THE INTEGRATED HYDROLOGIC AND SOCIETAL IMPACTS OF A WARMING CLIMATE IN INTERIOR ALASKA

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THE INTEGRATED HYDROLOGIC AND SOCIETAL IMPACTS OF A WARMING CLIMATE IN INTERIOR ALASKA

A

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By

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ABSTRACT

In this dissertation, interdisciplinary research methods were used to examine how changes in hydrology associated with climate affect Alaskans. Partnerships were established with residents of Fairbanks and Tanana to develop scientific investigations relevant to rural Alaskans. In chapter 2, local knowledge was incorporated into scientific models to identify a social-ecological threshold used to model potential driftwood harvest from the Yukon River. Anecdotal evidence and subsistence calendar records were combined with scientific data to model the harvest rates of driftwood. Modeling results estimate that between 1980 and 2010 hydrologic factors alone were responsible for a 29% decrease in the annual wood harvest, which approximately balanced a 23% reduction in wood demand due to a decline in number of households. The community's installation of wood-fired boilers in 2007 created a threshold increase (76%) in wood demand that is not met by driftwood harvest. Modeling of climatic scenarios illustrates that increased hydrologic variability decreases driftwood harvest and increases the financial or temporal costs for subsistence users.

In chapter 3, increased groundwater flow related to permafrost degradation was hypothesized to be affect river ice thickness in sloughs of the Tanana River. A physically-based, numerical model was developed to examine the importance of permafrost degradation in explaining unfrozen river conditions in the winter. Results indicated that ice melt is amplified by increasing groundwater upwelling rates, groundwater temperatures, and snowfall. Modeling results also suggest that permafrost degradation could be a valid explanation of the phenomenon, but does not address the potential drivers (e.g. warming climate, forest fire, etc.) of the permafrost warming.

In chapter 4, remote sensing techniques were hypothesized to be useful for mapping dangerous ice conditions on the Tanana River in interior Alaska. Unsupervised classification of high-resolution satellite imagery was used to identify and map open water and degraded ice conditions on the Tanana River. Ninety-five percent of the total river channel surface was classified as "safe" for river travel, while 4% of the channel was mapped as having degraded ice and 0.6% of the channel was classified as open water (overall accuracy of 73%). This research

demonstrates that the classification of high-resolution satellite images can be useful for mapping hazardous ice for recreational, transportation, or industrial applications in northern climates.

These results are applicable to communities throughout the North. For people that rely upon subsistence activities, increased variability in climate cycles can have substantial financial, cultural, recreational, or even mortal consequences. This research demonstrates how collaborations between scientists and local stakeholders can create tools that help to assess the impacts of increased environmental variability (such as flooding) or to detect or predict unsafe conditions (such as thin or unpredictable ice cover). Based upon this research, I conclude that regional-scale adaptations and technological advances (such as modeling and remote sensing tools) may help to alleviate the effects of environmental variability associated by climate.

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CHAPTER 1. INTRODUCTION

Interdisciplinary approaches to education and earth science have received growing attention in recent years (Rhoten and Parker 2004, Schmidt and Moyer 2008, Leemans et al. 2009, Fischer et al. 2012, McClain et al. 2012). The challenges posed by a changing climate are not well defined and are interdisciplinary by nature. For those interested in studying the impacts of changes in hydrology, the rapidly growing field of ecohydrology is enticing. Ecohydrologists find themselves at the nexus of ecology, hydrology, and sociology (McClain et al. 2012) and well poised to address scientific questions that transcend each of those disciplines. With a background spanning hydrology, engineering, biology, aquatic ecology, chemistry, environmental science, and policy, my ecohydrological interests motivated my pursuit of a Doctorate of Philosophy in Interdisciplinary Hydrology from the University of Alaska Fairbanks. The result of that work is presented in this dissertation entitled, "The Integrated Hydrologic and Societal Impacts of a Warming Climate in Interior Alaska."

1.1. RESEARCH QUESTIONS

My overall research goal has been to use interdisciplinary research methods to understand how changes in hydrology associated with climate affected social-ecological systems in Alaska. After my first year, I joined an interdisciplinary research team (Dangerous Ice project team) led by Drs. Knut Kielland and Bill Schneider. Their project team was exploring the social aspects of hazardous ice conditions on the Tanana River (Schneider et al. 2013a, 2013b, 2013c). This project allowed me to build upon Drs. Kielland and Schneider's existing relationships with rural subsistence users in Alaska to study linkages between changes in hydrology associated with climate and people in interior Alaska.

During my dissertation research, I collaborated with residents of Fairbanks and Tanana, Alaska to develop scientifically interesting research questions of relevance to rural Alaskans. As part of the Dangerous Ice project team, we collaborated with subsistence users to study hazardous ice conditions on the Tanana River. This research approach allowed me to participate in both formal and informal interviews and community meetings. While our primary purpose was to discuss past and present wintertime river conditions, Tanana residents repeatedly mentioned how their ability to harvest driftwood during summer flood events was becoming an important concern. Due to an interest in river processes and intentions of identifying hydrologically relevant community concerns, I followed up with the community to discuss the driftwood harvest. Their stories, knowledge, and records relating to flooding, driftwood mobility, and the driftwood harvest led to the production of Chapter 2, entitled “Integrating local knowledge and science: Economic consequences of driftwood harvest in a changing climate.”

In this paper, we hypothesize that local knowledge and science can be used in combination to model the harvest of driftwood and to estimate the financial and temporal costs associated with alternate fuel sources. We address five research questions to address the hypothesis.

1. What are the magnitudes of changes in the timing and frequency of peak flow events?
2. How do changes in hydrology correlate to reported observations regarding the driftwood harvest by Tanana residents?
3. How has the potential driftwood harvest been affected by changes in river hydrology?
4. How might the driftwood harvest be affected by future changes in river hydrology?
5. What are the estimated costs (time and financial) associated with changes in the potential driftwood harvest?

While the driftwood research was very interesting and important to residents of Tanana, the community members were also interested in collaborating on the Dangerous Ice project. The project was initiated in 2006, because river travelers had reported that wintertime travel on the Tanana River had become more dangerous in recent memory. We collaborated with subsistence users in Fairbanks and Tanana and we established field study sites near both communities. Our local collaborators led us to areas that have recurring thin or unpredictable ice conditions in most years. Many of these areas appeared to be associated with groundwater upwelling, where the ice was being degraded from below by warmer groundwater (in some cases, subpermafrost groundwater). These phenomena raised questions about whether changes in groundwater upwelling might explain changes in river ice thickness (as described by the project collaborators) and led to the production of Chapter 3, entitled “Modeling groundwater upwelling as a control on river ice thickness”.

In this chapter, we hypothesize that increases in groundwater upwelling associated with permafrost degradation have affected ice thickness on the Tanana River. I address three research questions to examine the hypothesis.

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 do increasing air temperatures, snow depths, and groundwater upwelling in an altered climate affect river ice thickness on the Tanana River?

While doing fieldwork, we traveled extensively on the river ice and mapped the locations with recurring dangerous ice conditions between Fairbanks and Nenana, Alaska on the Tanana River. We used a combination of visual cues based upon experience to identify the best travel routes through areas not previously traveled. I hypothesized that high-resolution satellite or airborne remote sensing products combined with automated classification tools can be used to identify dangerous ice conditions. This investigation resulted in Chapter 4 entitled, “Mapping hazardous ice conditions with high resolution satellite imagery,” which examined three primary questions:

1. Can satellite imagery be used to accurately map hazardous ice conditions in interior Alaska?
2. Can a single classification system be applied across multiple satellite images to map hazardous ice conditions accurately?
3. Are there spatial patterns that describe the general distribution of hazardous ice conditions between Fairbanks and Nenana, Alaska?

This Ph.D. thesis explores the complex and dynamic associations between climate, hydrology, and society, while exploring the use of local knowledge to identify research of interest to local residents. Each chapter of this dissertation examines the subject from different angles, but as a whole, the work demonstrates how participatory research can be used to solve scientific problems of importance to non-academics. This study demonstrates collaborative approaches to understand how a warming climate and variability in hydrologic processes affect the lives of subsistence users in Alaska.

1.2. BACKGROUND

The water cycle is essential to many earth system processes, and the study of hydrology is a means to understand its influence on those processes. Changes to the hydrologic cycle can be very important. Surface and groundwater hydrology can be impacted in many ways, including infrastructure development (dams, ditches, dikes, etc.), water resource development, climate variability, water policy, natural variability in precipitation, evapotranspiration, vegetation species composition or growth, and many other factors. Thus, the hydrologic cycle is closely linked to the physical environment, society, and the policies or cultures of our social systems. There are complex feedbacks between society, climate, the environment, and the hydrologic system, which is one reason that hydrologic responses are highly variable and difficult to understand or predict. In addition, the study of hydrology in arctic and sub-arctic environments of Alaska requires special consideration of the surface energy balance and effects of permafrost that are fundamentally different from temperate or tropical climates.

1.2.1. Air temperature

While the average monthly temperature in July is approximately 16°C (Hinzman et al. 2005b), the average air temperature was -2.9°C from 1906 to 2013. Air temperatures in interior Alaska can demonstrate extreme seasonal variability throughout the year. During the coldest winters, Fairbanks temperatures have dipped below -45°C, yet, the daily maximum temperature occasionally reaches as high as 33-34°C (Hinzman et al. 2005b).

Strong evidence of a warming climate in the arctic includes rising sea levels (ACIA 2005, Dyurgerov et al. 2010), increasing air temperatures (ACIA 2005, Bekryaev et al. 2010), reductions in glacial ice volume (ACIA 2005, Dyurgerov et al. 2010), reductions in sea ice extent and thickness (ACIA 2005, Kinnard et al. 2011), and warming permafrost (Lachenbruch and Marshall 1986, ACIA 2005, Hinzman et al. 2005a, Rowland et al. 2010, Smith et al. 2010). Between 1875 and 2008, average Arctic temperatures warmed at a rate of 1.36°C per century, nearly twice the warming trend in the rest of the northern hemisphere (0.79°C per century) (Bekryaev et al. 2010). Temperature records in Fairbanks indicate that the mean annual temperature rose 1.4°C from -3.6°C to -2.2°C between 1906 and 2006 (Figure 1.1) (Wendler and Shulski 2009).

Air temperature is driven by complex interactions and feedbacks between solar energy flux, greenhouse gas concentration, surface albedo, and other components of the earth system. Taking many of these relationships into account, predictions indicate that average arctic air temperatures will increase 1.5°C to 5°C over the next 100 years (IPCC 2001, 2007, ACIA 2005). However, the variability of multiyear temporal patterns associated with teleconnections (e.g. Arctic Oscillation, El Niño Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal Oscillation), combined with feedbacks between sea ice and albedo, make future arctic air temperatures difficult to predict (Manabe and Stouffer 1980, Serreze et al. 1997, 2009, Serreze and Francis 2006, Bekryaev et al. 2010, Saito et al. 2013, Walsh 2014).

1.2.2. Hydrology

As the Earth's surface temperatures change, the energy balance and the associated heat fluxes are affected. Changes in the energy balance influence the water balance through complex linkages. The water balance represents the basic individual components of the hydrologic cycle [runoff (R), precipitation (P), evapotranspiration (ET), change in groundwater and soil moisture storage (ΔGW), and change in storage (ΔS)] and can be represented by Eq. 1.1 (Hornberger et al. 1998).

$$R = P - ET - \Delta GW - \Delta S \qquad \text{Eq. 1.1}$$

Fluctuations in the hydrologic cycle can be difficult to associate directly to changes in climate; however, hydrologic variability can relate closely with the energy balance. When the hydrologic system has excess thermal energy, water temperatures and rates of evapotranspiration increase. With increases in evapotranspiration, atmospheric moisture (humidity) rises, and precipitation rates are elevated. When precipitation falls during the summer, it may generate runoff, evapotranspiration, groundwater storage, or other hydrologic storage components. Each of which affects the water and energy balance and continues to influence the system.

1.2.2.1. Precipitation

In Fairbanks, Alaska, annual precipitation averaged 28 cm between 1916 and 2006, but has ranged from 15 cm to 45 cm over that time (Wendler and Shulski 2009). The intensity of summer rains vary during May, June, and July, but on average, August has the highest total monthly rainfall. Typically, snow cover in interior Alaska persists from mid-October through

April or May. The annual maximum snow depth in Fairbanks has ranged between 40 and 200 cm. The maximum snow depth averages approximately 75 cm (with a snow water equivalent of approximately 11 cm) and occurs in mid-March or early April, (Hinzman et al. 2005b). On average 35% of the yearly total precipitation in Fairbanks occurs in the winter, although the winter contribution to the annual precipitation ranges between 13 to 77% (standard deviation equaled 13%) (Hinzman et al. 2005b). This is important because snow is an effective thermal insulator (Sturm et al. 1997). At depth of approximately 25 cm, the hiemal threshold is reached, which suggests that the snow depth is sufficient to insulate the ground surface from oscillations in air temperature (Pruitt Jr. 1957)].

In Interior Alaska, records indicate that precipitation decreased 11% over Interior Alaska between 1916 and 2006 (although not significantly) (Wendler and Shulski 2009). The decrease was related to the Pacific Decadal Oscillation (PDO) index, which was in its positive phase for much of the last 30 years. The PDO index is positive when there is a strong Aleutian Low during the winter, which changes the wind to a more southerly direction and Interior Alaska becomes sheltered from the Pacific's humid air by the Alaska Range (Wendler and Shulski 2009). Winds from the west are more likely to carry moisture-laden air currents to the Interior, which occurs more frequently when the PDO is negative. Thus, the recent reduction in precipitation in Interior Alaska relates to the low PDO index and its effect on atmospheric air currents. Figure 1.2 shows the cyclical oscillations in the precipitation anomaly for summers in Alaska relative to the 1971 and 2000 base period. A slight increase (approximately 5% per century) in the long-term trend is also evident. Figure 1.3 illustrates a longer-term cyclic trend in winter precipitation across Alaska with a decreasing long-term trend (approximately 10% per century) in winter precipitation relative to the 1971-2000 base period.

While patterns in Alaska indicate that less precipitation has been received, precipitation varies greatly by region. When examining global patterns in the arctic, annual precipitation appeared to increase by 1% per decade over the last century (Houghton et al. 2001, Arctic Monitoring and Assessment Programme 2011), which is similar to estimates by Walsh (2012) of a 5% increase in precipitation over the Arctic since 1950. In an analysis of gridded precipitation data sets across the arctic since 1950, slight increases in annual precipitation were observed in most data sets (ranging from -0.03 to 0.79 mm yr^{-2})(Rawlins et al. 2010). If the increases in arctic precipitation were genuine, most precipitation was likely to have fallen as snow during the winter months (Troy et al. 2012), which has been projected to continue increasing (Serreze and Hurst 2000, Tebaldi et al. 2006, Skific et al. 2009). When examining snow cover at a pan-arctic scale from 1979-2009, however, Liston and Hiemstra (2011) found that the onset of snow cover occurred later, the snow-free date in spring happened earlier, snow cover duration was shorter, and the maximum snow water equivalent had decreased.

1.2.2.2. Surface water

The monitoring of river discharge in large arctic rivers is another method of tracking changes in the hydrological cycle (White et al. 2007). Discharge measurements integrate precipitation, evapotranspiration, and changes in water storage across vast watershed areas. Numerous studies have analyzed river discharge from the largest rivers in the Arctic and sub-arctic. Discharge from Russian rivers increased over the period of record with most of the rise occurring in the recent decades (Yang et al. 2002, Peterson et al. 2002, McClelland et al. 2004). More specifically, Peterson et al. (2002) identified a 7% increase from 1939-1999 for the six largest arctic rivers in Russia. The increase in Eurasian arctic river discharge was likely caused by increased precipitation (snow or rain), permafrost thaw, and changes in fire regime in the rivers (Yang et al. 2002, Berezovskaya 2004, McClelland et al. 2004, Troy et al. 2012, Zhang et al. 2013). In Canadian rivers from 1989 and 2007, Déry (2009) reported a change in annual flows of greater than 15%, excluding rivers in the Hudson Bay region (Déry et al. 2005). In Alaska, glacially-fed rivers have been demonstrated to have increasing discharge, while non-glacial rivers showed the opposite trend (Hinzman et al. 2005a).

McClelland et al. (2006) compared discharges of all rivers in the Arctic Ocean and Hudson Bay systems from 1964 to 2000 and showed an overall increase of 3.8% (120 km^3). Many studies have also reported on the seasonality of changes in river discharge. Several groups have shown substantial increases in winter and spring discharge for Eurasian (Yang et al. 2002, Serreze et al. 2002, McClelland et al. 2004, Ye et al. 2004), Canadian (St. Jacques and Sauchyn 2009), and Alaskan arctic rivers (Walvoord and Striegl 2007, Brabets and Walvoord 2009, Lyon and Destouni 2010). In the Yukon River Basin in Alaska and Canada, Brabets and Walvoord (2009) found positive trends in winter discharge during the cold phase of the PDO in only the upper Yukon River Basin, while during the warm phase of the PDO, river discharge also increased in the middle and lower drainage basins of the Yukon River. After considering climate, dams, permafrost thaw, and wildfire as drivers of the increase in Eurasian river discharge, it was found that northward transport of moisture resulting from climatic warming was the most probable explanation (McClelland et al. 2004).

The size or number of surface water bodies has also been changing due to increased connectivity between surface and subsurface hydrologic systems caused by warming permafrost and changes in evapotranspiration relative to precipitation (Smith et al. 2005, Jorgenson et al. 2006, Jorgenson and Shur 2007, Smol and Douglas 2007, Yoshikawa et al. 2007, Roach et al. 2011). Permafrost degradation is considered a likely cause for increasing contributions of groundwater to winter discharge in the Tanana River in Alaska (Walvoord and Striegl 2007, Brabets and Walvoord 2009, Lyon and Destouni 2010). From the hydrograph in Figure 1.4, the dominance of the late summer glacial inflow is evident, but the seasonal decrease in groundwater contribution through the winter is also visible. In a related study, Jones et al. (2013) found that an increase in groundwater discharge resulting from permafrost degradation was a plausible mechanism to explain observations by rural Alaskans that river ice had become more dangerous in recent decades (Schneider et al. 2013c).

1.2.2.3. Flooding

If warming temperatures are the primary response of a warming climate, changes in precipitation are a second-level response derived from the indirect impacts of higher temperatures (through the increase in absolute humidity). Similarly, changes in flooding are a third-level impact of climate change. The further removed a response (such as flooding) is from its primary driver (warming temperatures in this example), the response signal will have more noise and be more difficult to relate directly to particular drivers.

Hydrologic studies have provided evidence that the hydrological cycle is changing (Brutsaert and Parlange 1998, Déry et al. 2009, Skific et al. 2009, Rawlins et al. 2010) and extreme events are occurring more frequently (Tebaldi et al. 2006). In addition, model projections for the 21st century generally indicate a more intense, wetter climate (Tebaldi et al. 2006), which are anticipated to result in both higher frequency and magnitude of flood events. These types of extreme events will likely be more important [to social and ecohydrological processes] than gradual changes in climate (Kane et al. 2003).

The flood history of the Tanana River during the Holocene is indicative of the influence regional climatic changes. Flooding is one of the primary factors controlling floodplain processes in Interior Alaska (Yarie et al. 1998). An analysis of protected floodplain terraces in a bedrock-sheltered side channel on the Tanana River indicated that more frequent flooding occurred during times of widespread glaciation in the mountains and periods with more frequent, high intensity storm events (Mason and Beget 1991). In the same area, alluvial sand deposits demonstrate a period of large flooding occurred between 2000 and 3000 years before present (Mason and Beget 1991).

In interior Alaska, spring break-up floods are significant hydrological events and spring break-up is a dominant hydrologic signal on the Yukon River hydrograph (Figure 1.5). In the Yukon River, flooding is an important hydrological and ecosystem process, especially for bank erosion, deposition of woody debris into the channel, and in the mobilization of driftwood (Alix and Brewster 2004, Wheeler and Alix 2004, Alix 2005). Besides being important ecologically, wood is an important natural resource for humans, particularly in treeless landscapes in the Arctic, where wood has a history of being highly valued and considered to be essential for subsistence users (Alix 2005). The mobilization of driftwood by flood events on the Yukon River is explored in Chapter 2.

1.2.2.4. Permafrost hydrology

Permafrost is important for hydrologic processes in arctic and sub-arctic landscapes. In frost-susceptible soils near saturation, the presence or absence of permafrost strongly affects soil hydraulic conductivity and the infiltration capacity to shallow or deep groundwater systems (Kane and Stein 1983, Mackay 1983, Zhao and Gray 1999, Woo 2012). Ice-rich permafrost soils greatly reduce the hydraulic conductivity and infiltration rates relative to the same soils in an unfrozen environment. In recent decades, it has been warming and thawing (commonly referred to as permafrost degradation) across the Arctic (Lachenbruch and Marshall 1986, Christiansen et al. 2010, Romanovsky et al. 2010, Smith et al. 2010, Woo 2012).

Much of the permafrost located in sporadic or discontinuous permafrost zones is near the freezing point of water and considered to be vulnerable to degradation under a warming climate (Jorgenson et al. 2001). The thawing of ice rich permafrost can significantly increase the permeability of the soil. Ice in the pore space of frozen soils melts and the reduction in volume can cause surface subsidence, consequently creating thermokarst features. A thermokarst pond may form in the sunken void created at the ground surface if water pools on top of the frozen permafrost or if the surface subsides to an elevation lower than the local groundwater table (Jorgenson and Osterkamp 2005).

Pooled surface or ground water contains significantly more heat energy than ground ice (depending on its volume and temperature). When permafrost is in contact with liquid water (especially when it is moving), it is particularly prone to increased thaw rates. As the ground warms, the groundwater temperature rises, which raises the heat content (Kurylyk and MacQuarrie 2014, Kurylyk et al. 2014b, 2014a). This process is a feedback loop, because thawed permafrost areas have greater hydrologic connectivity between surface and subsurface systems and can result in increased wetting (or drying depending upon site specific conditions), additional permafrost thaw, increased losses to evapotranspiration, greater atmospheric humidity, and more precipitation (Hinzman 2004).

1.2.2.5. Groundwater

Another hydrologic response to degrading permafrost is an increase in vertical and horizontal permeability of shallow and deep groundwater aquifers. The thawing of permafrost at depth in discontinuous permafrost areas can suddenly establish deep groundwater flow paths that drive abrupt, non-linear increases in groundwater discharge to streams (Bense et al. 2009). In arctic environments where cold season precipitation is in the solid phase and rivers are almost entirely covered by ice through the winter, the source of river water is entirely from groundwater sources during the winter. Therefore, sudden or gradual changes in winter river discharge are associated to altered groundwater flux rates to the river (Walvoord and Striegl 2007, St. Jacques and Sauchyn 2009, Brabets and Walvoord 2009, Lyon and Destouni 2010).

Groundwater discharge to the Tanana River (found within the Yukon River Basin) increased by 20% from 1967 to 2009 and was likely related to permafrost degradation (Walvoord and Striegl 2007, Brabets and Walvoord 2009, Lyon and Destouni 2010). Similarly, the analyses of stream flow records in the Yukon River Basin indicate an upward trend (0.7-0.9 percent year^{-1}) in groundwater contribution to total annual streamflow (Walvoord and Striegl 2007), which was modeled to be caused predominately by climate warming and permafrost thaw

(Walvoord et al. 2012). The potential impacts and monitoring or detection methods of increased groundwater flows into the Tanana River are explored further in Chapters 3 and 4 of this thesis.

Increasing minimum daily flows were found throughout Russia in permafrost and non-permafrost regions and were indicative of large-scale inputs from groundwater and unsaturated zones in the late 20th century (Smith et al. 2007). A reduction in the intensity of ground freezing and increases in precipitation were hypothesized to be the drivers of rising minimum daily flows. Satellite remote sensing (using data from the GRACE mission) and runoff records also suggest that groundwater storage increased in Russia's Lena and Yenisei watersheds, decreased in Canada's Mackenzie watershed, and was unchanged in Russia's Ob' watershed (Muskett and Romanovsky 2009). Muskett and Romanovsky (2009) hypothesized that the development of closed and open talik in the continuous permafrost zone and in the decrease of permafrost lateral extent in discontinuous permafrost zones were the drivers of the observed trends.

1.2.3. Ecosystem impacts

Permafrost degradation can lead to significant changes in ecosystem type, infrastructure stability, and land use (Osterkamp et al. 1975, Osterkamp and Romanovsky 1999, Hinzman et al. 2005b, Jorgenson and Osterkamp 2005). The response of boreal ecosystems to permafrost thaw can be quite variable. Jorgenson and Osterkamp (2005) identified 16 different categories of ecosystem response. Regions that become wetter may be transformed from one ecosystem type (such as forest) to another (such as wetland) and evapotranspiration will be greater. Alternatively, areas that experience drying may become more hospitable to upland vegetation, become more prone to forest fires, and experience changes in latent and sensible heat fluxes (Hinzman et al. 2013). Under drier and warmer conditions, some forest types, such as white spruce, grow with less vigor during drought stress (Barber et al. 2000).

Other types of ecosystem changes may occur as secondary responses to permafrost thaw. Forest fire, insect outbreak, and toppling of trees by wind have been linked to permafrost degradation (Jorgenson and Osterkamp 2005). As the distribution and composition of vegetation is modified on landscape scales, wind-redistribution of snow, snow cover, and seasonal albedo will be affected (Sturm et al. 2005, Chapin III et al. 2005). Changes in albedo will affect the heating of the atmosphere, adding to the approximately 3 W/m^{-2} $decade^{-1}$ of atmospheric warming already observed in arctic Alaska due to changes in albedo (Chapin III et al. 2005, Euskirchen et al. 2009).

