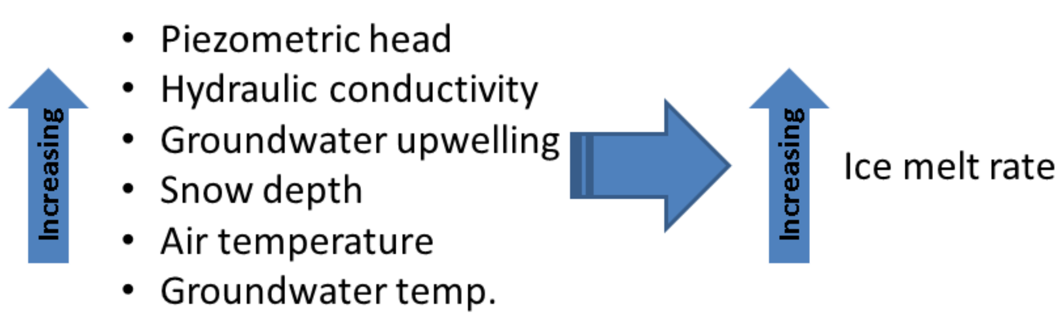

Figure 7: Summary of the factors that affect ice melt rate associated with groundwater flow into a hydrologic system with flowing water, based on numeric modeling results.

Increased air temperatures associated with climate change are warming permafrost, which is transforming some discontinuous permafrost areas to non-permafrost. These areas are expected to increase rates of exchange between surface water and groundwater. In areas with positive groundwater pressure, upwelling rates are expected to increase. Walvoord and Striegel (2007) estimate that winter groundwater discharge in the Tanana River has increased by approximately 20% between 1963 and 2005. Additionally, under an altered climate, increased winter air temperatures would be expected to decrease the temperature gradient. Increased snow depths in the area might also be expected. Thus, a future climate scenario might include estimates based upon these concepts to determine how ice conditions might be affected by groundwater upwelling in the region under an altered climate with degraded permafrost.

5. CONCLUSIONS

Rural Alaskans have indicated that travel conditions have gotten more dangerous in recent memory. Our modeling results illustrate a potential mechanism to account for changing travel conditions on side-sloughs of the Tanana River and other rivers in Interior Alaska. Degrading permafrost conditions have been reported as having increased groundwater upwelling, which could degrade ice from below and generate hazardous ice conditions on shallow channels. These hazardous areas are typically areas that appear to be safe for river travel, but in actuality are not safe. These areas could have stretches of thin ice that are difficult to predict without a better understanding of the potential mechanisms causing its existence. On the Tanana River, between Fairbanks and Nenana, field efforts show that dangerous areas are most commonly found along the southern river bank, which borders the Tanana Flats. The Tanana Flats is an area characterized by an extensive network of wetlands, bogs, and ponds, which are indicative of an area with substantial groundwater upwelling.

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