1.2.4. Wildfire

Drier arctic and sub-arctic landscapes are more prone to forest fire. During the 2000s, the area burned increased by 50% each decade since 1940 (Kasischke et al. 2010). Moreover, the increasing prevalence of fires occurring later in the growing season and on better-drained sites tend to burn more of the surface organic layers. Changes in climate are the most likely driver for such a dramatic increase in extreme fire events, but eventually vegetation succession and reductions in woody vegetation will lead to reduced vulnerability of the landscape to wildfire (Kasischke et al. 2010).

Feedback loops between forest fire and permafrost degradation can be significant. Yoshikawa et al. (2002) found that heat conduction was minimal during a fire, but the resulting changes in surface albedo and active layer thickness (the surficial layer that freezes and thaws each year above the permafrost layer) could significantly impact permafrost thaw three to five years after a fire. Thermal degradation of permafrost was reported to be minimal if 7-12 cm of the organic layer remained after a fire, but permafrost thaw after a fire resulted in a change in vegetation composition, hydrologic connectivity, and surface moisture (Yoshikawa et al. 2002).

1.3. STUDY AREA

The Yukon River Basin is partially glaciated and is dominated by discontinuous permafrost areas, although it also has continuous, sporadic, and isolated permafrost regions. The Yukon River flows approximately 2800 km from Atlin Lake in northwestern British Columbia, Canada (elevation 730 m) to the Bering Sea (Brabets et al. 2000). The hydrology of the river is dominated by spring melt and break-up (Figure 1.5). Spring break-up can be violent, which may relate to the physiography of the watershed. Water in the upper basin flows from south to north and breaks up in warmer southern areas before flowing north where the river ice is still stable. The majority of the summer discharge results from snowmelt, rainfall, and glacial melt (Brabets et al. 2000).

The largest tributary to the Yukon River (857,300 km^2 watershed area) is the Tanana River (115,500 km^2 watershed area) (Collins 1990, Brabets and Walvoord 2009), which is 824 km in length. The river confluence at the Yukon River has an elevation of 71 m (Anderson 1970, Ott et al. 2001) (Figure 1.6). Much of the Tanana River is characterized by discontinuous permafrost and is bordered by the Tanana Flats region to the south, which are part of the Tanana-Kuskokwim Lowlands (Anderson 1970). The Tanana Flats have a high water table fed by groundwater originating from glaciers in the Alaska Range to the south. The Alaska Range contributes approximately 85% of the river's water, with just four glacially-fed tributaries (the Nabesna, Delta, Nenana, and Kantishna Rivers) contributing about 60% of that amount (Anderson 1970, Ott et al. 2001). In addition, several large, braided, meltwater streams flow northward from the Alaska Range to the Tanana River, including the Delta, Gerstle, and Johnson rivers (Dingman et al. 1971, Nelson 1995). Thus, annual hydrology of the Tanana River is dominated by the late season input by glaciers (Figure 1.4).

1.4. FIGURES

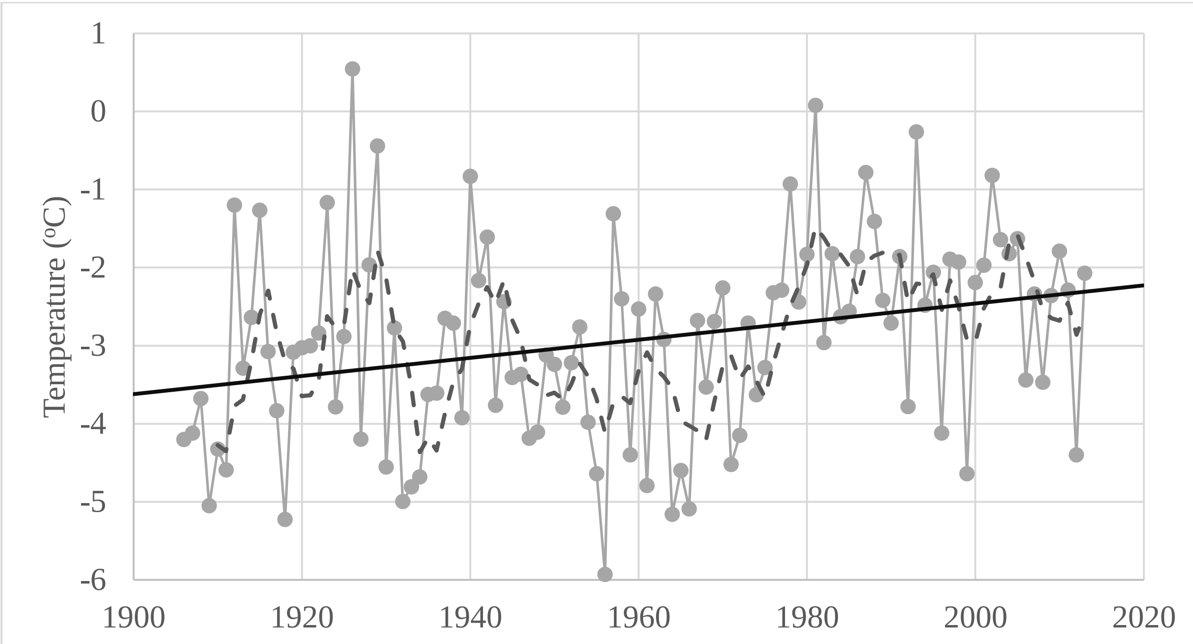

Figure 1.1. Mean annual temperatures at Fairbanks from 1906 to 2013 shows an increasing trend over 108 years. The points represent the annual values, the broken line shows the five-year running mean, and the solid line indicates the best linear fit. Data from 1906-1948 were gathered from Wendler and Shulski (2009) and 1949-2013 data were acquired from NOAA's National Climate Data Center.

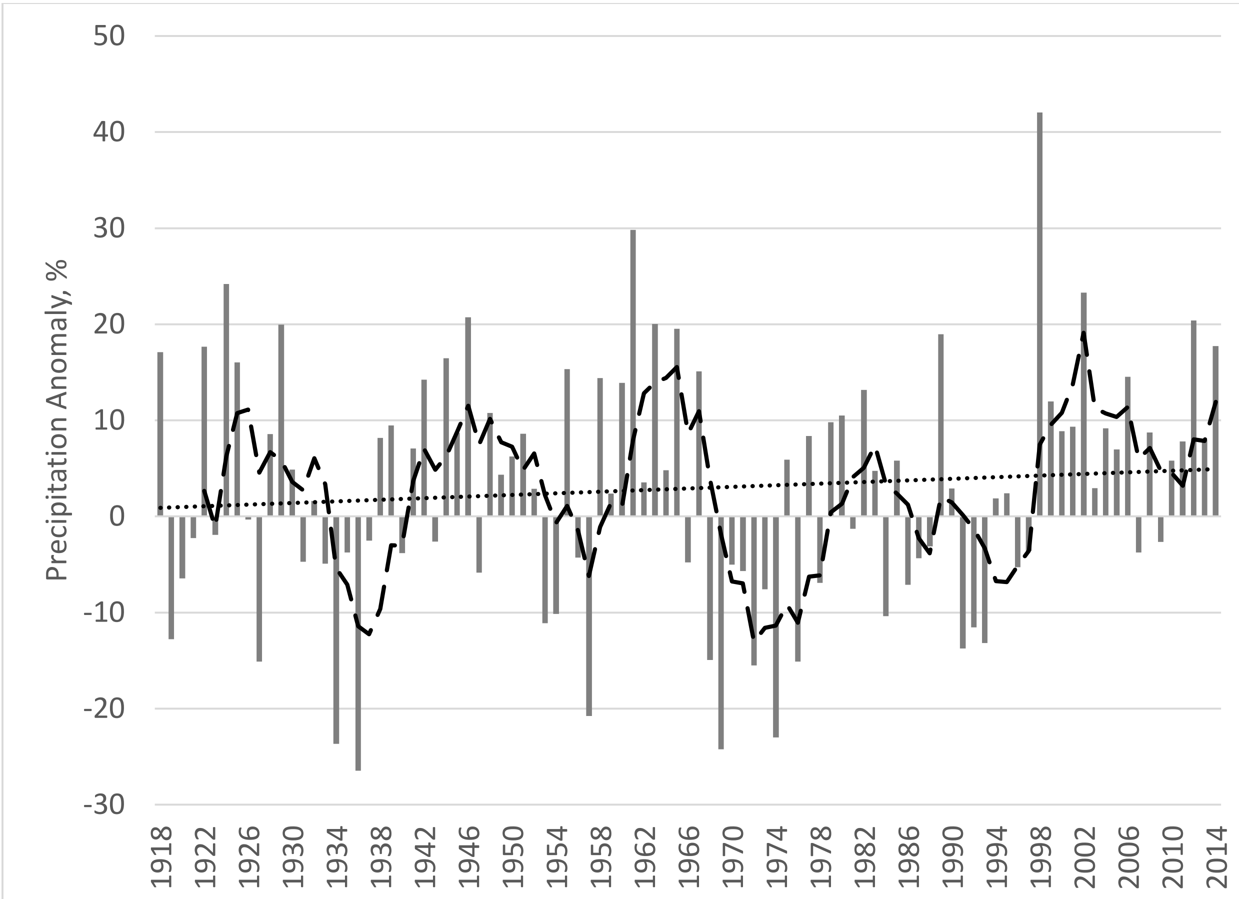

Figure 1.2. Annual summer precipitation anomaly for Fairbanks (April through September) relative to 1971 – 2000 base period illustrates oscillations in wetter and drier periods with a slight increasing trend in summer precipitation over of Alaska. The five-year running average (dashed line) and a best-fit trend line (dotted line) are also shown. Data are from NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/temp-and-precip/alaska).

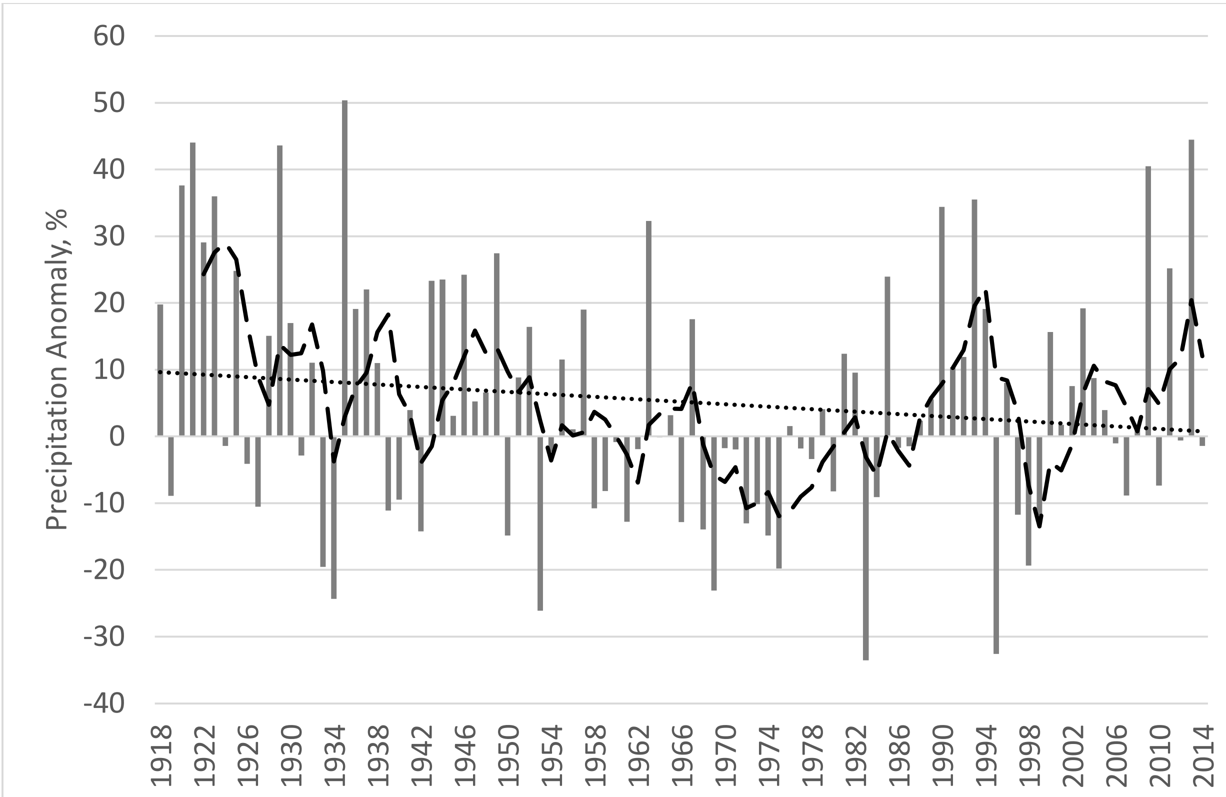

Figure 1.3. Annual winter precipitation anomaly for Fairbanks (October through March) relative to 1971 – 2000 base period illustrates multi-decadal oscillations with more or less snow with a slight overall decreasing trend in winter precipitation over of Alaska. The five-year running average (dashed line) and a trend line (dotted line) are also shown. Data are from NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/temp-and-precip/alaska).

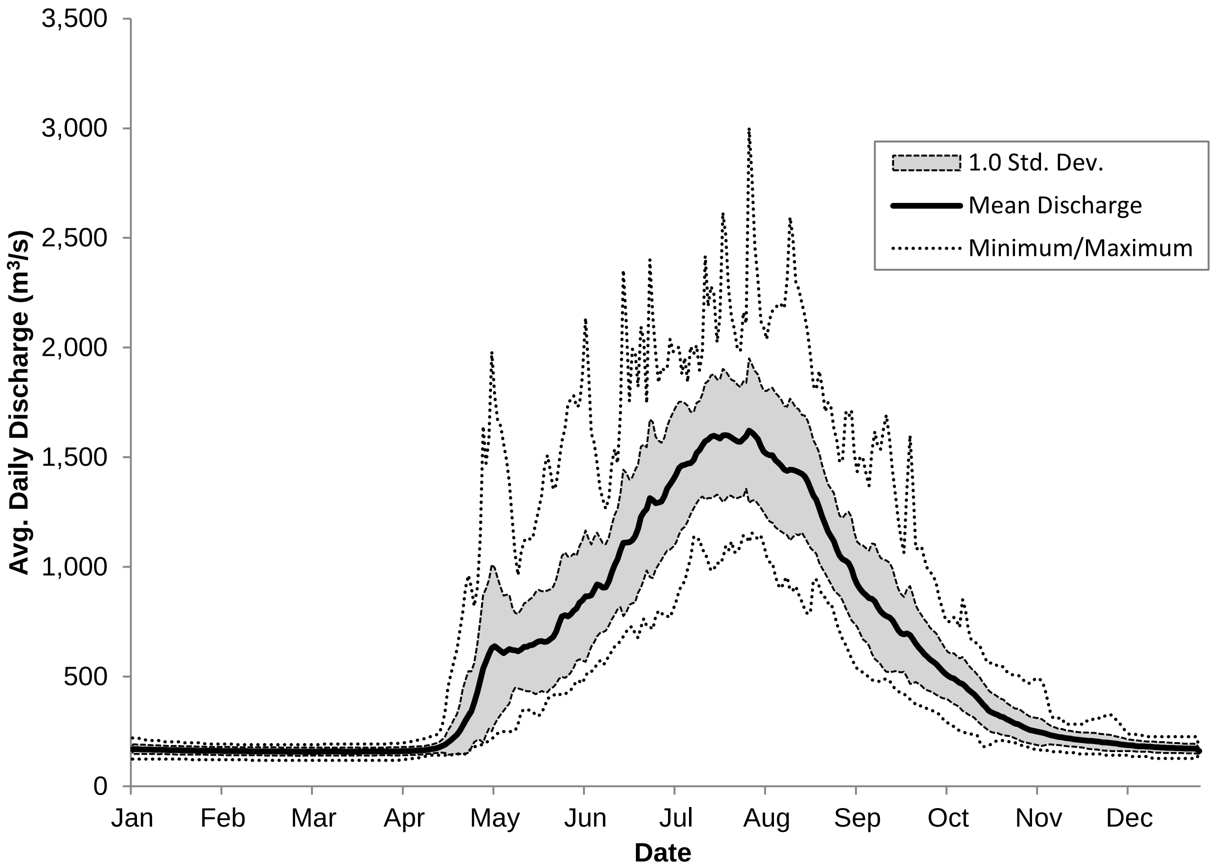

Figure 1.4. Annual hydrograph of the Tanana River at Fairbanks gauging station is characterized by the dominant influence of glaciers in that its flow generally increases through the summer and peaks when glacial melt is at its maximum in July. Figure based upon data from Tanana River at Fairbanks U.S.G.S. gauging station.

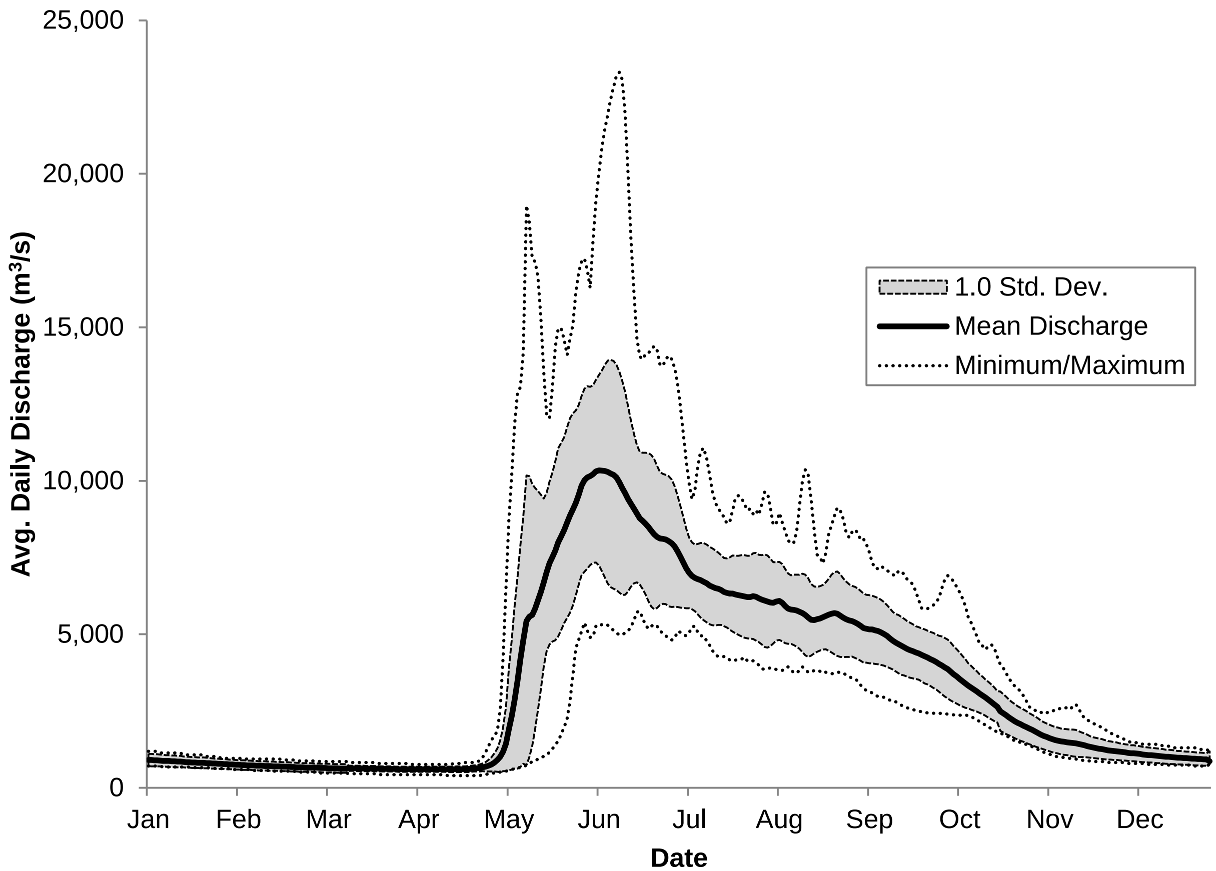

Figure 1.5. Annual hydrograph of the Yukon River at Stevens Village gauging station is characterized by the dominant nature of spring break-up, which is evident in the signal strength of May and June. Figure based upon data from Yukon River at Stevens Village U.S.G.S. gauging station.

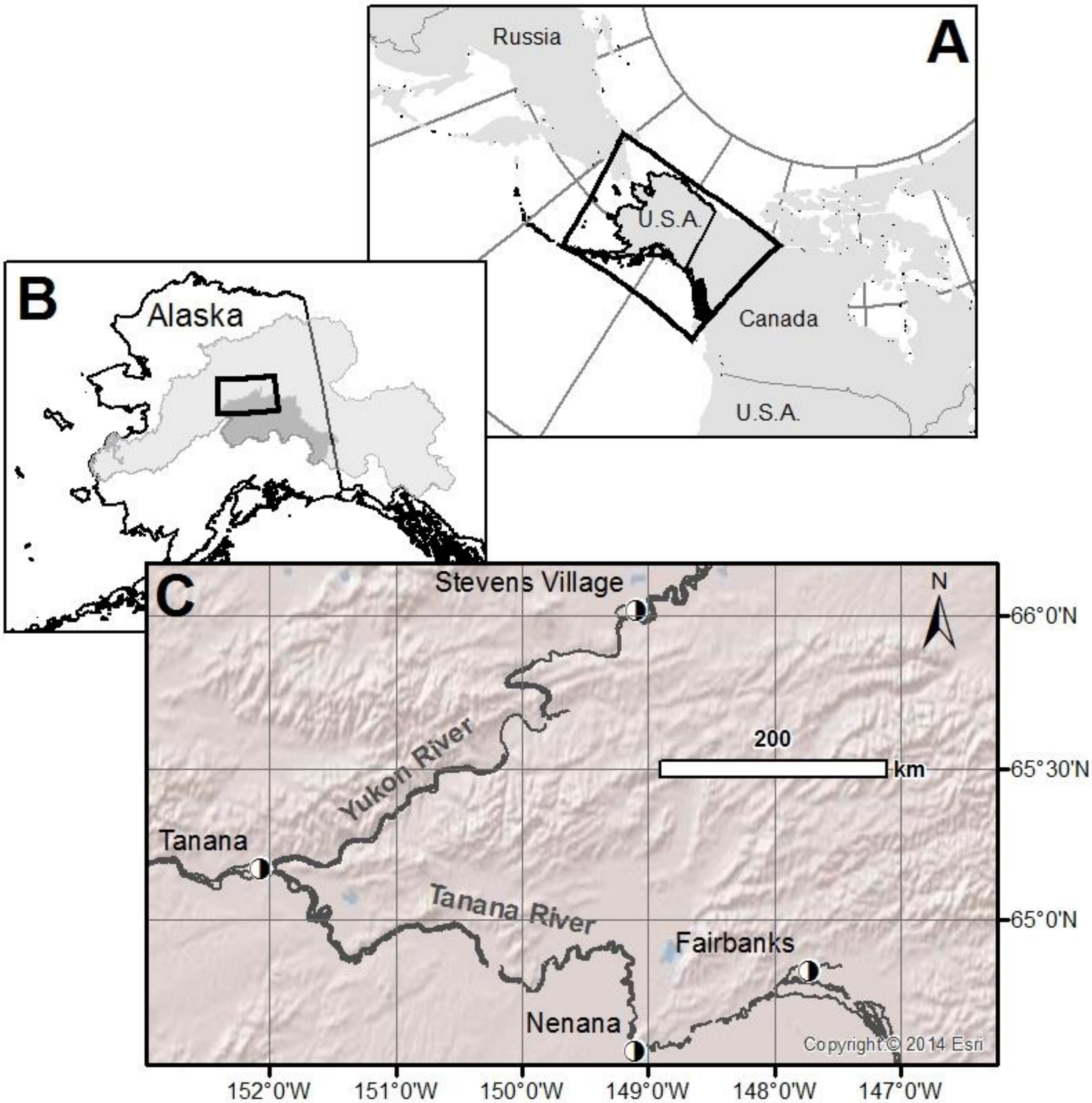

Figure 1.6. Study area map of interior Alaska. Panel A shows the regional location of Alaska relative to Canada, Russia, and the contiguous U.S.A. Panel B shows the Yukon and Tanana River watersheds within Alaska. Panel C illustrates the locations of the communities of Fairbanks, Nenana, Tanana, and Stevens Village relative to the Yukon and Tanana Rivers.

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CHAPTER 2. INTEGRATING LOCAL KNOWLEDGE AND SCIENCE: ECONOMIC CONSEQUENCES OF DRIFTWOOD HARVEST IN A CHANGING CLIMATE[3]

2.1. ABSTRACT

The integration of local knowledge and science represents an opportunity to enhance the understanding of interrelations among climate, hydrology, and social-economic systems while providing mutual benefits to scientists and rural communities. Insight from rural Alaskans helped to identify a social-ecological threshold used to model potential driftwood harvest from the Yukon River. Information from residents of Tanana, Alaska was combined with scientific data to model driftwood harvest rates. Modeling results estimate that between 1980 and 2010 hydrologic factors alone were responsible for a 29% decrease in the annual wood harvest, which approximately balanced a 23% reduction in wood demand due to a decline in number of households. The community's installation of wood-fired boilers in 2007 created a threshold increase (76%) in wood demand that is not met by driftwood harvest. Modeling analyses of numerous climatic scenarios illustrates that increases in hydrologic variability would decrease the reliability of future driftwood harvest. Economic analyses demonstrate that increased climatic variability could have serious economic consequences for subsistence users, while demanding more of their time. Lost time is important because it reduces their availability for performing other subsistence activities and learning to adapt to climate-related challenges. This research may benefit communities by providing a tool that can be used to predict the timing and duration of driftwood runs. Information gathered from discussions with local stakeholders provided critical information for model development and thus provided a better understanding of regional social-ecological dynamics. This research also illustrates the potential for regional-scale adaptations to limit the social-ecological impacts of extreme events and climate variations, while providing economic opportunities and energy independence that reduces their vulnerability to variations in climate.

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2.2. INTRODUCTION

Residents of Tanana harvest driftwood during flood events on the Yukon River, but have suggested that the driftwood harvest has been less reliable in recent decades. A participatory research approach uncovered linkages between climate, regional hydrology, and driftwood harvesting that help to learn more about the impacts of a changing climate on society, while developing a tool that the community can use to predict the timing of driftwood runs.

Research that bridges the gap between local knowledge and science can provide reciprocal benefits to scientists and local communities (Huntington 2000, Carmack and Macdonald 2008, Weatherhead et al. 2010, Huntington et al. 2011). Traditional knowledge and local observations have been used in conjunction with scientific methods to gain a better understanding of how rural people rely upon physical and natural phenomena (Krupnik and Jolly 2002, Chapin III et al. 2006, Carmack and Macdonald 2008, Pearce et al. 2009, Weatherhead et al. 2010, Druckenmiller et al. 2013, Eicken et al. 2014). However, a desirable research objective would aim to produce tools or other research products that will also benefit local collaborators (Nadasdy 1999, Cruikshank 2001).

Rural Alaskans have witnessed many transformations during their lifetimes (Lovecraft and Eicken 2011, Schneider et al. 2013), but little of their traditional knowledge related to environmental changes has been recorded, cataloged, or integrated into scientific endeavors. Yet, local knowledge can complement scientific research by providing social context and illustrating the applicability of research (Berkes 1999, Cruikshank 2001, Weatherhead et al. 2010). Many scientific studies present evidence of changing environmental conditions in northern latitudes (Cullather et al. 2000, Yang et al. 2004, Hinzman et al. 2005, Prowse et al. 2007), but it is less common to develop models based upon local or traditional knowledge although it is not unprecedented (Berman et al. 2004, Berman and Kofinas 2004, Nicolson et al. 2013).

Driftwood mobilization in the Yukon River is linked to river hydrology, and changes in discharge dynamics affect the availability of driftwood and the ability of rural Alaskans to harvest it as a resource. There is a trend towards increasing annual and summer discharge from the Yukon River basin due to increased glacial melt runoff, but flows are also affected by weather patterns associated with the Pacific Decadal Oscillation (Brabets et al. 2000, Brabets and Walvoord 2009). Conditions in Alaskan rivers are changing (e.g., ice conditions; timing of break-up and freeze-up; or the magnitude, timing, duration, or frequency of flood events) (Hinzman et al. 2005, Walvoord and Striegl 2007, Brabets and Walvoord 2009, Ge et al. 2012) and are projected to become more variable (ACIA 2005). Because rivers are integral to the subsistence lifestyles of rural Alaskans throughout the year (Wishart and Murray 2001, Alix and Koester 2002, Wheeler and Alix 2004), changing river character may impact social systems in rural Alaska.

Driftwood has always been very important to communities throughout Alaska (Alix and Koester 2002, Alix and Brewster 2004, Wheeler and Alix 2004, Alix 2005). In the western portion of the state, there is no large woody vegetation on the landscape so driftwood was traditionally the only source of large wood used as a fuel source and in construction. Now, wood for construction and fossil fuels are shipped to remote villages, and fossil fuels have largely replaced wood for heating and power generation. As a heating fuel, oil is very reliable and its acquisition demands less time than collecting wood, but fuel oil is significantly more expensive and cannot be locally sourced. Thus, dependence on fossil fuels decreases the community's self-reliance and increases vulnerability to cost fluctuations or supply disturbances due to external factors beyond the community's control.

Increasingly, villages in rural Alaska are trying to lessen their dependence on fossil fuels by converting to biomass fuel sources (Fresco 2006, Fresco and Chapin III 2009). The switch to biomass, a local and renewable fuel supply, is often driven by economics and a vision of self-reliance, but has many other benefits. It strengthens the local economy, creates jobs, retains money locally, reduces fuel costs, and increases self-sufficiency, thereby reducing the village's vulnerability to external factors (Fresco 2006, Fresco and Chapin III 2009). A number of Alaskan villages recently installed wood-fired boilers to generate heat and/or electricity for the municipality (Alfred Ketzler, personal communication). For the small city of Tanana, Alaska, the installation of wood-fired boilers in 2007 increased their annual demand for wood by approximately 76%. If using only wood, the average household in Tanana requires approximately seven cords (one cord has the dimensions of 1.2m x 1.2m x 2.4m) of wood annually for home heating (Alfred Ketzler, Tom Hyslop, Charlie Campbell, and Charlie Wright, personal communication), although the number of households has decreased from 113 in 1980 to 100 in 2010 (U.S. Census Bureau 1980, 2010). It should be noted that the municipality could use fuel oil if driftwood is not available. While some households can utilize fuel oil as a backup, not all households have the appropriate infrastructure to burn fuel oil for heating.

The hydrograph for the Yukon River at Stevens Village (200 km upstream from the city of Tanana) (Figure 2.1) shows the typical occurrence of spring break-up peak in mid-May and a predictable pulse of high water (commonly referred to as the "June Rise") that follows weeks later in early June (Figure 2.2). During most summers, large quantities of driftwood are carried by the Yukon River during the two distinct, high flow events. During spring break-up, driftwood accompanies rafts of river ice during high flows. A few weeks later in early June, the June Rise also carries high volumes of driftwood, but the absence of the associated river ice makes the wood more accessible and safer to collect. Driftwood is typically mobilized while river stage is rising and is deposited when the water levels decrease, or when wind or water currents push the wood ashore. While the Yukon River driftwood is mobilized, it is transported downstream. Tanana residents use boats to travel upstream to harvest floating driftwood. Harvesting mobilized driftwood requires the roots to be removed before transporting individual or rafts of logs back to town. The wood is collected for personal use, sold to other Tanana residents, or sold to the village or local tribal government. Its predictable nature, ease of access, and cost-effectiveness make driftwood the preferred wood source for Tanana and other Alaskan communities.

During a community meeting in spring 2011, Tanana residents discussed how river conditions have changed in recent decades. As evidence, they described the flood patterns and associated driftwood runs of 2009 and 2010 as unusual, although not unique. They associated driftwood supply to river hydrology and the challenges inherent in its acquisition. The magnitude of the 2009 Yukon River spring break-up flood was discussed, because it caused substantial damage in communities along the river, including the community of Tanana. The high water levels were blamed for a bad driftwood harvest, as it reportedly washed much of the driftwood from the river.

They also discussed the 2010 driftwood season. In mid-May, spring break-up flooding was normal, but the June Rise never materialized. After several weeks, the community became concerned that no driftwood had come downriver. In mid-July, their wood stacks were small, berry-picking season had started, and the fishing season was going strong. Even the municipal wood supply was meager. Since the installation of the wood-fired boilers, the local city and tribal governments have purchased 400-1000 cords of driftwood annually from locals (Alfred Ketzler, personal communication). According to Ruth Althoff, “finally in late-July, the river came up, but there was no wood, and then the river came up higher in mid-August and finally, there came the wood” (personal communication).

In-person interviews, recorded interviews, and a community meeting were conducted in Tanana to reveal that in recent decades, high-flow events that carry driftwood have become less predictable (Schneider et al. 2013). Variability in flood frequency, magnitude, duration, or timing affect driftwood flows in the river and the ability of Tanana residents to harvest it as a subsistence resource. These types of changes in river hydrology threaten their access to driftwood, and require the use of alternative fuels that may be more costly or time-intensive. Fuel oil is a readily available, but costly fuel alternative that demands less time relative to the wood options. Standing deadwood are dead standing trees harvested by residents in the winter using snowmobiles and sleds. Stranded driftwood is wood previously mobilized by the river and deposited on the riverbank, but accessible only in summer when not frozen in the mud or covered in snow. The source of standing deadwood varies over time, but the typical harvest technique often involves traveling over land and ice with snowmobile and sled to recently burned areas or forest groves that have been killed and maintained as potential wood sources. Stranded driftwood can require extensive effort to harvest and transport to town. Harvesters of stranded driftwood are likely to harvest from stretches of river relatively near Tanana. The advantage of standing deadwood is that it usually has a lower moisture content, but individual logs are typically smaller in diameter.

Due to the participatory process, the concerns of Tanana residents motivated a series of research questions that required incorporating local knowledge into the scientific process. To generate a better understanding of the social-ecological system, four research questions were examined:

1. What are the magnitudes of changes in the timing and frequency of peak flow events?
2. Are there changes in hydrology that correlate to reported observations regarding the driftwood harvest by Tanana residents?
3. How has the potential driftwood harvest been affected by changes in river hydrology?

4. How might the driftwood harvest be affected by future changes in river hydrology?
5. What are the estimated costs (time and financial) associated with changes in the potential driftwood harvest?

2.3. METHODS

2.3.1. Study area

Tanana is a small community [approximate population of 300 in 100 households (US Census Bureau 2010)] located on the north bank of the Yukon River, 3.3 km downstream from the confluence of the Yukon and Tanana Rivers in the state of Alaska, U.S.A (Figure 2.1). Its economy depends heavily on subsistence activities (hunting, fishing, and gathering). The positioning of islands in the river ensures that most driftwood from the Tanana River (which enters from the south) is not easily accessible to Tanana residents, therefore harvested driftwood originates primarily in the Yukon River (Charlie Wright, Charlie Campbell; personal communication).

The Yukon River is a glacierized basin, with 59% (508,400 km^2) of the catchment area above the Stevens Village gauge. Less than 1% of the catchment above the gauge is glaciated (Brabets et al. 2000). The hydrology of the Yukon River is dominated by spring melt and break-up. Spring break-up can be rather violent, which may relate to the physiographic orientation of the watershed. Water in the upper basin flows from south to north and breaks up in warmer southern areas before flowing north where the river ice is still stable. The majority of the summer discharge results from snowmelt, rainfall, and glacial melt (Brabets et al. 2000).

2.3.2. Local knowledge

After reviewing recorded interviews of six Tanana residents (Schneider et al. 2013), a local Tanana resident organized a community meeting (hosted by the University of Alaska Fairbanks) on the subject of changing river conditions in March 2011. Eighteen community residents came to the meeting and shared stories and observations relating to the river. The community meeting was not focused on the harvest or use of driftwood; however, it became apparent that driftwood was an issue of concern for Tanana residents. Follow-up discussions were initiated with the meeting participants who had concerns about the driftwood harvest. Additional interviews were held with residents based upon referrals. Follow-up discussions involved semi-formal unrecorded interviews during which open-ended questions were asked about flooding, driftwood harvest, driftwood processing, wood use, fuel oil consumption, and related topics. The interview subjects included two individuals who harvest and sell wood locally, three individuals who harvest wood for personal use, and the city manager who championed the installation of the city's wood-fired boilers and developed the incentives program facilitating the purchase and sales of harvested wood. The interviewers did not make an effort to solicit participation based upon demographic criteria, but sought participation from community members considered local experts on harvesting driftwood or the driftwood economy in the city of Tanana. Follow-up interviews were used to resolve discrepancies between interview subjects. Minor differences between responses were averaged across interviewees to avoid subjective assessment of respondent accuracies. There were no substantive differences between interviewee responses.

2.3.3. Driftwood mobilization threshold

Based upon local knowledge and subsistence records, a 'driftwood mobilization threshold' was identified. Above this discharge, unlimited driftwood was assumed to be mobilized by the river until the discharge peaks. To develop this threshold value, interview data from 2009 and 2010 (see introduction) were related to the USGS gauging station data at Stevens Village. Additionally, one long-time Tanana resident kept records of his subsistence activities associated with the driftwood harvest since 1989 (Table 2.1). During an informal interview, he shared his driftwood records. The records include the date, the number of logs harvested, and relevant notes. The discharge at Stevens Village two days prior to the harvest date (the approximate conveyance period between Stevens Village and Tanana) were analyzed and compared to the interview data associated with the 2010 hydrologic year to validate the concept of a driftwood mobilization threshold.

Tanana residents suggested that driftwood from the Tanana River is silt-laden and less desirable to use as firewood. In addition, driftwood from the Tanana River typically flows on the far side of islands in the Yukon River near the community. Therefore, only hydrologic data for the Yukon River were analyzed, despite the fact that driftwood in the Tanana River (which is hydrologically influenced by glaciers) would be mobilized independent of the timing of driftwood runs in the Yukon River.

2.3.4. Hydrologic variability

River discharge data were analyzed to determine whether changes in hydrology reported by Tanana residents correspond to records from the USGS Stevens Village gauging station, which is the next gauging station upstream on the Yukon River. Peak annual discharge data were analyzed for the period of record (1977-2013) to determine the Log-Pearson Flood Flow Frequency (using the Log-Pearson Flood Flow Frequency from USGS 17B MATLAB® extension). The average daily discharge was used to analyze the number of years that small floods (<1.25 year recurrence interval) were not realized in a given year. The hydrographic record was separated into early (1977-1993) and late (1994-2013) phases based upon the analysis of small floods.

For each phase, the first two flood peaks of the year were categorized as associated with spring break-up, June Rise (or post break-up flood peak that exceeds the driftwood mobilization threshold) or other. For each flood peak, the day of year, magnitude, and duration of the rising limb of the hydrograph were determined. The data were summarized for each year of the period of record.

2.3.5. Driftwood harvest model

Interviews and census data were used to develop model parameters (Table 2.2) for calculations of the annual village wood harvest (H_{annual}, Eq. 2.1), demand (D_{annual}, Eq. 2.2), and deficit (Def_{annual}, Eq. 2.3). The annual driftwood harvest was estimated from the number of households in Tanana (n_{HH}), the percentage of households harvesting driftwood ($\%_{HH}$), the harvest rate (dH_{HH}/dt), and the annual number of driftwood days (t_w). The annual village demand was the sum of the municipal demand (D_M) and the number of households multiplied by the average household demand (D_{HH}) for wood. The total municipal demand would provide 100% of the heating wood supply for the village. The deficit is the difference between D_{annual} and H_{annual}.

$$H_{annual} = \%_{HH} n_{HH} \left(\frac{dH_{HH}}{dt}\right) dt_w \qquad \text{Eq. 2.1}$$

$$D_{annual} = n_{HH} D_{HH} + D_M \qquad \text{Eq. 2.2}$$

$$Def_{annual} = H_{annual} - D_{annual} \qquad \text{Eq. 2.3}$$

2.3.6. Driftwood harvest in a changing climate

To understand how an increasingly variable climate may influence Tanana's driftwood harvest, scenarios were developed to examine the potential response of the driftwood harvest to increasing variability in the annual number of driftwood days. Assuming that changes in variability in the 1994-2013 phase represents a directional change from the 1977-1993 phase (ACIA 2005, Arctic Monitoring and Assessment Programme 2011), the observed variability was increased by factors of 0, 1, 2, and 3 to assess the impacts of climate variability on the driftwood harvest. Thus the 1977-1993 data set is referred to as the 0x scenario and the 1994-2013 data set is referenced as the 1x scenario, while the 2x and 3x scenarios are assumed to have double and triple the variability observed between the 0x and 1x scenarios. To assess the variability of the different scenarios, Easyfit (v5.5) was used to perform the Anderson Darling test ($p<0.01$) to determine that the distribution of annual driftwood days for the period of record could be best represented by a geometric probability density function (pdf) for discrete data [$f(x; q) = q\,(1-q)^x$ for $x \geq 0$, $q=0.11859$]. The early (1977-1993) and late (1994-2013) phase datasets were then fit to geometric distributions ($q_{0x}=0.11258$ and $q_{1x}=0.12422$ respectively). Assuming the 1977-1993 distribution as a benchmark [0x scenario with q_{0x} and variance (σ^2) of 70.02 ($\sigma^2 = (1-q) / q^2$)], the difference between σ^2 of the 0x and the 1x scenarios was multiplied by 0, 1, 2, and 3 and added to the benchmark to derive the desired variance of geometric pdfs for each scenario. q was determined to provide the desired pdf ($q_{0x}=0.\ 11258$, $q_{1x}=0.12422$, $q_{2x}=0.14058$ and $q_{3x}=0.16610$) from which 1000 random points were generated to define the 0x-3x scenarios. These data represent the annual number of driftwood days for each scenario, which were used as input in the driftwood harvest model. The model output estimates the annual harvest and deficit based upon annual driftwood days, while considering the increased demand for fuel wood since 2007 and the installation of additional wood-fired boilers in 2013 (increasing demand by an estimated 98 cords of wood annually).

2.3.7. Economic analyses

The costs (financial and time) associated with the harvest and use of substitute fuels were assessed when insufficient driftwood was harvested to meet city's needs. Costs were estimated using a linear activity analysis model using fixed-input parameters based on interviews. The percentage of each fuel type used to meet the city's total wood deficit was modified for each assessment. Five assessments were modeled based upon the approximate 1994-2013 deficit. During that time, the driftwood harvest model estimated an average deficit of 903 cords annually. Each assessment calculates the costs associated with using alternate fuels for the deficit. The costs are calculated for the following situations to meet the deficit: harvesting driftwood (mobilized by the river, if it was available); harvesting stranded driftwood from river banks; collecting standing deadwood as the wood substitute; using only fuel oil; and using a mix of alternative fuels for the driftwood deficit (25% stranded driftwood, 25% standing deadwood, and 50% fuel oil). The full activity analysis model is described in Appendix A2 and estimates the temporal and financial costs associated with each situation.

2.4. RESULTS

2.4.1. Hydrologic variability

The magnitudes of flood recurrence intervals were determined for the Yukon River at Stevens Village for the period of record and separately for the early and late phases of the record (Table 2.3). From 1977 to 1993, the annual peak discharge failed to exceed the 1.25 year flood event [11,000 m^3/s (cms)] in only 1 out of 17 years (5% of the years), but from 1994-2013, this threshold was not reached in 25% of the years (5 out of 20 years). A one-tailed student t-test assuming unequal variance verifies that the peak annual discharge is significantly different ($p < 0.05$) between phases.

The date, day of year, magnitude and number of days of the rising limb were determined for each year (1977-2012) (Table 2.4). There was no significant difference between the dates of the spring break-up peak between the early or late phases (Figure 2.3). Additionally, the median date of the secondary flood peak that exceeds the driftwood mobilization threshold is similar between the two periods. Yet, the variability for the recent period after 1993 [standard deviation (s.d.) = 25 days] is much greater than the period prior (s.d. = 7 days).

2.4.2. Local knowledge and driftwood mobilization threshold

According to Mrs. Althoff (personal communication), in August 2010, the river exceeded flows of the previous two months and carried driftwood with it. This information was used in conjunction with USGS discharge data to determine that a flow at Stevens Village between 8,800 and 10,500 cms mobilized large amounts of driftwood. Mr. Hyslop's subsistence records (Table

2.1) were also analyzed in conjunction with USGS river discharge data. Two days (the approximate conveyance time of flow between Stevens Village and Tanana) before the date Mr. Hyslop caught driftwood in any given year, the discharge at Stevens Village averaged 10,000 cms (s.d. = 2,100 cms, which is between the upper and lower threshold estimates derived from Mrs. Althoff's story regarding 2010 driftwood season). Both analyses support the concept of a driftwood mobilization threshold at a discharge of 10,000 cms (Figure 2.2). Above this discharge, unlimited driftwood is assumed to be mobilized by the river until the discharge peaks.

Residents also suggest that the driftwood harvest runs have become shorter. One resident stated that residents may have just 1-3 days to harvest driftwood, whereas historically the driftwood run lasted 4-5 days (Schneider et al. 2013).

2.4.3. Driftwood harvest model

Figure 2.4 illustrates that the modeled driftwood harvest for Tanana was more variable in most years since 1993, while extremes did occur in the earlier phase. According to the model, variations in river hydrology combined with increased municipal demand (and decreased cumulative household demand) result in an increasing annual wood deficit for Tanana (Figure 2.5).

While modeling predicts that it has been always been necessary to supplement the driftwood harvest, 44% of wood demand was met with only mobilized driftwood from 1977-1993. Between 1994 and 2006 (prior to installation of municipal wood-fired boilers), 42% of wood demand was met with mobilized driftwood. After 2000, a smaller number of households in the city (113 to 100 households) decreased the wood demand by 23%, although the installation of the city's wood-fired boilers in 2007 subsequently increased demand by 76%. Therefore, after 2007, the average harvest was only 21% of city's total wood demand. Thus, despite an average decrease in the modeled annual harvest of 29% due to hydrologic factors alone, the average wood deficit (730 cords) after 2007 was 90% greater than before 1993 and was 140% higher than the period between 1994 and 2006 (Figure 2.5).

2.4.4. Driftwood harvest in a changing climate

With increasing variance in the exponential distribution of driftwood days, there were more years with no driftwood days (Figure 2.6), thus the median number of driftwood days decreased (Table 2.5). Similarly, the median driftwood harvest is modeled to become smaller.

Thus, in scenarios with more variability, the median deficit is projected to become greater (Table 2.5).

2.4.5. Economic analyses

There is an inverse relationship between the economic costs and time investment for the use of each alternative fuel type to meet the energy needs associated with the average modeled driftwood deficit from 1994-2013 (Figure 2.7). The harvest of standing deadwood is modeled to require the least amount of money, but additional time compared to driftwood. The use of only fuel oil saves a substantial amount of time over all wood options (9,000 – 15,000 hours annually), but there are substantial costs associated with fuel oil (approximately $533,000 for the whole community). Results illustrated that a mix of alternative fuels (fuel equivalent of the modeled wood deficit substituted with 25% stranded driftwood, 25% standing deadwood, and 50% fuel oil) balances the monetary and temporal costs of each alternative. In addition, based upon the economics model, the time associated with the harvest of driftwood equates to a value of $36.00 - $59.00 per hour.

2.5. DISCUSSION

2.5.1. Local knowledge

This research originated from a public meeting where residents of Tanana reported that the driftwood harvest had become less reliable in recent decades. They discussed how they typically harvested driftwood during the June Rise, a relatively predictable rise in the hydrograph in early June, but the June Rise was not occurring with the same regularity to which they were accustomed. Our results (Figure 2.3) support this observation by showing that the timing of flood peaks not associated with spring break-up (yet sufficient to mobilize driftwood) has become more variable since 1994. There is some evidence that June Rise events are initiated by precipitation events in portions of the upper watershed. Interviewees also suggest this linkage, but additional research on the subject may provide insight into the drivers of the June Rise.

2.5.2. Driftwood mobilization threshold

Through the participatory research process, it was determined that once the river stage exceeds a driftwood mobilization threshold, driftwood becomes readily available for harvest. This is an illustration of how different types of knowledge (scientific data and local knowledge) may be integrated to study a phenomenon. In this case, the context of the information was related to river hydrology to identify a 'driftwood mobilization threshold,' a level of river discharge that once exceeded, mobilizes driftwood until the river discharge peaks.

The concept of a driftwood mobilization threshold was used as a simple representation of a complex system to develop a driftwood harvest model. The concept has limitations in its applicability, because an increasing demand for wood eventually results in limitations in the available driftwood supply for downstream villages. Conversely, if upstream villages start using more wood, the wood available in Tanana could be reduced. Driftwood is differentially distributed in space and time throughout the river. Despite these limitations, increasing amounts of driftwood are mobilized as the river discharge increases during spring melt. Initially, the amount of mobilized driftwood rises with increasing discharge, with the amount of mobilized wood leveling off as the river reaches flood stage and spills onto the floodplain. Additionally, driftwood is deposited on riverbanks at river bends, during periods of high wind, and as water levels fall. Storm intensity, flood history, and fire history in the watershed also affect the bank erosion and the associated wood deposition into the river channel (Ott 1989, Yarie et al. 1998, Mason 1998, Ott et al. 2001, Alix 2005, Rowland et al. 2010).

It would be worthwhile to examine relationships between high flows, bank erosion, and the deposition of wood into the river channel. Typically, episodic erosion of the river bank occurs during high river stages (Yarie et al. 1998) and causes wood to fall into the channel (Ott 1989, Ott et al. 2001). Areas where the vegetative armoring is compromised (such as areas of recent forest fires) are more prone to bank erosion and the associated deposition of wood into the channel (Ott 1989, Ott et al. 2001). An analysis of the movement and life cycles of driftwood in the Yukon River watershed would provide valuable information about its ecology and social ecological importance in the Yukon. Such an analyses may inform the State of Alaska and villages along the Yukon River about the sustainable harvest capacity of driftwood from the Yukon River watershed, which may become an issue if more communities increase their harvest of driftwood.

When the community of Tanana installed their wood-fired boilers in 2007, the total fuel wood demand increased by 76% and raised the community fuel wood deficit (Figure 2.5). Because hydrologic factors were responsible for a 29% decrease in the driftwood harvest and the decreased number of households reduced wood demand by 23%, the model indicates that the increased municipal demand for wood had a much greater effect on the total wood consumption compared to changes in hydrology or population.

The number of days that the river exceeds the driftwood mobilization threshold is greater than the number of days that locals suggest that driftwood is available in a given year. According to the model, the mean number of annual driftwood days was 7.4 days since 1977 and was not different between the early and late phases of the study period. Local residents suggest that the number of driftwood days have decreased from 4-5 to 1-3 in recent decades. This discrepancy may be founded in either the use of local knowledge or the concept of a driftwood mobilization threshold. It is likely a combination of both.

2.5.3. Driftwood harvest in a changing climate

The model corroborates local reports of a less reliable driftwood harvest in recent decades. According to interviews about the potential rates of wood harvest and the number of households harvesting driftwood, historically Tanana needed an estimated 23 driftwood days to harvest its annual wood demand, while since 2007 an estimated 35 driftwood days are needed annually. Historically, Tanana could expect to meet 8-35% of its heating fuel needs using driftwood. Since 2007, the average modeled harvest would meet 15% of Tanana's wood requirements, and the city could reasonably expect to obtain between 7 and 31% of its wood demand from driftwood in most years.

Modeling results suggest that increased hydrologic variability may make the ability to harvest driftwood less predictable, and variations in the timing of flood events may become more inconvenient for rural Alaskans. Adaptations to these changing conditions include importing wood from other regions (which is not unprecedented), or enabling more Tanana residents to harvest wood when driftwood is mobilized. This might include providing financial loans to households to purchase or repair boats, recruiting more wood harvesters, and long-term wood storage. Another option includes gathering wood during spring break-up, which is a far more dangerous activity. In some cases, Tanana residents have resorted to navigating through the ice and driftwood in search of good pieces of driftwood. This also requires more forethought because boats must be prepared at times when they are preoccupied with winter or other spring subsistence activities.

2.5.4. Driftwood economics

The economics analysis illustrates the potential reasons that one fuel source may be selected over another. While modeling analyses indicate that the collection of standing deadwood is the cheapest option, these results will vary based upon the actual location from which wood is collected. Additionally, modeling results do not take into account wear-related expenses on snow machines or boat motors. There is an inverse relationship between the times required to use different wood sources compared to fuel oil. In a subsistence-based economy, it is assumed that most households would have a greater ability to use time-resources over cash resources due to the limited availability of cash. Certain individuals in a village have jobs or other sources of a cash income. In these cases, it is assumed that there would be less flexibility to use time for subsistence activities, but cash resources may be substituted to obtain the necessary fuel supplies to be prepared for a winter in Alaska. In the case of Tanana, the city government and individual households use cash resources to purchase fuel oil or wood, depending upon their needs. The economics analysis was performed at the community-level, so differences in household or collective behaviors between households were not considered. Thus, the costs for the entire community were assessed over time.

2.5.5. Model uncertainty

There is uncertainty associated with each component of the model. The concept of a driftwood mobilization threshold is not a static entity, and at no point is there actually an unlimited amount of wood mobilized in the river. As mentioned previously, it is a useful assumption that assists in the study of a complex social-ecological system and during driftwood mobilization events, and it is reasonable that the driftwood supply far exceeds the demand by Tanana residents. Although the installation of wood-fired boilers is an increasing trend in remote Alaskan communities, so this assumption may become invalid if the demand for Yukon River driftwood continues to increase along the Yukon River. In time it may become necessary to allocate the driftwood resources by village to ensure downriver needs are also met (Annear, et al. 2004).

The driftwood mobilization threshold concept could be refined to represent the mobilization of driftwood more dynamically during high flow or wind events. An assessment of the average village and household effort to collect driftwood would also be reasonable. Village and household demand is relatively predictable and could be modeled annually based upon the local winter weather. Each input parameter in the economic model adds uncertainty to the model, but a reasonable effort was used to provide the best available estimates for each. Estimated fuel costs will change over time and could be updated or modeled. Wood deposition into the river could also be modeled in relation to permafrost thaw, bank erosion, or fire frequency.

2.5.6. Model application

By monitoring the USGS gauging station at Stevens Village, Tanana residents could utilize the driftwood mobilization threshold (Figure 2.2) to gain lead-time on driftwood runs, thus providing more predictability to an erratic system. Such tools would be useful for preparing for the driftwood harvest. The model cannot provide advance notification of driftwood flows, but they could use the driftwood mobilization threshold to infer that a driftwood run is not likely over the next few days. In some cases, the upstream social network informs Tanana residents about approaching driftwood runs, but more often, they rely only upon their knowledge of the annual subsistence cycle.

2.6. CONCLUSIONS

The general principles illustrated by this research are applicable to river communities throughout the sub-Arctic, although glacially-fed rivers have different hydrologic patterns. Driftwood is mobilized periodically during high flow events. Subsistence users may or may not gather driftwood as a natural resource, but they likely follow similar subsistence cycles specific to their community.

The livelihood of Alaskan subsistence users is driven by subsistence cycles and is made more challenging by irregular environmental conditions. Increasing variability in climate cycles has serious consequences, which affects them financially and make them unavailable for other subsistence, cultural, or recreational activities. Tools that reduce the uncertainty associated with environmental variability are especially helpful for people who rely upon natural and seasonal cycles. This research demonstrates that scientists, in partnership with local stakeholders, have the capacity to develop these types of tools.

This study also illustrates the dynamic connections between climate, hydrology, and society, while utilizing local knowledge as a bridge to develop capacity for rural communities. In interior Alaska, few scientific investigations have been developed based upon the interest and concerns of local residents. A participatory research process was used to understand how increasing natural variability in climate and natural processes affect the lives of subsistence users in Alaska. Observations of local collaborators support international reports by climate scientists that predict environmental conditions to become more variable as global temperatures increase (ACIA 2005). Thus, the concerns of rural and native people converge with climate scientists. This study suggests that regional-scale adaptations may help mitigate the impacts of extreme events and climate variability, while providing opportunities for economic growth and energy independence that increase society's adaptive capacity to environmental variations.

2.7. ACKNOWLEDGEMENTS

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2.8. FIGURES

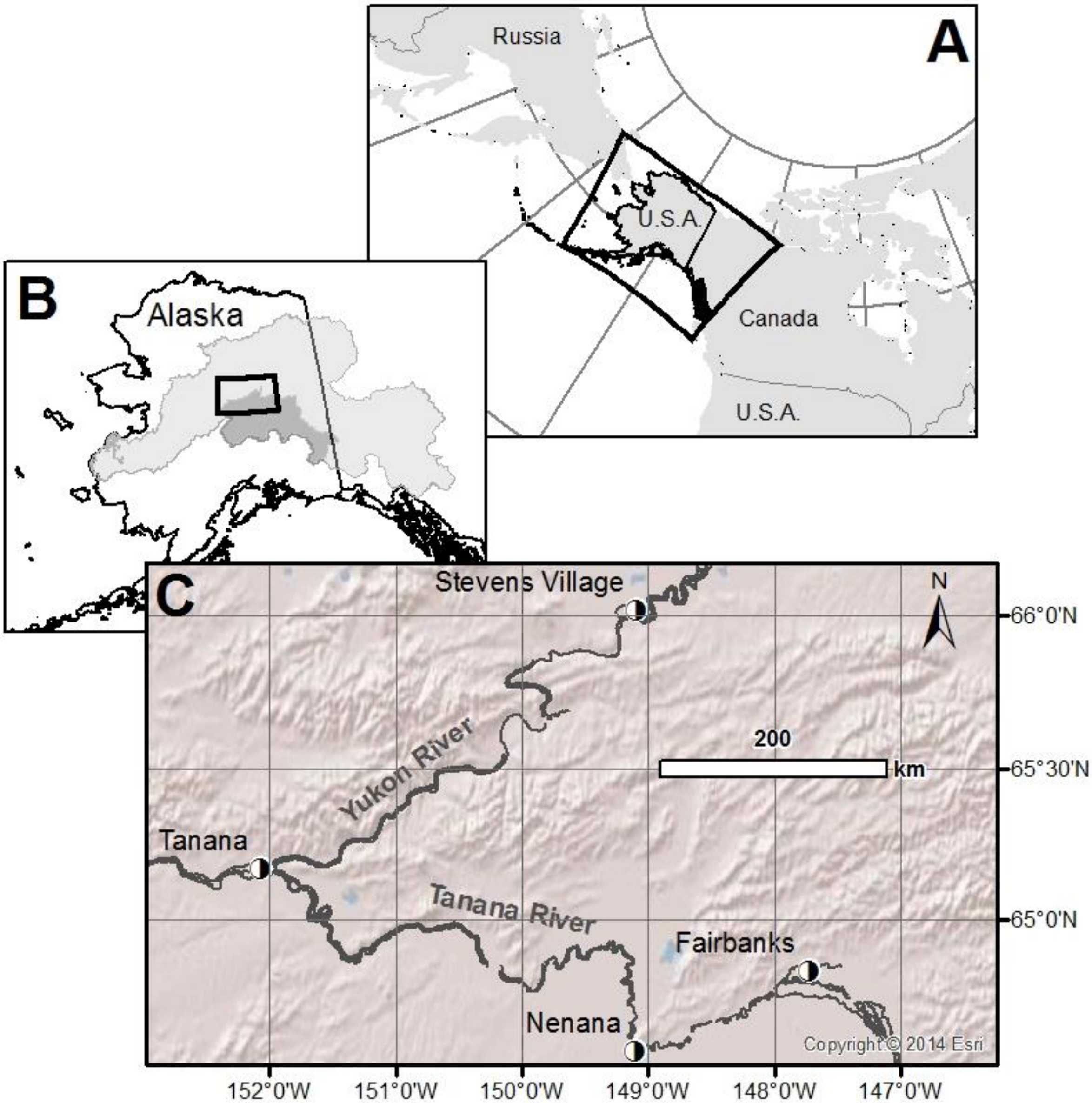

Figure 2.1. Study area map of Tanana, Alaska and vicinity. Panel A shows the regional location of Alaska relative to Canada, Russia, and the contiguous U.S.A. Panel B shows the Yukon and Tanana River watersheds within Alaska. Panel C illustrates the locations of the communities of Fairbanks, Nenana, Tanana, and Stevens Village relative to the Yukon and Tanana Rivers.

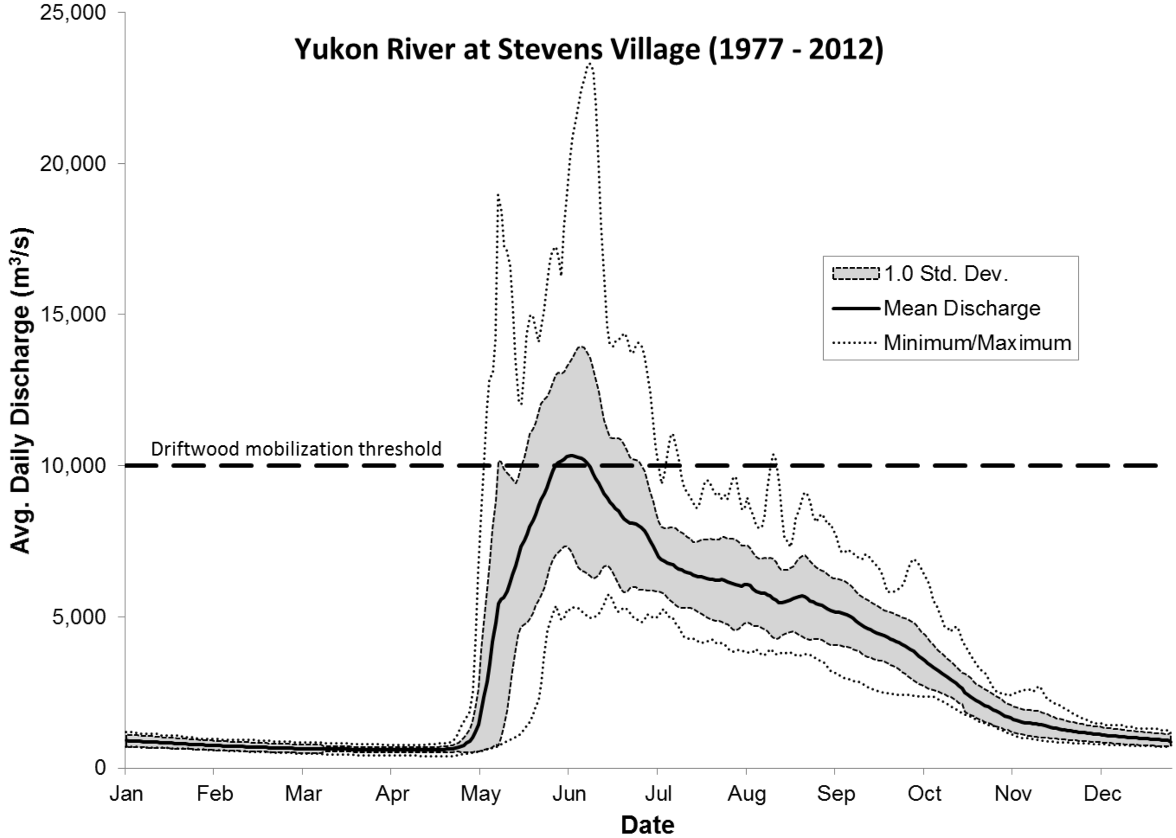

Figure 2.2. Annual hydrograph of the Yukon River at Stevens Village guaging station (1977-2012) illustrates the typical spring break-up flood and the larger “June-Rise” that occurs soon after spring break-up. The driftwood mobilization threshold is also depicted. Figure based upon data from U.S.G.S. gauging station for Yukon River at Stevens Village.

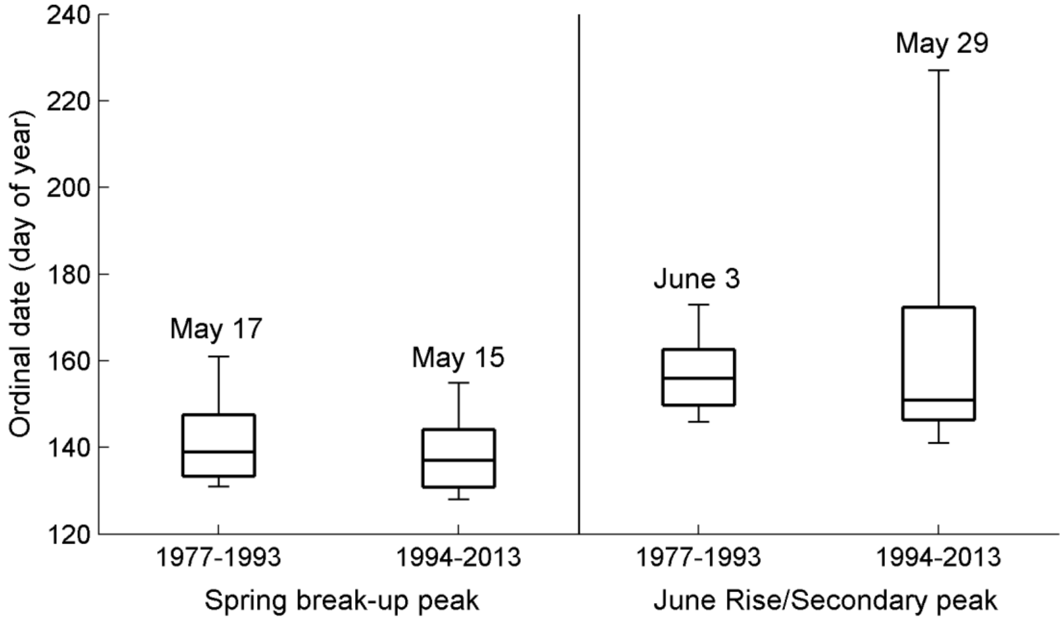

Figure 2.3. Timing of spring break-up flood peaks and the June Rise flood peaks shows the minimum, 25^{th} percentile, median (date specified), 75^{th} percentile, and maximum dates of spring break-up flood peaks and the June Rise / secondary peaks that exceed the driftwood mobilization threshold and are expected to carry driftwood, while illustrating that the June Rise has been more variable since 1994.

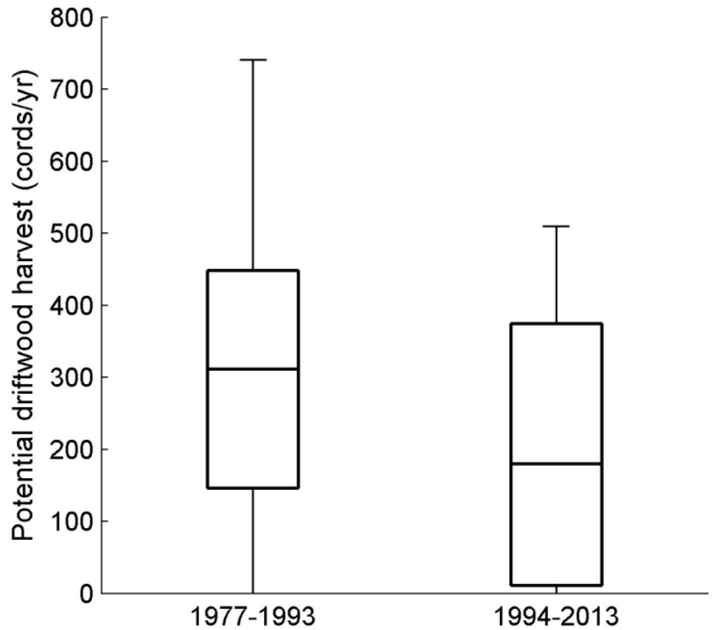

Figure 2.4. Potential driftwood harvest for Tanana showing the minimum, 25th percentile, median, 75th percentile, and maximum potential driftwood harvest for the early and late phases of the period of record and the expected reduction in harvest volumes in the future.

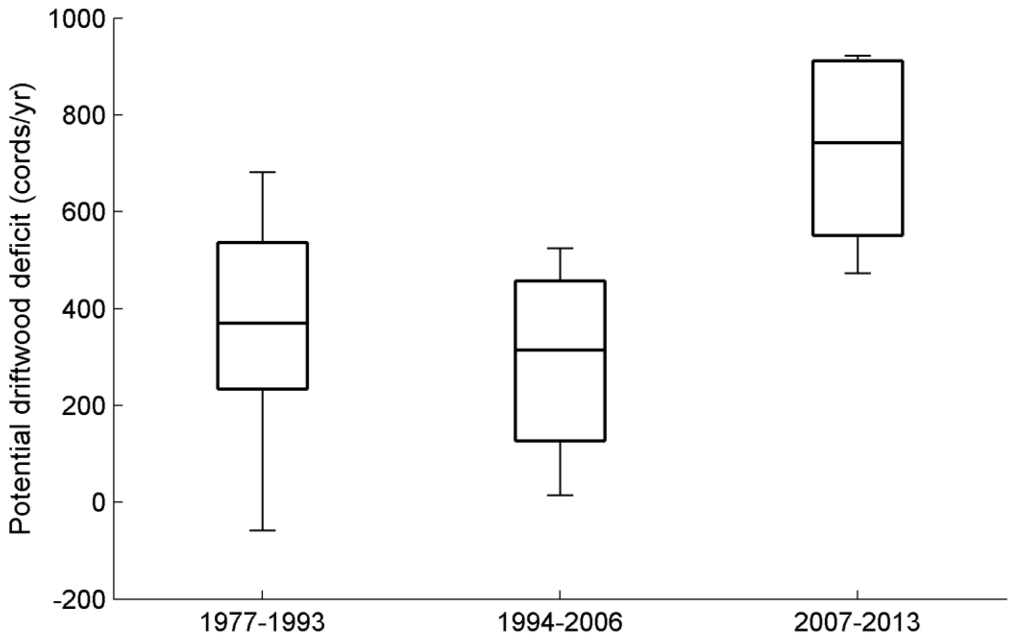

Figure 2.5. Estimated driftwood deficit for Tanana illustrating that the increased demand for wood after 2007 had a large impact on the amount of wood available in the village.

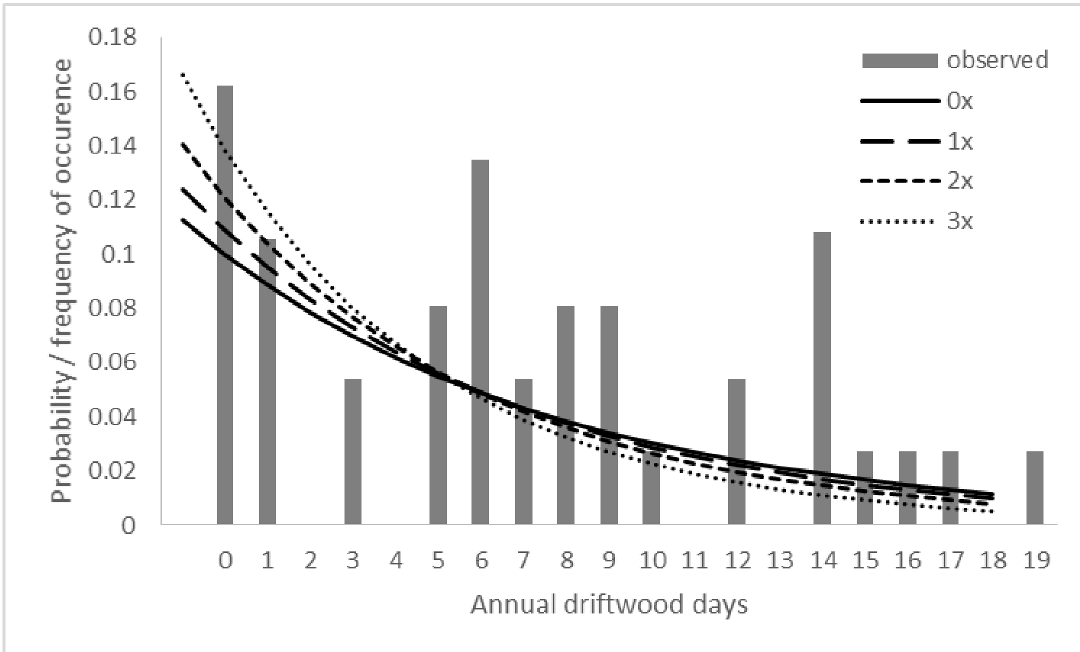

Figure 2.6. Annual driftwood days under different climatic scenarios shows the observed frequency (for all years) and expected probability of occurrence of the annual number of driftwood days under four scenarios (0x-3x) with increasing variability from the observed data.

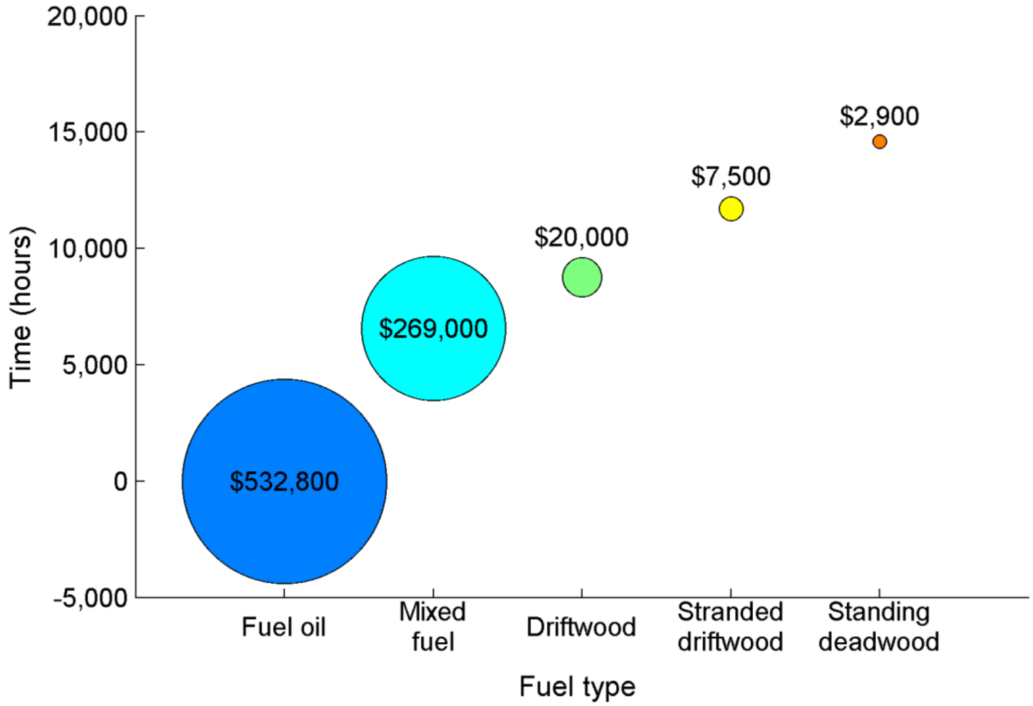

Figure 2.7. Estimated costs associated with driftwood deficit alternatives associated with the harvest of the average modeled wood deficit (730 cords) from 2007-2013 using each fuel type alone, versus a mix of 25% stranded driftwood, 25% standing deadwood, and 50% fuel oil. The size of the bubble is proportional to the estimated financial cost (rounded to the nearest $100 U.S. dollars). Time costs include the time required to gather and process wood.

2.9. TABLES

Table 2.1. Driftwood records kept by Mr. Tom Hyslop (Tanana, Alaska) by calendar year.

Harvest date	Number of logs	Notes
6/3/1989	29	
5/23/1990	6	
5/1/1991	-	Calendar not found
5/1/1992	-	Calendar not found
5/1/1993	0	Low water year
5/1/1994	0	Low water year
5/1/1995	0	Low water year
5/1/1996	-	Calendar not found
5/1/1997	-	Calendar not found
5/1/1998	-	Calendar not found
6/1/1999	-	Calendar found - no records
5/29/2000	46	
6/11/2001	36	
6/1/2002	-	Calendar not found
6/5/2003	35	
5/23/2004	21	
5/15/2005	22	
5/1/2006		Calendar not found
6/1/2007	-	Calendar found - no records
5/24/2008	20	Small logs
5/11/2009	0	Big flood
8/13/2010	14	
5/28/2011		Huge driftwood run
5/1/2012	-	Calendar not found

Table 2.2. Driftwood harvest model parameters.

Parameter	Variable	Value	Source
Number of village households	n_{HH}	Estimated: 1977-1993: 113 households 1994-2013: 100 households	1977-1993: 1980 U.S. Census, 1994-2013: 2010 U.S. Census
Percentage of village households harvesting driftwood each driftwood day	$\%_{HH}$	Assumed: 10%	Interviews: Charlie Wright, Charlie Campbell, Alfred Ketzler
Average daily rate of driftwood harvest	dH_{HH}/dt	Assumed: 2 cords per driftwood day per household	Interviews: Charlie Wright, Charlie Campbell, Alfred Ketzler
Average annual household demand	D_{HH}	Assumed: 7 cords per household per year	Interviews: Charlie Wright, Charlie Campbell, Alfred Ketzler, Tom Hyslop
Average annual municipal wood demand	D_M	Assumed: 1977-2006: 0 cords 2007-2013: 300 cords	Interview: Alfred Ketzler
Driftwood days	t_w	Calculated	Interviews, USGS gauging station data
Total annual driftwood harvest	H_{annual}	Calculated	
Total annual village wood demand	D_{annual}	Calculated	
Potential annual driftwood deficit	Def_{annual}	Calculated	

Table 2.3. Calculated flood recurrence intervals for the Yukon River at Stevens Village (rounded to nearest 100 m^3/s) for two phases of the period of record and the entire 37 years of data.

Flood recurrence interval (years)	1977-1993	1994-2013	1977-2013
1.01	9,400	7,600	8,200
1.25	12,000	10,300	11,000
2	13,100	11,400	12,100
5	14,500	12,600	13,500
10	18,200	15,600	16,900
25	20,800	17,500	19,300
50	23,500	19,400	21,500
100	24,400	20,000	22,300

Table 2.4. Flood peak characteristics for the period of record.

Early Phase (1977-1993)					Late Phase (1994-2012)				
Year	**Date**	**Day of Year**	**Peak Q (cms)**	**# Days Rising Limb**	**Year**	**Date**	**Day of Year**	**Peak Q (cms)**	**# Days Rising Limb**
1977	5/26/1977	146	12,500	2	1994	5/10/1994	130	12,200	4
1977	6/8/1977	159	18,100	7	1994	5/30/1994	150	10,900	3
1977	6/30/1977	181	11,100	3	1994	6/30/1994	181	11,500	3
1978			< 10,000	0	1995	5/9/1995	129	12,900	3
1979	5/11/1979	131	12,800	1	1995	5/15/1995	135	11,800	2
1980	5/25/1980	146	11,500	3	1995	5/19/1995	139	11,300	1
1981	5/31/1981	151	11,300	5	1996			< 10,000	0
1982	6/6/1982	157	16,200	12	1997	5/22/1997	142	11,600	4
1982	6/21/1982	172	13,100	2	1997	6/23/1997	174	14,300	10
1983	6/8/1983	159	14,500	6	1998	6/1/1998	152	10,500	2
1984	5/31/1984	152	11,900	4	1998	6/4/1998	155	10,400	1
1984	6/22/1984	174	10,300	2	1999			< 10,000	0
1985	5/31/1985	151	16,500	6	2000	5/29/2000	150	11,400	2
1985	6/8/1985	159	16,100	3	2000	6/8/2000	160	12,400	6
1986	6/14/1986	165	11,900	8	2000	6/15/2000	167	14,000	5
1987	5/31/1987	151	13,300	4	2000	6/20/2000	172	14,100	2
1987	6/2/1987	153	13,400	1	2000	6/23/2000	175	14,400	2
1987	6/9/1987	160	14,700	4	2001	6/1/2001	152	12,400	4
1988	5/21/1988	142	12,500	4	2001	6/13/2001	164	15,600	8
1988	5/30/1988	151	11,800	4	2002	5/26/2002	146	13,100	6
1989	5/11/1989	131	13,100	2	2003			< 10,000	0
1989	6/5/1989	156	10,700	1	2004	5/26/2004	147	13,200	5
1989	6/11/1989	162	11,100	2	2004	5/30/2004	151	12,500	1
1990	5/26/1990	146	14,600	5	2004	6/2/2004	154	12,400	1
1991	5/13/1991	133	17,100	8	2005	5/15/2005	135	11,300	3
1992	6/11/1992	163	23,300	13	2005	5/22/2005	142	13,800	6
1992	6/22/1992	174	14,100	3	2005	6/5/2005	156	11,600	5
1992	6/28/1992	180	14,100	3	2006	5/25/2006	145	14,100	7
1993	5/23/1993	143	15,000	5	2007			< 10,000	0
1993	6/8/1993	159	13,200	10	2008			< 10,000	0
1993	6/10/1993	161	13,300	1	2009	5/11/2009	131	19,000	1
					2009	5/30/2009	150	10,600	3
					2009	6/3/2009	154	11,200	2
					2010	8/15/2010	227	10,400	1
					2011	5/31/2011	151	17,300	7
					2011	6/28/2011	179	11,300	2
					2012	6/3/2012	155	13,400	8
					2012	6/18/2012	170	10,500	4
					2012	7/10/2012	192	11,100	3

Table 2.5. Climate variability scenarios: parameter definition and results summary.

Parameter	Percentile	Variability Scenario			
		0x	1x	2x	3x
Driftwood days	25%	2.0	2.0	1.0	1.0
	50%	5.0	5.0	4.0	3.5
	75%	10.0	9.0	8.0	7.0
Driftwood harvest (cords)	25%	60	60	30	30
	50%	150	150	120	105
	75%	300	270	240	210
Driftwood deficit (cords)	25%	235	384	385	535
	50%	865	865	895	910
	75%	955	955	985	985

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2.12. APPENDIX A2. DRIFTWOOD ECONOMICS MODEL

Appendix A2 provides details about the economics model and analyses presented in the paper above.

Table A2.1 defines the parameters used to estimate costs and identifies the source for the parameterization. The fuel equivalent (D_{fuel}) of each substitute fuel type used to meet any wood deficit (Def_{annual}) was estimated based on specified proportions of each potential fuel type used as a driftwood substitute ($\%_{fuel}$) in the entire village (Eq. A2.1). The potential substitute fuel types include stranded driftwood, standing deadwood, and fuel oil.

$$D_{fuel} = \%_{fuel}(Def_{annual}) \qquad \text{Eq. A2.1}$$

Fuel = stranded wood, standing wood, or fuel oil

The number of trips ($Trip_{fuel}$) needed to gather sufficient stranded or standing wood to meet the village's demand (D_{fuel}) for that fuel type were estimated from the amount of the fuel (H_{fuel}) that could be harvest on each trip (Eq. A2.2). The financial costs ($Cost_{fuel}$) associated with the number of trips were also calculated. We used the number of trips, the mean travel distance ($\overline{Dist}_{fuel}$), estimated miles traveled per gallon of gasoline ($MPG_{vehicle}$), and the unit cost of gasoline ($UnitCost_{gas}$)]. From this we subtracted the cost to harvest and process the equivalent amount of mobilized driftwood [based upon the villages annual driftwood deficit (Def_{annual}), the boats fuel consumption rate (GPH_{drift}]), the unit cost of gas, and the harvest rate for driftwood (H_{drift})] (Eq. A2.3).

$$Trip_{fuel} = D_{fuel}/H_{fuel} \qquad \text{Eq. A2.2}$$

Fuel = stranded or standing wood

$$Cost_{fuel} = \left\{Trip_{fuel}\left[\frac{\overline{Dist}_{fuel}}{MPG_{vehicle}}\right]UnitCost_{gas}\right\} - \left\{\frac{Def_{annual}GPH_{drift}UnitCost_{gas}}{H_{drift}}\right\} \qquad \text{Eq. A2.3}$$

Fuel = stranded or standing wood

The amount of time required to collect and process (cut, split, and stack) sufficient wood ($Time_{fuel}$) to meet the village needs were calculated from number of trips, estimated time per trip ($\overline{Time}_{trip}$), number of people per trip ($People_{trip}$), village demand for that fuel type, estimated time for processing ($\overline{Time}_{process}$), and estimated number of people involved in processing ($People_{process}$)]. From this we subtracted the estimated time to collect and process the equivalent amount of mobilized driftwood [calculated from estimates of driftwood harvest rate (H_{drift}), time required for harvesting driftwood ($\overline{Time}_{drift}$), and the number of people involved in the harvest of driftwood ($People_{drift}$)] (Eq. A2.4).

$$Time_{fuel} = \{Trip_{fuel}\,\overline{Time}_{trip}\,People_{trip} + D_{fuel}\,\overline{Time}_{process}\,People_{process}\} - \{H_{drift}\,\overline{Time}_{drift}\,People_{drift}\} \qquad \text{Eq. A2.4}$$

Fuel = stranded wood or standing wood

Additionally, the cost for using fuel oil ($Cost_{oil}$) to meet the equivalent energy demand (D_{oil}) of the village was calculated using the energy equivalent of fuel oil relative to driftwood ($Equiv_{oil}$) and the unit cost of fuel oil ($UnitCost_{oil}$) (Eq. A2.5).

$$Cost_{oil} = D_{oil}Equiv_{oil}UnitCost_{oil} \qquad \text{Eq. A2.5}$$

Estimates of the total financial and temporal costs were also calculated (Eq. A2.7 and Eq. A2.8) by summing the individual costs for each fuel type.

$$Cost_{total} = Cost_{stranded} + Cost_{standing} + Cost_{oil} \qquad \text{Eq. A2.7}$$

$$Time_{total} = Time_{stranded} + Time_{standing} + Time_{oil} \qquad \text{Eq. A2.8}$$

Table A2.1. Input and output parameters for the economic analyses of the driftwood harvest alternatives.

	Parameter	Symbol	Assigned value
Wood / driftwood	Deficit (cords)	Def_{annual}	903
	Demand (cords equivalent)	D_{fuel}	Calculated
	Harvest rate (mobilized driftwood, cord/ hour)	H_{drift}	0.25
	People (number during driftwood harvest)	$People_{drift}$	2
	Processing rate (cut and split) (cord/hour)	$Time_{process}$	0.5
	Processing people (person)	$People_{process}$	2
	Gallons per hour (boat)	GPH_{drift}	1
	Estimated economic costs – driftwood	$Cost_{drift}$	Calculated
	Time estimate - harvest and process (hours)	$Time_{drift}$	Calculated
Stranded driftwood	Deficit replacement from stranded driftwood (%)	$\%_{stranded}$	25
	Average round trip miles traveled for stranded driftwood	$Dist_{stranded}$	3
	Boat fuel economy (miles / gallon)	$MPG_{vehicle}$	2
	Gas costs ($/gallon)	$Cost_{gas}$	$6.85
	People (number / trip)	$People_{trip}$	3
	Harvest rate (Cords stranded driftwood / trip)	$H_{stranded}$	1
	Average time (hour / trip)	$Time_{trip}$	8
	Number of trips - stranded driftwood	$trip_{stranded}$	Calculated
	Estimated economic costs - stranded driftwood	$Cost_{stranded}$	Calculated
	Time estimate (man-hours)	$Time_{stranded}$	Calculated
Standing dead wood	Deficit replacement from standing wood (%)	$\%_{standing}$	25
	Average round trip miles traveled for standing wood	$Dist_{standing}$	2
	Snow machine fuel economy (miles / gallon)	$MPG_{vehicle}$	7
	Gas costs ($/gallon)	$Cost_{gas}$	$6.85
	People (number / trip)	$People_{trip}$	2
	Harvest rate (Cords standing wood / trip)	$H_{standing}$	0.3
	Average time (hour / trip)	$Time_{trip}$	4
	Number of trips - standing wood	$trip_{standing}$	Calculated
	Estimated economic costs - standing wood	$Cost_{standing}$	Calculated
	Time estimate (man-hours)	$Time_{standing}$	Calculated
Fuel oil	% fuel oil replacement	$\%_{oil}$	45
	Gallons equivalent (Gallons fuel oil / cord)	$Equiv_{oil}$	122†
	Fuel oil costs: ($/gallon)	$UnitCost_{oil}$	$6.00
	Estimated Fuel costs	$Cost_{oil}$	Calculated
	Time estimate (man-hours)	$Time_{oil}$	Calculated
Total	Total Economic Costs	$Cost_{total}$	Calculated
	Total Time Investment (man-hours)	$Time_{total}$	Calculated

†(USDA Cooperative Extension Service 2008)

CHAPTER 3. MODELING GROUNDWATER UPWELLING AS A CONTROL ON RIVER ICE THICKNESS[4]

3.1. 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 greater groundwater recharge increasing groundwater input to river baseflow. In winter, interior Alaskan rivers are exclusively fed by groundwater, which provides an external source of heat. In fact, some portions of rivers fed by groundwater maintain thin ice cover throughout the winter, or remain ice-free, despite very cold air temperatures. These ice conditions represent a significant danger to rural Alaskans who extensively use rivers for wintertime travel in this largely roadless area.

A physically-based, numeric model was developed to examine the importance of permafrost degradation in explaining unfrozen river conditions in the winter. Results show that ice melt was amplified by increased hydraulic gradients, groundwater upwelling rates, air temperature, groundwater temperatures, and snowfall. Assuming that a warming climate in discontinuous permafrost regions would increase groundwater flow into rivers and increase snow depths, these changes could contribute to decreased ice thickness and more hazardous conditions for winter travelers. The model examines the physical mechanisms that underlie dangerous ice conditions in winter and early spring, and suggests that permafrost degradation or other climate-related phenomenon contributes to mid-winter ice degradation in a warming climate.

3.2. INTRODUCTION

Historically, many Alaskan villages and towns were established along waterways, which served as transportation corridors throughout most of the year. Because of the limited road network, frozen river systems are still important transportation networks in rural Alaska. Collaborative partnerships were established with several local (non-academic) Alaskans who have extensive experience traveling on Alaskan rivers in all seasons. Their observations on the Tanana River (Jones et al. 2013, Schneider et al. 2013a, 2013c) mirror those found by Herman-

[4] Jones, C.E., K. Kielland, & L.D. Hinzman. 2014. Modeling groundwater upwelling as a control on river ice thickness. Submitted to *Hydrology Research*.

Mercer *et al.* (2011) who reported that rural Alaskans have observed that thin ice was becoming more common on the Yukon River in recent winters. Such ice thinning represents a significant danger to winter travelers.

One potential mechanism for thinning ice relates to changes in permafrost distribution. Ice-rich permafrost is an effective barrier to water transport and recharge (Burt and Williams 1976, Horiguchi and Miller 1980, Kane and Stein 1983), but warming temperatures have caused significant permafrost degradation across the Arctic (Jorgenson et al. 2001, Hinzman et al. 2005, Romanovsky et al. 2010). Permafrost degradation in discontinuous permafrost regions has been described as a potential mechanism for increased hydrologic connectivity between surface and ground water systems. Permafrost is typically impermeable to water infiltration and prevents groundwater recharge by forcing near-surface water to flow laterally and quickly into streams. With permafrost thawing, there is more infiltration to subpermafrost groundwater, which delays the rapid runoff from a watershed and allows for more sustained subsurface discharge throughout the winter. Permafrost degradation has been associated with lake drainage (Yoshikawa and Hinzman 2003); increased daily summer and winter minimum river flows (Smith et al. 2007); and increases in winter river baseflow (Walvoord and Striegl 2007, St. Jacques and Sauchyn 2009, Brabets and Walvoord 2009, Lyon and Destouni 2010). During winter, Alaskan ice-covered rivers are fed entirely by groundwater. Therefore increased winter baseflow is likely associated with the increased groundwater input corresponding with permafrost degradation (Walvoord and Striegl 2007, St. Jacques and Sauchyn 2009, Brabets and Walvoord 2009, Lyon and Destouni 2010) in discontinuous permafrost regions.

Heat provided by groundwater upwelling can degrade river ice from below (Figure 3.1). Field observations confirm that groundwater heat flux exceeds atmospheric heat losses and dangerously thin ice conditions can be maintained for extended periods despite very cold wintertime air temperatures. In recent decades, there are reports that thin ice and open water may be more prevalent on interior Alaskan rivers in winter (Herman-Mercer et al. 2011, Jones et al. 2013, Schneider et al. 2013c). These conditions appear to be caused by a combination of factors that include fast moving turbulent water, warm air temperatures, and groundwater upwelling in shallow areas.

The Tanana Flats, which are found to the south of the Tanana River, have a high groundwater table and have exhibited extensive permafrost degradation since the 1700’s (Jorgenson et al. 2001). Much of the Tanana River and its neighboring regions appear 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 during winter are hypothesized to be caused by increased groundwater flow caused by permafrost degradation, which has been intensified by a warming climate.

In this paper, fluctuations in groundwater hydrology were modeled to assess the potential impacts on river ice dynamics. In collaboration with rural Alaskans, changes in hydrology were explored to examine how residents of interior Alaska could be affected by a changing thermal balance between increasing groundwater discharge and winter air temperatures in areas with recurring dangerous ice conditions in the Tanana River. Field studies were initiated in locations identified by local residents as having thin ice in most years. Based upon field observations, a numerical model was developed to explore the relationship between seasonal groundwater flows and ice thickness under changing environmental conditions. The model was designed to address the 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 do increasing air temperatures, snow depths, and groundwater upwelling in an altered climate affect river ice thickness on the Tanana River?

3.3. METHODS

3.3.1. Field studies

Two field sites near Fairbanks that have recurring thin or unpredictable ice conditions in most years were selected for field investigations. Sam Charley Slough and Hot Cake Slough were established as study sites within the Bonanza Creek Long-Term Ecological Research (LTER) area on the Tanana River, located approximately 15 km southwest of Fairbanks, Alaska, United States of America [Longitude: 148˚ 7’ 22”; Latitude: 64˚ 43’ 26”] (Figure 3.2). This region is characterized by discontinuous permafrost and is bordered by the Tanana Flats region, which are part of the Tanana-Kuskokwim Lowlands (Anderson 1970). The Tanana Flats is an area with a high water table fed by groundwater originating from glaciers in the Alaska Range found to the south. The Alaska Range glaciers (typically found above 1525 m) are also the primary source of water for the Tanana River (120 m elevation at Hot Cake Slough)(Anderson 1970).

Hot Cake Slough has a persistent open water feature that attains a thin ice cover periodically during extremely cold (-25 to -40°C) winter periods. Sam Charley Slough is more unpredictable; a solid ice cover forms in the early winter that typically degrades between January and March despite very cold air temperatures. Field studies included daily time-lapse photographs of the study areas. The water depth, channel velocity, and ice-free winter discharge were measured using a Marsh McBirney Flow-mate 2000 electromagnetic flow meter and showed little variation through the winter. Channel slope was measured using a level over a distance of 100 m. The local hydraulic conductivity (K, m/day) of the sediment within the open water feature of Hot Cake Slough was measured at a streambed sediment depth of 20 cm using the falling head permeameter method (Todd and Mays 2005). Nested piezometers (installed from 20 to 120 cm below channel thalweg) were installed in the open water feature of Hot Cake Slough and used to calculate the local vertical groundwater upwelling rate. From the measured hydraulic conductivity and hydraulic gradient (dh/dz), the vertical groundwater upwelling rate (Q_{GWz}, m^3/day) was calculated using Darcy's Law (Todd and Mays 2005).

Salinity tracers were used to measure the horizontal groundwater flow velocity ($V_{GWx,}$ m/day) between shallow (1.6 m) groundwater wells (Todd and Mays 2005). Since water was entering the channel both horizontally and vertically, the horizontal flow velocity, water depth of the channel (D, m), and vertical upwelling rate, the total groundwater flow (Q_{GW}, m^3/d) into the channel at Hot Cake Slough was calculated per unit area.

The vertical temperature profile from the groundwater through the water column, ice, snow, and air within the river channel was measured on fifteen-minute intervals at one location in Sam Charley Slough and two different points in Hot Cake Slough (referenced as the upstream and downstream study sites). The temperature profile was monitored using thermistor strings calibrated to 0.0°C in a continuously flowing ice bath. Finally, on April 26, 2013, snowmobiles were used to map dangerous ice conditions between Fairbanks and Nenana, Alaska, a distance of 185 km by river (Schneider et al. 2013b).

3.3.2. Modeling impact of groundwater flow on ice thickness

The physical system is represented by Figure 3.3, which illustrates how groundwater affects river ice thickness under observed field conditions (gradually and spatially variable, unsteady flow). From Figure 3.3, a physically-based numerical model was developed using MATLAB® (version 2011b) to explore the heat balance between groundwater discharge and thermally degraded ice-covered areas in the Tanana River. The model estimates the potential ice melt rate caused by groundwater under static or dynamic environmental conditions (assuming constant wind velocity, snow density, upwelling rate, and groundwater temperature with static or dynamic air temperature and snow depths.) Ice-free conditions are not considered in this model. Appendix A3 summarizes symbol definitions and units.

The model represents the heat flux process (Eq. 3.1) for a system where water [and the associated heat flux, ϕ (W/m^2)] flows laterally in (with ϕ_{in}) and out (with ϕ_{out}) of a volumetric cell, while the groundwater flows into the volume vertically (with ϕ_{GW}) (Figure 3.3). Snow, ice, and atmospheric conditions affect the heat transferred from the water column to the ice and lost to the atmosphere. The heat flux from the water column to the ice (ϕ_{trans}) equals the sum of the energy available for ice melt (ϕ_{melt}) and the heat flux to the atmosphere (ϕ_{loss}). The remainder (ϕ_{gain}) of the energy determines whether the water column cools (if negative) or warms (if positive).

$$0 = \phi_{in} + \phi_{GW} - \phi_{out} - \phi_{loss} - \phi_{melt} - \phi_{gain} \qquad \text{Eq. 3.1}$$

The surface and subsurface water inflow and outflow have a specified flow rate (Q, m^3/s) and temperature (T, °C), thus the associated heat flux can be calculated [Eq. 3.2] relative to the freezing point of water (T_{melt}, °C) using the volumetric heat capacity (C_v, J/m^3·°C) of water.

$$\phi = C_v Q \,(T - T_{melt}) \qquad \text{Eq. 3.2}$$

In ice modeling applications, a heat transfer coefficient (α, W/m^2·°C) which is a function of flow rate, is often applied to Eq. 3.2 in the form of Eq. 3.3 (Williams 1963, Wankiewicz 1984, Calkins 1984, Marsh and Prowse 1987). The coefficient influences the heat transfer rate from the water column into the ice [which equals ϕ_{trans} (the sum of ϕ_{loss} and ϕ_{melt})]. Larger coefficients transmit more heat to the ice allowing the water column to lose heat at a faster rate, thus the water column temperature asymptotically approaches T_{melt}.

$$\phi_{loss} + \phi_{melt} = \phi_{trans} = \alpha(T - T_{melt}) \qquad \text{Eq. 3.3}$$

To maintain the independence of the flow rate from the heat transfer coefficient, an alternate heat transfer coefficient (α', W/m^2·°C) was used [Eq. 3.4]. In addition, by substituting stream width (*b*, m), flow velocity (*V*, m/s), and channel depth (*D*, m) for Q [Eq. 3.5], changes in D and V associated with the specific flow rates (Q) were incorporated into the model calculations.

$$\alpha = \alpha' C_v Q \qquad \text{Eq. 3.4}$$

$$\alpha = \alpha' C_v bDV \qquad \text{Eq. 3.5}$$

After the initial time-step, water depth of the volumetric cell was estimated assuming subcritical flow based upon the initial depth and the volumetric flow of groundwater into the volumetric cell. Flow velocity was calculated using Manning's Equation (Sturm 2001) with an estimated composite Manning's N (incorporating ice cover and channel roughness) of 0.30 and the measured water surface slope.

Eq. 3.6 is a generally applicable expansion of Eqs. 3.2-3.5, where dT is the temperature differential from a reference temperature.

$$\phi = \propto' C_v bDV \, \mathrm{dT} \qquad \text{Eq. 3.6}$$

In the model, the initial ice thickness (y_{ice}, m) and snow depth (y_{snow}, m) were specified over a 1.0 m^2 unit area; atmospheric temperature (T_{air}, °C) and snow depth were defined dynamically, while wind velocity (V_{wind}, m/s) was assumed constant. The boundary between the ice and the water was set to T_{melt} and heat was conducted from the water through the ice and snow before being lost to the atmosphere (when the air temperature is less than 0.0°C).

The heat transfer coefficient in this model was calibrated to field observations at Hot Cake Slough by defining the initial temperature of the water column to be 0.0°C. This temperature was allowed to asymptotically approach a constant downstream water column temperature at an air temperature of -9°C with a snow cover of 2.5 cm (which is similar to field observations). Due to the unsteady flow conditions associated with groundwater heat flux into the channel, the modeled water column temperature fluctuates and is spatially variable, thus the model builds upon the basic heat transfer equations (Michel 1971, Ashton 1982, 2010, Wankiewicz 1984, Calkins 1984, Marsh and Prowse 1987).

The model assumes thorough mixing of groundwater and lateral channel flow (Ashton 1982). When using a heat transfer coefficient, the temperature of the channel outflow changes over time and the volumetric flow from the cell equals the sum of the lateral and groundwater flow. ϕ_{trans} (sum of ϕ_{loss} and ϕ_{melt}) was determined [Eq. 3.3] and used in combination with ϕ_{in}, ϕ_{GW}, and ϕ_{out} [Eq. 3.2] to calculate ϕ_{gain} [Eq. 3.1]. The model calculates the water column temperature of the next time step using ϕ_{gain} [Eq. 3.2].

ϕ_{loss} depends upon the thickness (*y*, m) and thermal conductivity (*k*, W/m·°C) of the ice and snow, T_{melt}, T_{air}, and V_{wind} [Eq. 3.7] (Ashton 1982, 2010). The model calculates k_{snow} from snow density measurements (Sturm et al. 1997) and the surface resistance of the boundary layer is estimated using the approach discussed in Starosolszky (1968).

$$\phi_{loss} = \frac{T_{melt} - T_{air}}{\frac{y_{ice}}{k_{ice}} + \frac{y_{snow}}{k_{snow}} + \frac{1}{10 + V_{wind}}} \qquad \text{Eq. 3.7}$$

The model subtracts ϕ_{loss} from ϕ_{trans} [Eq. 3.3] to calculate ϕ_{melt}. ϕ_{melt}, the latent heat of fusion for water (λ_{fusion}, J/kg), and the density of ice (ρ_{ice}, kg/m^3) are then used to calculate the potential ice melt rate ($\frac{dy_{ice}}{dt}$, m/day) using Eq. 3.8.

$$\frac{dy_{ice}}{dt} = \frac{\phi_{melt}}{\lambda_{fusion}\,\rho_{ice}} \qquad \text{Eq. 3.8}$$

3.3.3. Sensitivity analyses

Analyses were performed to estimate the sensitivity of the model to changes in the most important input variables. Specific initial conditions were used as model input for the standard analyses (Table 3.1). Each input variable was increased and decreased by 30% to determine the resulting sensitivity of ice melt. The 30% change in each input variable was selected as an arbitrary, yet consistent proportional modification to assess the relative response of the model.

3.3.4. Confidence analysis

A confidence analysis was performed to estimate model performance relative to the estimated measurement accuracy of each input variable (Table 3.2). Modified input values were varied by increasing and decreasing the initial value by its estimated percent accuracy. All of the modified input values that would maximize (or minimize) the ice melt rate were used simultaneously to determine how uncertainty in the input variables affects model output. The resulting change in the potential ice melt rate represents the relative uncertainty in the model.

3.3.5. Climate change scenarios

Three scenarios (Table 3.3) were developed to compare the modelled ice melt rates under cool, moderate, and warmer conditions. Input data approximating moderate conditions in early March in interior Alaska were developed based upon available historic and field observations. Compared to the moderate scenario, under the cooler [warmer] scenario the air temperature was assumed to be 3°C cooler [warmer], snow depth was assumed to be 5 cm less [greater], and the upwelling rate was assumed to be 20% less [greater]. The scenario upwelling rates were based upon upwelling estimates of Walvoord and Striegel (2007) who report a 20% increase in the winter baseflow (and winter groundwater upwelling rates) between 1963 and 2005 for the Tanana River, which they attribute to permafrost degradation . Under each scenario the average daily temperature was held constant.

3.4. RESULTS

3.4.1. Field studies

The vertical hydraulic conductivity (K_{sat}) was measured to be 4.0 m/day. The vertical hydraulic gradient varied with the depth of each piezometer. The 1.90 m deep piezometer had a consistently lower flow rate than the 1.10 m deep piezometer. For the end of March and April of 2013, the average piezometric head at 1.10 m depth was 0.13 m (s.d. = 0.09) (Figure 3.4) and the calculated vertical groundwater flow rate averaged 1.14 m/day (s.d. = 0.83) (Figure 3.4). On two different days, horizontal groundwater velocities were measured to be 0.5 and 0.3 m/day at a depth of 1.6 m, which corroborates measurements of 0.3 m /day reported by Clilverd *et al.* (2008) in similar substrates from nearby LTER sites. With these groundwater flow rates and a channel depth of 20 cm, the total groundwater velocity into the channel was calculated to be 1.2 m/day.

In March 2013, the vertical temperature profile measured nearly constant groundwater temperatures of 3.2°C at a depth 0.35 m below the thalweg at the downstream site in Hot Cake Slough, while the upstream site in Hot Cake Slough had a groundwater temperature of 2.7°C. At the downstream site, the water column temperature averaged 1.5°C, while the upstream site water column averaged 2.0°C (Figure 3.5).

Time-lapse photos were used to observe site conditions on a daily basis (Figure 3.1). Using the photo series, changes in site conditions were observed over three different winter seasons. Notably, despite much colder air temperatures in the winter 2011-2012, there was more open water in Hot Cake Slough than in winter of 2012-2013. There were not enough data collected in the 2010-2011 season to compare the period of ice cover.

During a late season survey of the Tanana River in 2013, field personnel found many areas appearing hazardous along the southern river bank between Fairbanks and Nenana (185 km by river), which borders the Tanana Flats. During this survey, 150 km of anastomosing (multithreaded, but stable) river channel were mapped as unsafe for traveling (Schneider et al. 2013c).

3.4.2. Controls over ice dynamics

The groundwater upwelling rate and its associated energy flux increases linearly as the hydraulic gradient increases with a constant groundwater temperature (Figure 3.6). At a groundwater upwelling temperature of 4.0°C, the heat flux would melt up to 60 mm of ice per day under conditions with no heat losses to the atmosphere or the water column, e.g., if 100% of the groundwater heat was used to melt river ice (Figure 3.7). The potential ice melt rate rises with increasing air temperature, hydraulic gradient, groundwater upwelling, ice thickness, or snow depth. The potential ice melt rate increases with the upwelling rate when modeled with conductive and convective heat losses to the atmosphere and the use of a heat transfer coefficient [calibrated to field conditions ($\alpha' = 6.68 \times 10^{-5}$)]. Given the measured groundwater flow velocity into channel (1.2 m / day), the modeled ice melt rate decreased at a rate directly proportional to air temperature (Figure 3.8).

The ice thickness would increase despite the groundwater heat flux when there is no snow at temperatures less than approximately -12°C. However, the presence of snow radically changes these relationships (Figures 3.9 and 3.10). At the coldest air temperatures (while including conductive and convective heat losses and a changing water column temperature), the potential ice melt rate is positive with a snow cover of 20 cm. Moreover, the variability in ice melt rates associated with colder air temperatures is tempered by increasing snow cover (Figure

3.10) and ice melt is largely independent of air temperatures when snow depths are greater than 25 cm. This depth represents the hiemal threshold (Pruitt Jr. 1957), which varies according to snow density, but is defined as the snow depth at which the physical and biological systems under the snow are essentially thermally isolated from variation in air temperature.

The response surfaces of the potential melt rate over a range of groundwater upwelling rates and air temperatures emphasizes the concept of the hiemal threshold (Figures 3.10 and 3.11). As noted, at a snow depth of 25 cm, the air temperature has an insignificant effect on the potential ice melt rate (Figures 3.11a, b, and c), while an increasing groundwater flow rate is directly proportional to the ice melt rate. Similarly, the complexity of the response surface of the potential ice melt rate over a range of snow depths and air temperatures (Figures 3.11 d, e, and f) show that the importance of air temperature is attenuated with increasing snow depth in relation to initial ice thickness. It also illustrates the linear response of ice melt relative to changes in air temperature and the steep response gradient at low snow depths.

3.4.3. Sensitivity analysis

Table 3.1 shows that the calculated ice melt rate was most sensitive to increases in the groundwater temperature, vertical upwelling rate, water depth, snow depth, and air temperature, respectively. The sensitivity of each variable changes depending upon initial conditions. At the conditions specified (Table 3.1), the 30% changes in the groundwater temperature, water depth, or snow depth each affected the ice melt calculations by more than 30%. However, if the initial snow depth was decreased from 25 to 2 cm, the effect of a ±30% change in snow depth would be amplified and the potential ice melt would be changed by -50 to +60%.

3.4.4. Confidence analysis

A confidence analysis was performed to gain an understanding of model performance based upon the measurement confidence of the input variables. Under the assumption that each input variable has errors associated with its measurement, confidence in model performance would decrease with increasing measurement errors. Table 3.2 suggests that if the estimated minimum and maximum errors of all input variables were realized simultaneously, the modeled ice melt rate would range from -27% to +28% of the initial calibrated output value of 8.9 mm/day (e.g., 6.8 – 11.9 mm/day)

3.4.5. Climate scenarios

Under cooler conditions, the model estimated the potential ice melt rate to be 5.2 mm/day. Under persistent conditions in this scenario, a 10 cm ice sheet would take more than 19 days to melt. Under moderate conditions, the model estimated the potential ice melt rate to be 9.3 mm/day (a 44% increase from the moderate climate scenario) and would cause 10 cm of ice to melt after 10.7 days. Under the warmer scenario, the potential ice melt rate increased by 40% from 9.3 mm/day (moderate conditions) to 13.0 mm/day (Table 3.3). If these conditions persist, a 10 cm ice sheet would melt in less than 8 days. The latter two model estimates are similar to field observations.

3.5. DISCUSSION

Our findings show that increased groundwater upwelling can decrease river ice thickness under winter conditions in the subarctic. Increases in the snow depth increase the thermal insulation of the ice and decrease the heat losses from the groundwater and river water to the air, thus causing more heat energy to be available for the degradation of the ice. At air temperatures less than 0.0°C, increased temperatures reduce the temperature gradient between the liquid water and the air, thereby decreasing the heat loss and raising the ice melt rate. Finally, increases in groundwater temperature would increase the groundwater heat flux (Kurylyk *et al.* 2013; Kurylyk *et al.* 2014) and would increase the ice melt rate, although we assumed groundwater temperatures do not change significantly.

Degrading permafrost, warming air temperatures, forest fires, or changes in precipitation are factors that could affect groundwater flow rates. Walvoord and Striegel (2007) hypothesized that permafrost degradation has caused a 20% increase in winter groundwater discharge in the Tanana River between 1963 and 2005. Increased air temperatures associated with climate warms permafrost and can transform discontinuous permafrost zones into areas without permafrost. These areas increase water exchange rates between surface and ground water (Hinzman et al. 2013b). In areas with positive hydraulic gradient (groundwater pressure), upwelling rates increase.

Rowland *et al.* (2010) emphasized the importance of using interdisciplinary methods when considering landscape responses to permafrost thaw. In our field area, forest fire frequency has increased significantly in the last two decades (Kasischke et al. 2010, Hinzman et al. 2013a).

When fires reduce the thickness of the insulating organic layer over the permafrost, the surface energy balance is altered to promote permafrost thaw and thermokarst formation (Yoshikawa et al. 2002). Fire kills most vegetation and decreases transpiration, which leaves more water available for runoff or infiltration. Elevated surface water infiltration could also contribute to discharge into river channels. In a discontinuous permafrost area, this mechanism could partially explain increases in winter baseflow of rivers (Yoshikawa et al. 2002, McClelland et al. 2004). In the Tanana River basin, there have been large wildfires that have occurred in our study area as recently as 2010 (AICC 2010), and such events may increase baseflow due to decreased transpiration and increased permafrost thaw.

Climate models project that warmer winter temperatures will also result in greater snowfall or changes in the timing of snow accumulation. Our model results imply that changes in the timing or magnitude of snow accumulation can have a strong influence on potential ice melt rates by groundwater. It should be emphasized that during late winter in interior Alaska, snow depths typically exceed the hiemal threshold, thereby thermally isolating the water column from warm or cold air temperatures. Thus, when considering future climate scenarios, ice conditions are expected to be affected by changes in groundwater upwelling rates more strongly than by warmer air temperatures, because under late winter conditions the upwelling rate and snow depth exert a more dominant influence on river ice thickness compared to air temperature.

3.6. CONCLUSIONS

Rural Alaskans have observed that winter travel conditions have become more dangerous due to thin or open ice in recent memory (Herman-Mercer et al. 2011, Schneider et al. 2013a, 2013c). Our modeling results illustrate a potential mechanism to account for changing travel conditions on the Tanana River and other rivers in interior Alaska. Degrading permafrost in distant recharge areas could allow for enhanced infiltration and greater fluxes in groundwater upwelling areas, which degrades ice from below and can generate hazardous ice conditions on river channels. The combination of local knowledge of rural Alaskans and hydrological modeling coupled to climate projections suggest that permafrost degradation, forest fires, and associated increases in groundwater upwelling may elevate the dangers related to winter travel on river ice in areas with discontinuous permafrost in Alaska.

Warming air and surface temperatures, land cover change, forest fire, and development are thawing permafrost throughout the Arctic and sub-arctic (Jorgenson et al. 2001, Hinzman et al. 2005, Romanovsky et al. 2010). Unfrozen fine-grained soils are more permeable than their frozen form and are associated with higher groundwater flow rates. Our research illustrates the magnitude of the potential impact of increased groundwater upwelling on river ice thickness under varying environmental conditions. The most significant drivers were vertical upwelling rate, snow depth, water column depth, air temperature, and groundwater temperature. Our findings indicated that relatively small changes in upwelling, groundwater temperature, or snow depth could have substantial impacts on ice thickness. Because ice melt is so sensitive to snow depth and because this parameter can increase in the span of hours, rapidly changing snow conditions affect the relative safety of winter travel on river ice.

In sub-arctic environments, winter travel on rivers is not only common, but also a common aspect of subsistence lifestyles and recreational activities. Predictable and reliable environmental conditions help maintain an enjoyable quality of life for subsistence peoples. While people are adaptable to the impacts of extreme events and variable conditions, these types of events increase their vulnerability to external forces that factor into individual or household decisions to migrate from subsistence lifestyles in remote communities to jobs in cash-based economies in cities. This study illustrates the importance of using applied science to investigate the complex interactions between climate, hydrology, and society to understand how increasing variability in climate and natural processes may affect the lives of subsistence users in the North.

3.7. ACKNOWLEDGEMENTS

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3.8. FIGURES

Figure 3.1. Hot Cake Slough study area photo illustrating how open water is maintained through periods of very cold air temperatures (-30°C).

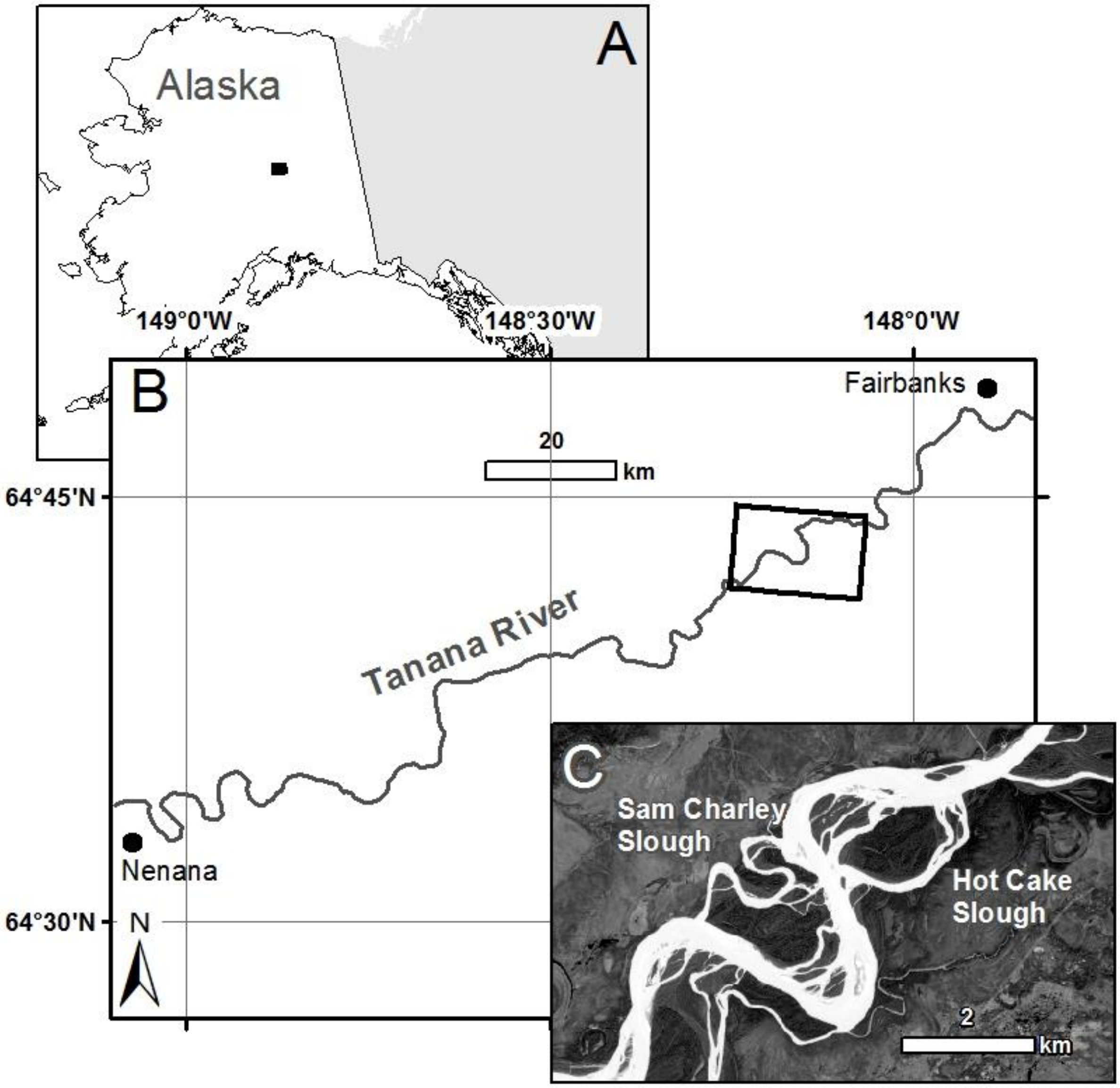

Figure 3.2. Study area map of Sam Charley and Hot Cake Sloughs of the Tanana River in Alaska. Panel A illustrates the position of Panel B within the state of Alaska. Panel B shows the position of Panel C relative to Fairbanks. Panel C shows the slough locations.

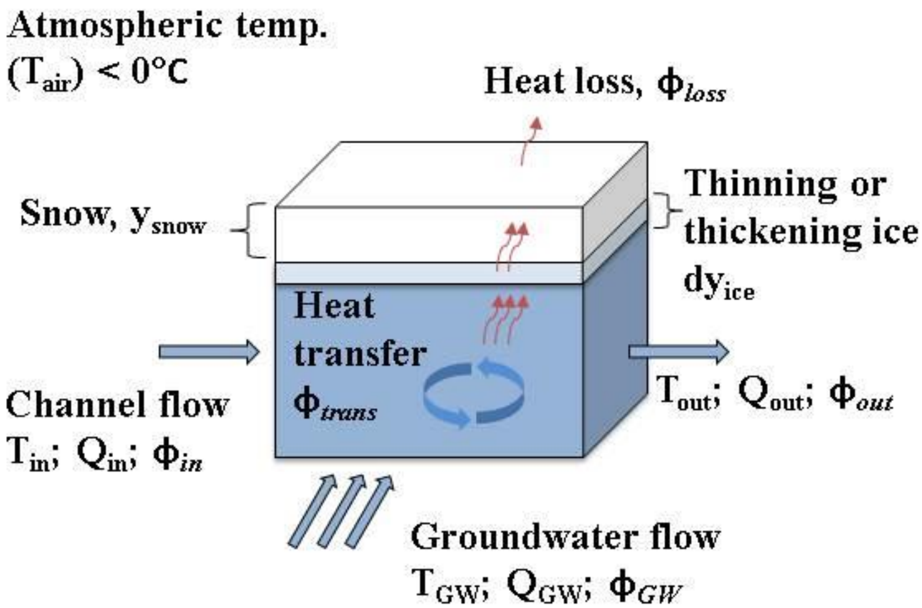

Figure 3.3. Conceptual diagram of groundwater heat affecting river ice thickness in subarctic rivers (see variable definitions in Appendix A3).

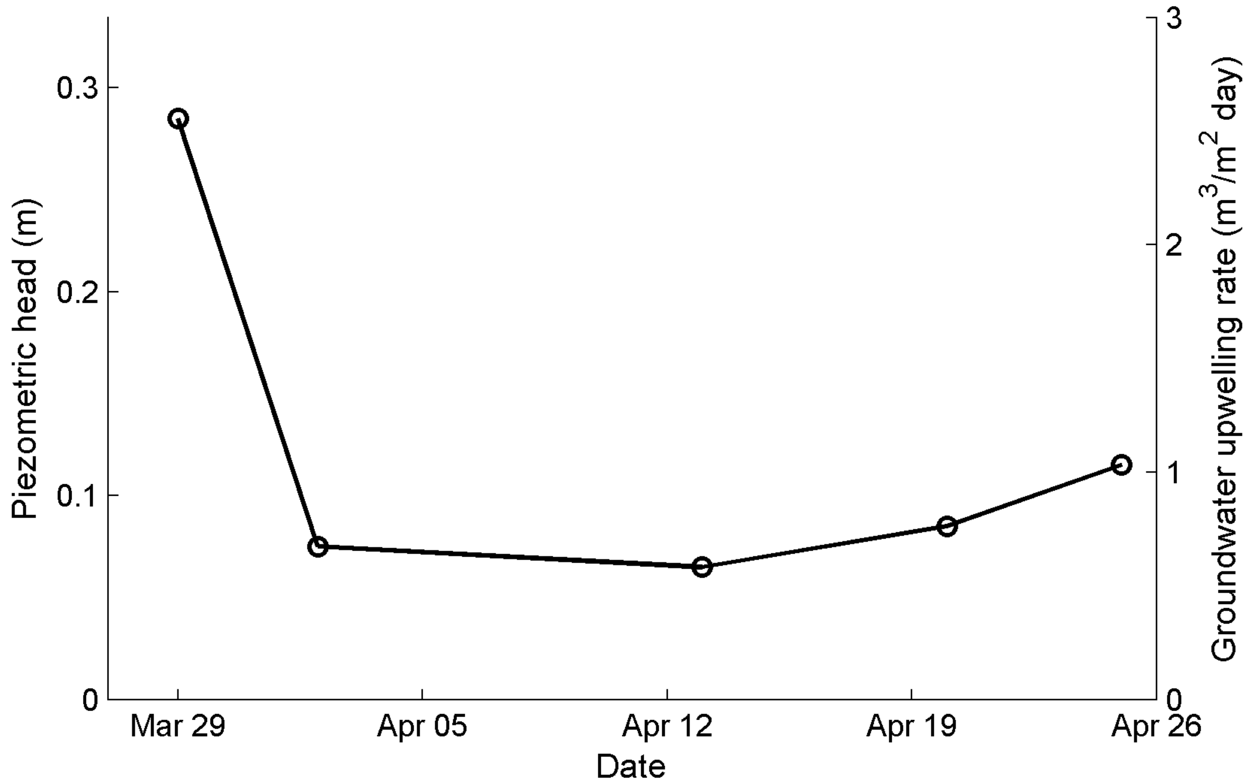

Figure 3.4. Piezometric head and groundwater upwelling rate as measured 1.10 m beneath the channel bottom of Hot Cake Slough of the Tanana River.

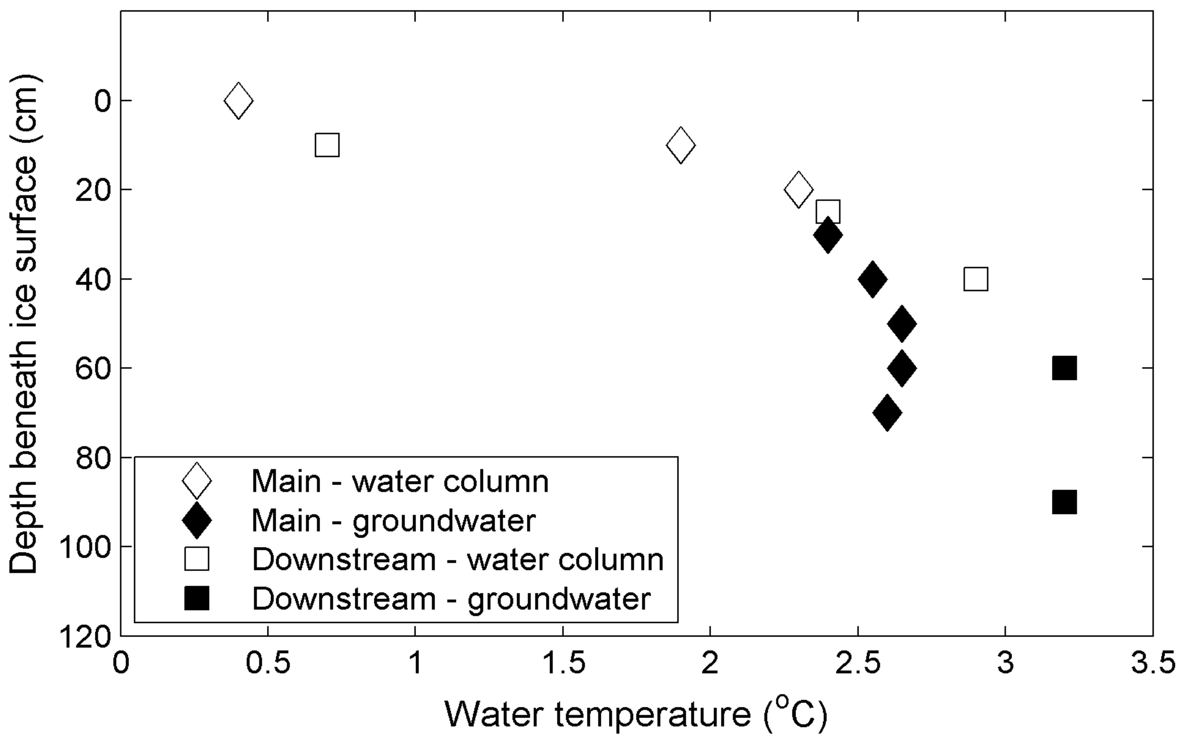

Figure 3.5. Water temperatures in the Hot Cake Slough of the Tanana River (March 19, 2013) at the upstream and downstream monitoring stations.

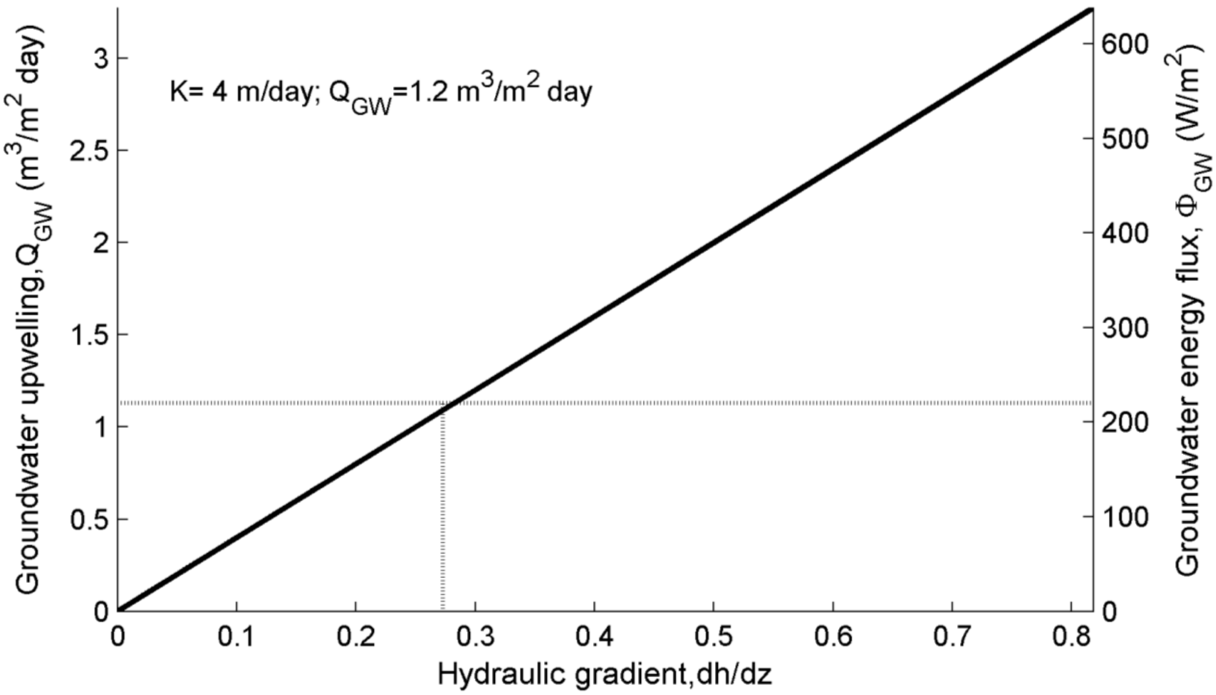

Figure 3.6. Hydraulic gradient relative to the groundwater upwelling rate and its associated heat flux at a groundwater temperature of 4°C at the measured vertical hydraulic gradient.

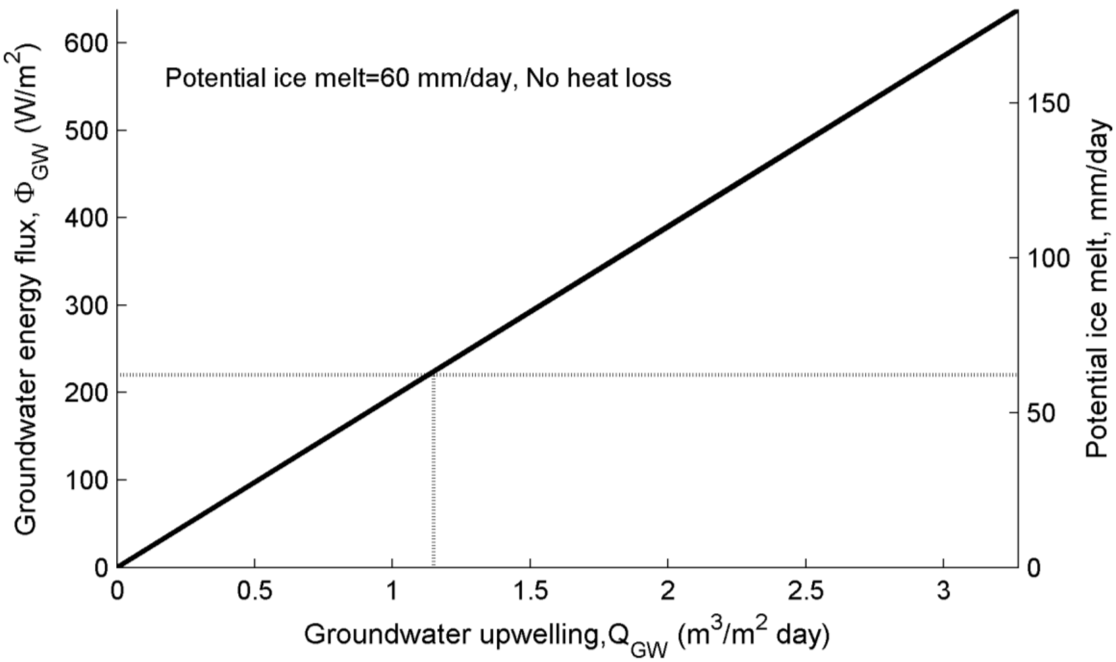

Figure 3.7. Heat flux and potential ice melt associated with variable groundwater upwelling at a temperature of 4°C assuming a system with no atmospheric heat losses or gains (perfectly insulated from the atmospheric temperature).

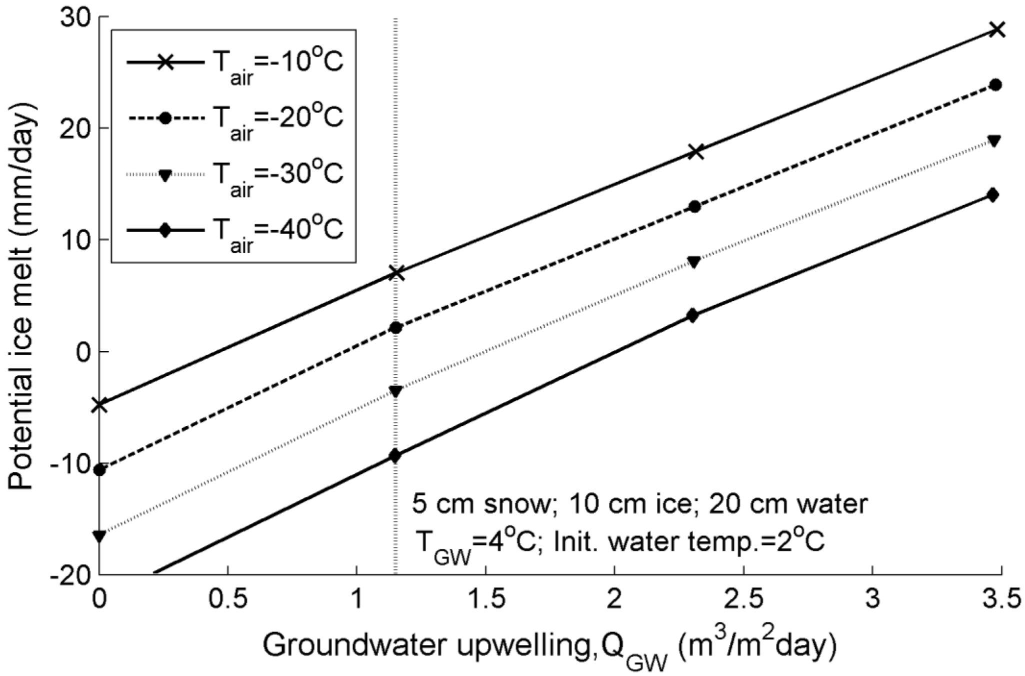

Figure 3.8. Potential ice melt with varying upwelling rates at different air temperatures (or rate of thickening when ice melt rates are negative).

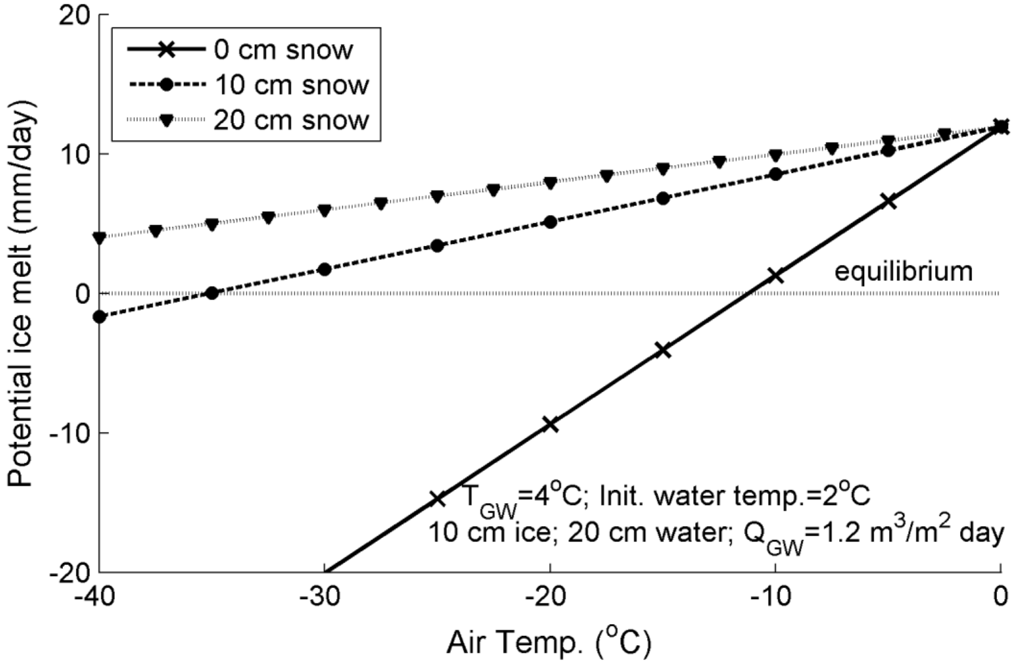

Figure 3.9. Potential ice melt with varying temperatures at different snow depths.

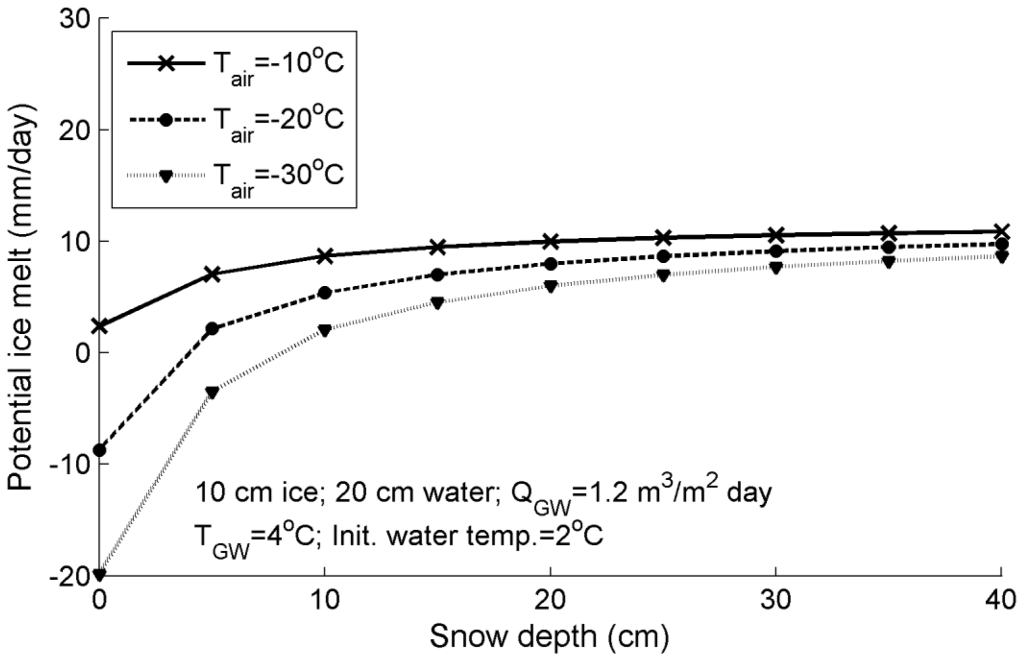

Figure 3.10. Potential ice melt with varying snow depths at different air temperatures.

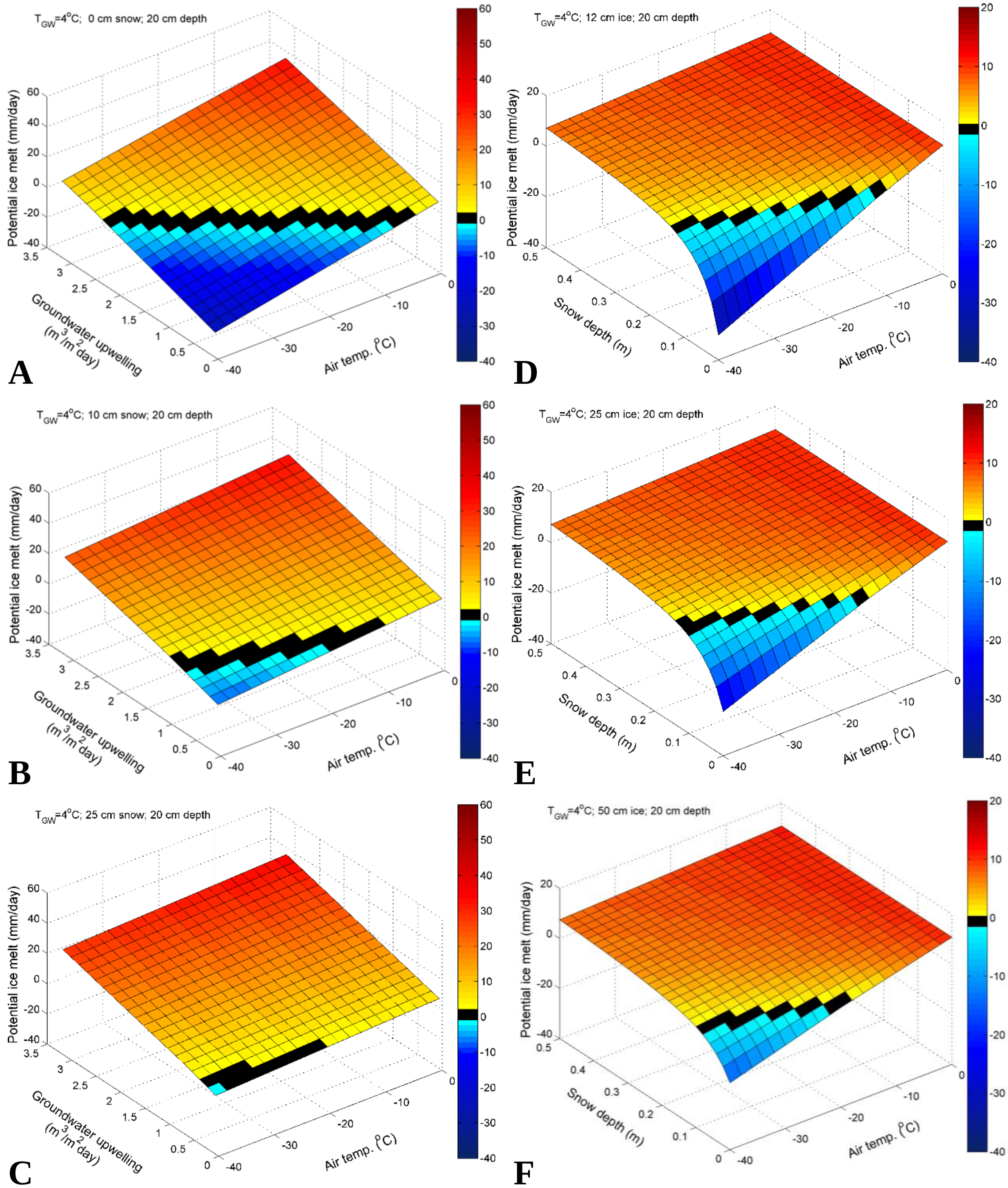

Figure 3.11. A-F. Three dimensional melt rate response curves. Melt rate over a range of air temperatures and groundwater upwelling rates (down the left column) or snow depths (down the right column) given specific initial conditions (noted in the upper left).

3.9. TABLES

Table 3.1. Sensitivity analyses assess the model's response to changes in input variables

Variable	Units	Initial	Variability	Sensitivity of ice melt rate
Groundwater temperature	°C	4.0	+/- 30%	+/-38%
GW vertical upwelling rate	m/day	1.1	+/- 30%	+/-38%
Water depth	cm	20	+/- 30%	+/- 34%
Snow depth	cm	25	+/- 30%	-13% to +8%*
Air temperature relative to freezing pt. of water	°C	-20	+/- 30%	+/-11%
Heat transfer coefficient, α'		$6.68x10^{-5}$	+/- 30%	-8% to +4%
Water column temperature relative to freezing pt. of water	°C	2.0	+/- 30%	+/-4%
GW horizontal flow rate	m/day	0.3	+/- 30%	-4% to +2%
Initial ice thickness	cm	10	+/- 30%	+/- 0.4%
Wind speed	m/s	1	+/- 30%	+/- 0.2%

*When initial snow depth equals 2 cm and is modified by +/- 30%, the sensitivity ranges from +60% to -50%.

Table 3.2. Confidence analyses assessed the effect of potential measurement errors

Variable	Units	Initial	Measurement confidence	Total estimated confidence in modeled ice melt rate
GW vertical upwelling rate	m/day	1.1	+/- 30%	Melt estimate = 9.3 mm/day [confidence range -27% to +28%]
GW horizontal flow rate	m/day	.30	+/- 30%	
Initial ice thickness	cm	10	+/- 1.0%	
Snow depth	cm	20	+/- 0.5%	
Water depth	cm	20	+/- 0.5%	
Wind speed	m/s	1	+/- 50%	
Air temperature relative to freezing pt. of water	°C	-15	+/- 0.5%	
Groundwater temperature relative to freezing pt. of water	°C	4.0	+/- 0.5%	
Initial water column temperature relative to freezing pt. of water	°C	2.0	+/- 0.5%	

Table 3.3. Climate scenario analyses were performed to assess potential impacts of changing temperature, snow depths, and groundwater upwelling rates on river ice thickness

Variable	**Units**	**Cooler scenario**	**Moderate scenario**	**Warmer scenario**
GW vertical upwelling rate	m/day	0.88 (-20%)	1.1	1.3 (+20%)
GW horizontal flow rate	m/day	0.3	0.3	0.3
Initial ice thickness	cm	10	10	10
Snow depth	cm	15	20	25
Air temperature	°C	-18	-15	-12
Water depth	cm	20	20	20
Initial water column temperature	°C	2.0	2.0	2.0
Ice melt rate	mm/day	5.2	9.3	13.0
Complete ice melt	days	19.1	10.7	7.7
Change in ice melt rate	%	-44%	N/A	+40%

3.10. REFERENCES

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3.11. APPENDIX A3. VARIABLE AND SYMBOL DEFINITIONS

Table A3.1. Definitions of variables and associated units

Variable	Definition	Units
α	Heat transfer coefficient	$W/m^2 \cdot °C$
α'	Heat transfer coefficient, alternate form	$W/m^2 \cdot °C$
b	Channel width	m
C_{v,H_2O}	Volumetric heat capacity of water	$J/m^3 \cdot °C$
ρ_{H2O}	Density of water	kg/m^3
ρ_{ice}	Density of ice	kg/m^3
D	Depth, water	m
K	Hydraulic conductivity	m/day
k_{ice}	Thermal conductivity of ice	W/m·°C
k_{snow}	Thermal conductivity of snow	W/m·°C
ϕ_{GW}	Heat flux, groundwater	W/m^2
ϕ_{in}	Heat flux, water column inflow	W/m^2
ϕ_{loss}	Heat flux, total conductive and convective losses	W/m^2
ϕ_{melt}	Heat flux, used to melt ice	W/m^2
ϕ_{out}	Heat flux, water column outflow	W/m^2
ϕ_{trans}	Heat flux, transferred into ice	W/m^2
ϕ_{gain}	Heat flux, retained in water column	W/m^2
λ_{fusion}	Latent heat of fusion for water	J/kg
Q	Volumetric flow rate	m^3/s
T	Temperature	°C
T_{air}	Air temperature	°C
T_{melt}	Melting/Freezing temperature of water	°C
V	Velocity, water	m/s
V_{wind}	Velocity, wind	m/s
y_{ice}	Ice thickness	m
Δy_{ice}	Change in ice thickness	m
$\dot{y}_{melt}$	Ice melt rate	m/day
y_{snow}	Snow depth	m

Table A3.2. Definition of symbols and acronyms

Symbol / Acronym	Definition
°	Geographic degrees
’	Geographic minutes
”	Geographic seconds
Δ	Change
GW	Groundwater
LTER	Long-term ecological research

CHAPTER 4. MAPPING HAZARDOUS ICE CONDITIONS WITH HIGH-RESOLUTION SATELLITE IMAGERY[5]

4.1. ABSTRACT

In interior Alaska, frozen river systems are important transportation corridors, due to the very limited road network. Long-time Alaskan residents report that winter travel conditions on Interior rivers have become more dangerous in recent memory. To address this concern, we used remote sensing to map dangerous ice conditions on the Tanana River in Interior Alaska. Unsupervised classification of high-resolution satellite imagery was used to identify and map open water and degraded ice conditions. The classification system performed well for numerous Geoeye-1 and Worldview-2 satellite images. Ninety-five percent of the total river channel surface was classified as "safe" for river travel, while 4% of the channel was mapped as having degraded ice and 0.6% of the channel was classified as open water. An accuracy assessment indicated that snow, degraded ice, and open water were mapped with an overall accuracy of 73%. Over 95% of the classification errors were caused by shadowing of trees or topographic features in the snow, which are relatively easy to discern visually and avoid. This research demonstrates that the classification of high-resolution satellite images is useful for mapping hazardous ice conditions for a multitude of recreational, transportation, or industrial applications in northern climates.

4.2. INTRODUCTION

Hazardous ice conditions on rivers can be defined as ice-covered areas that are expected to be safe, but actually are not. This is a subjective assessment that is difficult to test without entering dangerous or undesirable situations. In interior Alaska, frozen river systems are important transportation corridors, due to the limited road network. For this reason, many Alaskan villages and towns were established along waterways. Partnerships were established with local (non-academic) Alaskans who have extensive experience traveling on Alaskan rivers in all seasons. They reported that hazardous ice conditions on the Tanana River had become

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[5] Jones, C.E., K. Kielland, A. Prakash, & L.D. Hinzman. 2014. Mapping dangerous ice conditions on the Tanana River using high-resolution satellite imagery. Manuscript submitted to *Arctic, Antarctic, and Alpine Research.*

more prevalent in recent decades (Schneider et al. 2013a, 2013b). Their observations on the Tanana River are similar to published findings from the Yukon River (Herman-Mercer et al. 2011). The hazardous ice conditions are caused by numerous factors including fast moving turbulent water, warm air temperatures, and groundwater upwelling in areas with shallow water (Jones et al. 2013), which can represent significant danger to winter travelers.

Much of the Tanana River and its neighboring regions are fed by groundwater (Anderson 1970). Jones et al. (2013) hypothesized that observations of more thin ice and open water on the Tanana River during winter were primarily associated with augmented groundwater flow caused by permafrost degradation that may have intensified since the 1960's (Walvoord and Striegl 2007, Brabets and Walvoord 2009, Lyon and Destouni 2010). Heat provided by groundwater can degrade river ice from below and field observations confirm that areas fed by groundwater in the Tanana River can maintain thin ice conditions or open water (Figure 4.1) for extended periods despite cold (-30 to -40°C) winter air temperatures (Jones et al. 2013).

Advances in technology have led to the deployment of satellites, which acquire images in the visual and infrared spectral regions at increasing spatial resolution. To get a good temporal coverage of a study area, data sets from multiple satellites are utilized. Recently, the University of Minnesota's Polar Geospatial Center has provided support to Arctic and Antarctic researchers in the United States who are funded by the National Science Foundation by providing high-resolution satellite imagery at no cost. Therefore, high-resolution satellite imagery has become readily available for polar scientists in the U.S. Satellite imagery has been used to monitor ice conditions in freshwater water bodies in remote regions across vast areas (Duguay et al. 2002, Duguay and Lafleur 2003, Jeffries et al. 2005, Gauthier et al. 2006, 2014, van Breukelen 2010). Gauthier (2014) used spaceborne synthetic aperture radar (SAR) data to map ice roughness for remote Canadian communities while collaborating with rural communities to groundtruth their data product. Spaceborne SAR and optical data have also been used to monitor onset of river ice breakup (Floyd et al. 2014) and assess ice thickness on freshwater lakes (Duguay and Lafleur 2003, Jeffries et al. 2005). Airborne thermal infrared has also been used to assess ice thickness of new sea ice and other characteristics (Emond et al. 2010). Airborne ground penetrating radar is yet another remote sensing product that has been used to examine ice thickness (Arcone and Delaney 1987, Delaney et al. 1990, Yankielun et al. 1992, Arcone et al. 1997).

In this paper, we describe the use of high-resolution optical and near-infrared satellite imagery to map the spatial distribution of dangerous ice conditions (degraded ice or open water) on the Tanana River in Alaska. Field surveys were used to evaluate the accuracy of the unsupervised classification product. The mapping approach was developed to address several research questions:

1. Can satellite imagery be used to map hazardous ice conditions in interior Alaska accurately?
2. Can a single classification system be applied across multiple satellite images to map hazardous ice conditions accurately?
3. Are there spatial patterns that can describe the general distribution of hazardous ice conditions between Fairbanks and Nenana, Alaska?

4.3. METHODS

4.3.1. Study area

The study area included most of the Tanana River between the Alaskan communities of Fairbanks and Nenana (Figure 4.2). This region is characterized by discontinuous permafrost and is bordered by the Tanana Flats region, an area with a high water table fed by groundwater originating from glaciers in the Alaska Range (Anderson 1970). The Alaska Range glaciers (typically found above 1525 m) are also the primary source of water for the Tanana River (120 m elevation) (Anderson 1970).

4.3.2. Field surveys

The study region has persistent open water features that are only periodically covered by thin ice at extremely cold temperatures (-30 to -40°C). Daily time-lapse photographs were used to monitor the ice degradation and open water in Hot Cake and Sam Charley Sloughs in March and April of 2011, 2012, and 2013. Crews traveled throughout the field area mapping ice conditions during the winter and springs of 2010-2013. In addition, snowmobiles were used to map dangerous ice conditions of the entire study reach on 16 April 2013.

During the comprehensive 2013 field survey, ice conditions were assessed on approximately 300 km of anastomosing (multithreaded, but stable) channels within the 90 km reach of the Tanana River between Fairbanks and the community of Nenana, Alaska. The integrity of the ice was assessed visually and classified as open water, degraded ice, or relatively safe ice (referred to as “safe” ice). Degraded ice was characterized by having thin (thermally degraded rather than wind-blown) or absent snow conditions [indicative of groundwater inflows that thermally degrade the ice and snow from beneath the ice (Jones et al. 2013)]. Snow or ice that is thermally degraded can be differentiated from wind-blown ice using subtle visual cues. In some cases, ice with very thin snow that has ablated or sublimated (due to the subsurface warmth of warmer waters beneath the ice) can be distinguished from ice covered by deeper snow with more powdery or crusty in texture. It is also possible to see anomalous pits or snow-free areas distributed between areas with deeper snow, which is another pattern that is found in dangerous areas. Frost-covered trees are regularly encountered and are another indicator of nearby open water. Overflow is another ice-related, hazardous condition regularly encountered in cold climates on rivers, but was not assessed during this field effort. Overflow occurs when the weight of snow depresses the ice and liquid water from beneath the ice flows through cracks and weak spots in the ice, thus partially flooding the snowpack.

4.3.3. Image acquisition and processing

Georeferenced, orthorectified Worldview-2 (WV2) and Geoeye-1 (GE1) imagery were acquired from the Polar Geospatial Center (University of Minnesota) at no cost for the entire study area (Table 4.1). In addition, georeferenced, orthorectified Spot5 (SP5) false-color infrared imagery were obtained from the Geographic Information Network of Alaska (University of Alaska Fairbanks). The WV2 data consisted of 8-band imagery acquired by the satellite on April 17, 2013. Three GE1 4-band composite images were acquired on April 21, 2013. The WV2 and GE1 imagery represented winter conditions. The SP5 data were acquired in July 2009 and October 2010 under snow-free conditions without ice cover (Table 4.1).

Using ArcGIS (ESRI, version 10.2.1 with Spatial Analyst), an unsupervised iso-clustering classification (8 classes over 10 iterations) was applied to the SP5 data sets to generate a channel mask of the late autumn, low-water river channel. The channel mask distinguishes the wetted channel area from other land cover types (forest, burned forest, exposed sand bar, etc.). The minimum number of classes needed to distinguish wetted sand bars from the water within the banks of the channel was used. Using the channel mask, the extract by mask tool was applied to the WV2 and GE1 imagery to generate WV2 and GE1 imagery for the river channel only (imagery of the surrounding non-wetted channel landscape was removed). An unsupervised iso-clustering classification (ten iterations) created a raster image with ten classes (the minimum number of classes that correctly distinguished the subtle differences between degraded snow and snow in Hot Cake Slough). This process uses an isodata clustering algorithm to determine the characteristics of the natural groupings of cells in multidimensional space. The image classes were separated into thematic groups based upon field surveys of Hot Cake Slough that has representative areas of the three classes of ice condition (Table 4.2).

4.3.4. Accuracy assessment

The accuracy of the classification was evaluated by using a random number generator to select 50 uniquely numbered pixels from each ice condition class, as suggested for stratified random sampling applications less than 4,000 km^2 with fewer than 12 classes (Congalton and Green 2008). Using a manual assessment, the randomly selected classified pixels were compared to areas mapped as dangerous during field surveys to determine whether they were successfully categorized as open water, degraded ice, or snow. If they were not correctly classified, the actual class according to a visual interpretation was identified (alternatives included degraded ice, tree shadow, snow shadow, windblown sand, or woody debris). The assessment was performed in two distinctly separate analyses. The first analysis considered pixels misclassified as tree shadows, while the second analysis excluded those pixels, but considered additional pixels to ensure a 50-pixel sample size. For each evaluation, the producer's, users, and overall accuracy were determined and summarized (Story and Congalton 1986, Congalton and Green 2008). In addition, the total percentage of the channel area covered by each class was determined.

4.4. RESULTS

4.4.1. Field surveys

During field mapping efforts, a field crew mapped approximately 300 km of multi-threaded channels on the Tanana River within a 90 km reach of river between Fairbanks and Nenana, Alaska. Mapping efforts resulted in 150 km of anastomosing river channel being mapped as unsafe for winter travelers. Many of these areas were located along the southern limits of the Tanana River, but some were also located in sloughs in northern portions of the river.

4.4.2. Unsupervised classification

Based upon an appraisal of the unsupervised iso-clustered classification, the results generated maps that well represented on-the-ground field conditions (Figure 4.3A - D). The classification indicated that greater than 95% of the river channel surface was occupied by undegraded snow mapped as “safe” for river travel. Approximately four percent of the channel had degraded ice conditions, while 0.6 percent of the channel was classified as open water.

4.4.3. Accuracy assessment

When including tree shadows in the assessment, the producer’s accuracy was demonstrated to be 100% when identifying undegraded snow, while the user’s accuracy was 86% (Table 4.3). This indicates that 100% of the areas identified visually as snow were classified correctly using the remote sensing classification, while 86% of the pixels classified as undegraded snow were correctly classified. Similarly, the open water had a 100% producer’s accuracy, but only a 70% user’s accuracy. The producer’s accuracy of classifying degraded ice was shown to be 82%, while the user’s accuracy was only 62%. The overall accuracy was estimated to be 73%. In addition, 14% of the pixels classified as snow were found in close proximity to areas identified as being dangerous in field surveys. In some cases, pixels erroneously classified as degrading ice were determined to be tree shadows (16%), snow shadows [20% (due to topographic variation)], or woody debris (2%). Finally, of the 50 pixels classed as open water, 26% were determined to be tree shadows and 4% were windblown sand.

By excluding tree shadows from the evaluation, the producer’s accuracy for the classification of snow was reduced to 96%, while the user’s accuracy was not affected (Table 4.4). The accuracy of classifying degraded ice was unchanged. The user’s accuracy associated with the classification of open water increased to 94% and the producer’s accuracy remained 100%. The overall accuracy increased from 73 to 81% when excluding tree shadows.

4.5. DISCUSSION

Overall, the unsupervised classification system functioned quite well considering the minimal calibration efforts used to define the classes. At first glance, the most disconcerting error was that 14% of the pixels identified as undegraded snow were in very close proximity to areas mapped as dangerous (according to field surveys). However, the field-based classification was inherently different from the image-based classification. Field classification was based on linear sampling where entire extents of degraded ice were recorded as individual units, while minor intermittent stretches of undegraded ice or snow within those units were essentially ignored. In the image-based classification, each pixel received a unique class identity without considering any spatial patterns based upon proximity. The reaches identified as dangerous were hazardous in a practical sense, although technically, portions may have been passable. In future research, classification algorithms could be refined to incorporate spatial proximity and spatial patterns of the classified pixels (Koperski et al. 1998). An object-based classification approach, rather than a pixel-based, may have been helpful, although it would come with additional complexities in data processing (Raza et al. 2012).

Other persistent errors occurred in the classification of shadows, which accounted for 95% of the errors in the degraded ice class and 87% of the errors in the open water classification. Yet, pixels identified as degraded ice were properly classed more than 60% of the time. Most pixels that were incorrectly identified as degraded ice were actually shadows caused by trees or snow topography. Most of these shadows are found within 8 to 30 meters of the southern bank of the river. Similarly more than 70% of the pixels identified as open water were correctly grouped and 26% were erroneously identified as open water, but were actually shadows.

The high percentage of errors caused only by shadowing makes this classification system conservative in terms of safety. Generally, if an area of a channel is mapped as dangerous, it is prudent to avoid the area rather than seeking passable trails through mapped danger zones. Significant efforts have been employed to minimize the effects of shadowing in remote sensing analyses (Itten and Meyer 1993, Giles 2001, Dare 2005, Sohn and Yun 2008). Multisource data fusion (Dare 2005, Smikrud et al. 2008) may be the most promising approach to minimize the effects of shadowing. Multiple satellite or airborne images could be acquired at different times of day with a different sun angles. A classification method similar to the approach described above could be applied to a fusion product of the images, which would minimize the effects of shadowing, thus increasing the accuracy of the analyses. Alternatively, an analyst could manually clip out areas with substantial shadowing along the south bank, but this would be labor intensive and while it would increase the performance of the classification system, it defeats the purpose of having a quick automated mapping system.

The improved performance of a classified product without tree shadows was estimated by excluding pixels found within tree shadows from the accuracy assessment. In doing so, the overall accuracy was improved from 73 to 81%, by improving the classification of open water, however, the user's and producer's accuracy was not greatly affected other than the 24% improvement in the user's accuracy for the open water classification.

The value of the classification scheme is in its simplicity and ability to be produced quickly. Given a visual estimation of dangerous ice conditions, human judgment should be used during the decision-making process to determine whether specific areas mapped as dangerous should be avoided or traversed with caution.

Another consideration is the detailed assessment of hazardous river conditions in much of the field data over the study area were gathered on a single date, late in the winter season when some may consider that river travel should be avoided. In winter 2013, the ice went out on the Tanana River in Nenana, Alaska on 20 May 2013, which broke the record for the latest break-up date during the Nenana Ice Classic (a competition for which people guess the date and time that the ice goes out in Nenana). While it is never assumed safe to travel on the river, the condition of the ice was deemed acceptable by field personnel.

A comprehensive field survey did occur over a single day in 2013, but the field crews spent substantial amounts of time traveling on the river and assessing ice conditions over three full winter seasons. Personnel also worked with long-time winter travelers to identify areas that are persistently dangerous in most years. In addition, when the field map was shown to Alaskans with many years of experience traveling on the river, they acknowledged the accuracy the field maps. Finally, the satellite imagery was acquired by the satellites soon after the field survey (Worldview-2 images acquired one day after; Geoeye-1 images acquired five days after). Thus, the field assessment included data that was mapped near the time of the image acquisition. For these reasons, the analyses were considered appropriate and valid for the objectives of the study.

Only a portion of one Geoeye satellite image was used to calibrate the classification system (Hot Cake Slough). Specific classes from the unsupervised classification were grouped into classes that represented hazardous ice conditions near Hot Cake Slough, which the authors visited on a weekly basis for a minimum of three winters. After the resulting classification system was applied to the entire image, a visual assessment of the results determined that the map well represented field observations for other areas found within the image. The classification system was then applied to two additional Geoeye images and a Worldview-2 image and the results appeared reasonable across all images based upon the experience and observations of the survey team. It should be reiterated that overflow (liquid water from beneath the ice flows through cracks and weak spots in the ice and partially floods the snowpack) was not mapped or assessed and is difficult to identify visually, although other satellite remote sensing approaches may be useful to identify areas with overflow.

To address the original research questions, we conclude that satellite imagery can be used to map hazardous ice conditions in interior Alaska using a single classification system across multiple satellite images and satellite platforms. It was also evident that much of the degraded ice is found along the southern limits of the Tanana River channel, which is due to groundwater discharge from the Alaska Range to the Tanana Flats and the Tanana River.

4.6. CONCLUSIONS

The classification system developed here could be applied across various satellite images and different satellite platforms to identify hazardous ice conditions with similar results as field surveys. Our results suggest that mapping dangerous areas on rivers in other geographic areas is possible and could be a valuable resource for winter travelers in arctic regions. Partnerships with rural Alaskans that regularly travel on rivers in the winter provided insight into the applicability and value of identifying areas with hazardous ice conditions. At numerous times throughout this research, winter river travelers sought out members of our project team to discuss river safety, acquire maps of river hazards, and to discuss and share anecdotes about wintertime misadventures on the river. In some cases, their accidents resulted in wet clothing and having to build a fire to dry off, but in other cases, the consequences have been quite dire, resulting in personal injury and even death. In interior Alaska, such losses are a regular occurrence, and these accidental mortalities have resulted in the loss of all types of people, ranging from children to experienced elders with a lifetime of experience traveling on rivers.

Through field efforts, it has been found that certain areas are often dangerous year after year in most winters. Thus, a remote sensing analysis over several years of imagery in early, mid, and late winter could provide a good assessment of ice condition for river reaches in northern climates. Given the robust application across satellite platforms, it is possible that the classification system could be applied more broadly to ice covered rivers in the North, but additional testing is needed.

If high-resolution satellite imagery can be obtained quickly after acquisition by the satellite, the approach could be used to assess present-day field conditions of ice-covered water bodies, which could be very important for industry, transportation authorities, specialized groups (adventure race organizers), field researchers, or other wintertime river users. Satellite remote sensing is a very useful tool that can be used not only by specialized experts for analyses over vast field areas, but can also be used by laypersons to obtain information across a wide range of disciplines and interests. Google Earth is a tool that has been widely adopted and is used to satisfy the unspecified curiosity of people worldwide. NASA's Earth Observing System Data and Information System (EOSDIS) recently developed Worldview, an open-source product that allows the public to view and download full-resolution satellite imagery in real-time (within 3 hours of acquisition) using its Global Imagery Browse Services. In the future, simple spatial classification systems, such as the one described, could be applied to real-time visualization platforms for high-resolution satellites. The potential benefits for people worldwide would be significant.

4.7. ACKNOWLEDGEMENTS

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4.8. FIGURES

Figure 4.1. A winter traveler encounters hazardous river conditions on the Tanana River on April 16, 2013. Photo credit: Dashiell Feierabend.

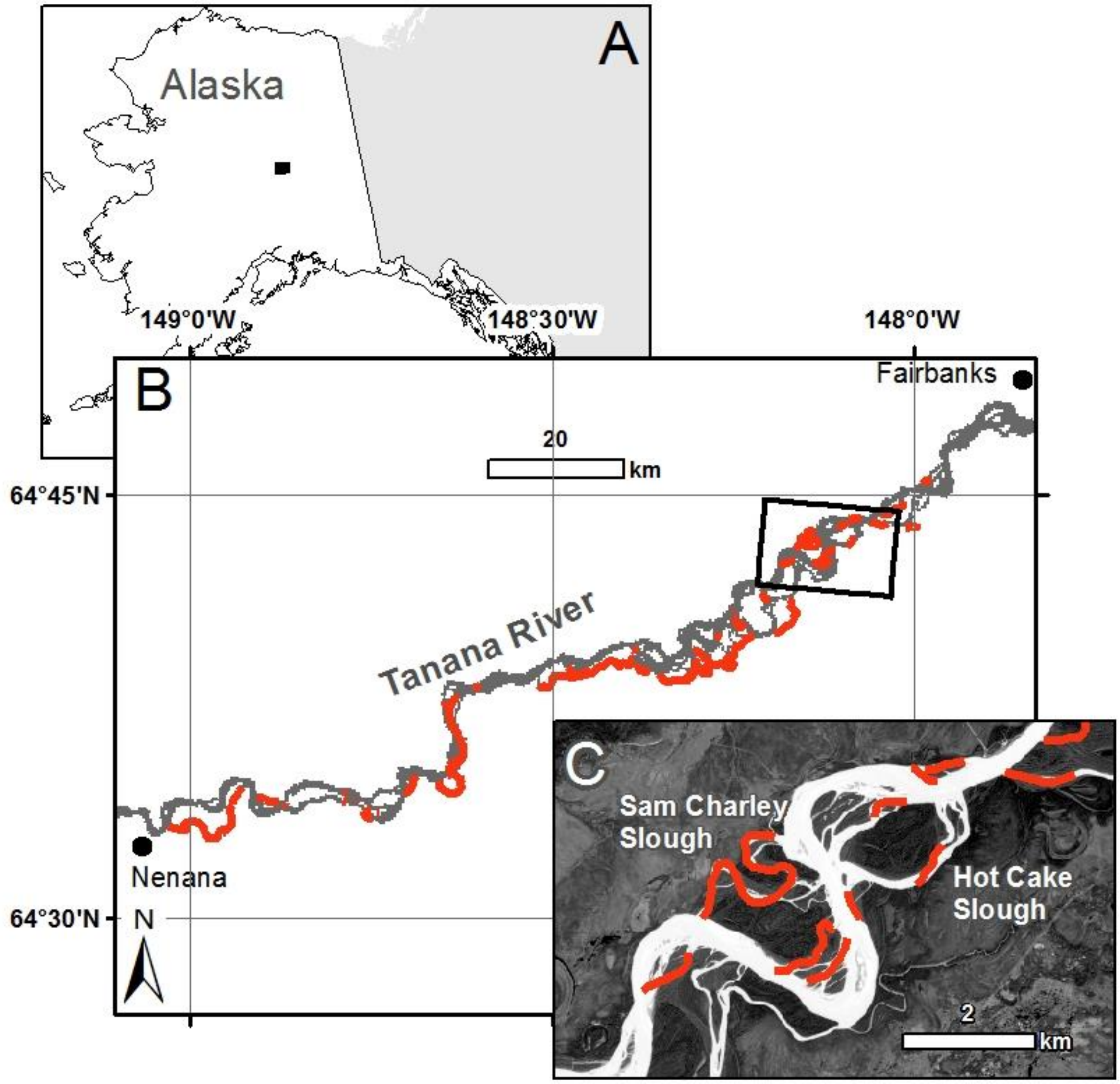

Figure 4.2. Panels A through C identify the location and extent of the study area and the locations of Hot Cake and Sam Charley Sloughs in the Tanana River in Alaska. The areas identified in red were mapped as dangerous according to field surveys. The inset black boxes in panels A and B mark the image extent shown in panels B and C, respectively.

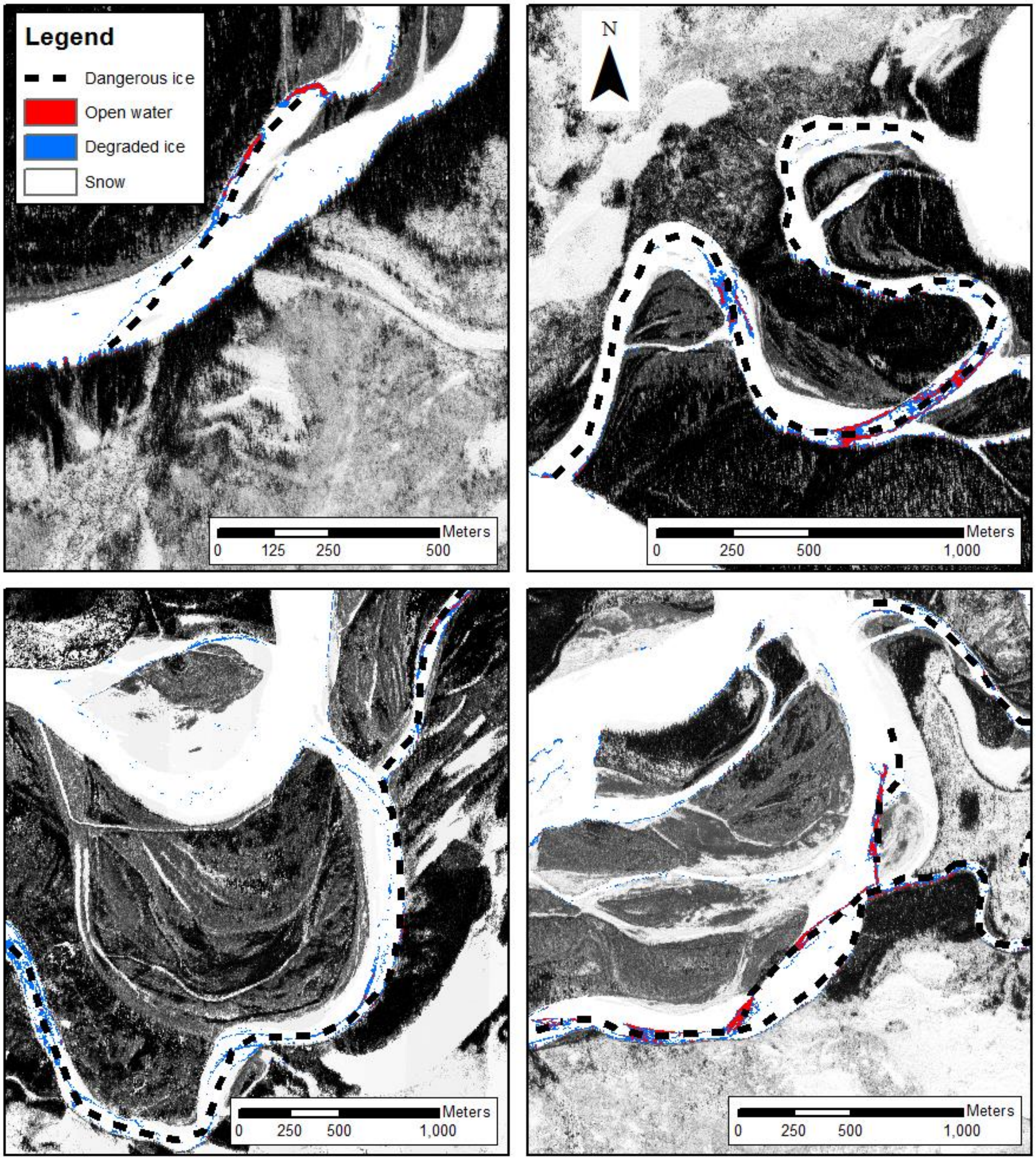

Figure 4.3. A) Open water and degraded ice on Hot Cake (upper left) and Sam Charley Sloughs (upper right) were classified well (21 April 2013 imagery). Areas mapped as dangerous in two unnamed sloughs [lower left (17 April 2013) and right (21 April 2013)] were also mapped well, although some areas mapped as degraded ice were not classified as hazardous during field surveys. The black dotted line indicates areas mapped as dangerous during field surveys.

4.9. TABLES

Table 4.1. Satellite imagery metadata

Satellite platform	Image date	Image time (GMT)	Scene ID	# Bands	Bands used[6]	Spatial resolution (m)
Geoeye-1	21-Apr-2013	9:44:30 PM	GE01_13APR212144296-M1BS-10504100029D8100	4	4,3,2	1.79
Geoeye-1	21-Apr-2013	9:44:31 PM	GE01_13APR212144309-M1BS-10504100029D8100	4	4,3,2	1.79
Geoeye-1	21-Apr-2013	9:44:32 PM	GE01_13APR212144322-M1BS-10504100029D8100	4	4,3,2	2.01
Spot5	Sep-2010		1022-1162	4	4,3,2	2.5
Spot5	Sep-2010		1024-1162	4	4,3,2	2.5
Spot5	Jul-2009		1024-1164	4	4,3,2	2.5
Spot5	Jul-2009		1026-1164	4	4,3,2	2.5
Spot5	Jul-2009		1028-1164	4	4,3,2	2.5
Spot5	Jul-2009		1028-1166	4	4,3,2	2.5
Worldview-2	17-Apr-2013	9:30:59 PM	WV02_13APR172130589-M1BS-103001002172AC00	8	8,5,3	2.20

[6] GeoEye-1 band wavelength (λ) range (μm): $\lambda_{Band\ 2}$ = 0.510-0.580; $\lambda_{Band\ 3}$ = 0.655-0.690; $\lambda_{Band\ 4}$ = 0.780-0.920

Worldview-2 band wavelength range (μm): $\lambda_{Band\ 3}$ = 0.510-0.580; $\lambda_{Band\ 5}$ = 0.630-0.690; $\lambda_{Band\ 8}$ = 0.860-0.900

Table 4.2. Remote sensing classification resulting from unsupervised iso-cluster analysis in ArcGIS.

Ice condition	**Numeric class**
Open water	2
Degraded ice	3, 4
Undegraded snow	5, 6, 7, 8, 9, and 10
No data	1

Table 4.3. Accuracy assessment that includes tree-shadowing errors suggests that 70% of the open water and 62% of the degraded ice was correctly classified according to the user's accuracy.

		Groundtruth data							
		Snow	**Degraded Ice**	**Open Water**	**Tree shadow**	**Snow shadow**	**Windblown sand**	**Woody debris**	**Total pixels**
Remote Sensing Class	Snow	43	7	0	0	0	0	0	50
	Degraded Ice	0	31	0	8	10	0	1	50
	Open Water	0	0	35	13	0	2	0	50
Total pixels		43	38	35	21	10	2	1	150
Producer's accuracy		100%	82%	100%	0%	0%	0%	0%	
User's accuracy		86%	62%	70%	0%	0%	0%	0%	

Overall accuracy = (43+31+35)/150 = 73%

Table 4.4. Accuracy assessment that excludes tree-shadowing errors improved the overall (81%) and user's accuracy for open water areas.

		Groundtruth data					
		Snow	**Degraded Ice**	**Open Water**	**Snow shadow**	**Windblown sand**	**Woody debris**	**Total pixels**
Remote Sensing Class	Snow	43	7	0	0	0	0	50
	Degraded Ice	2	31	0	15	0	2	50
	Open Water	0	0	47	1	2	0	50
Total pixels		45	38	47	16	2	2	150
Producer's accuracy		96%	82%	100%	0%	0%	0%	
User's accuracy		86%	62%	94%	0%	0%	0%	

Overall accuracy = (43+31+47)/150 = 81%

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CHAPTER 5. CONCLUSIONS

In this dissertation, the complex relationships between climate, hydrology, and society were investigated using fieldwork, numerical modeling, satellite remote sensing, and local knowledge. Issues important to rural Alaskans were identified through collaborations with local and regional experts that rely upon subsistence activities to supplement their livelihood. The participatory research approach provided an increased awareness of how varying environmental conditions associated with a warming climate are perceived to affect subsistence users. Their stories and personal anecdotes provided context for the development and calibration of numerical models related to hydrologic phenomenon. For subsistence users, the interaction with research scientists was said to provide new ways of considering, examining, and understanding hydrologic processes and environmental phenomenon through cross-team learning. These types of collaborative partnerships demonstrate how research scientists can work with non-academics to find solutions to real world problems, while offering mutual benefits to each group.

Changes in climate are predicted to be greatest in magnitude in the Arctic (ACIA 2005, Arctic Monitoring and Assessment Programme 2011), and rural residents of northern regions are being impacted by environmental processes associated with climate and increasing variability of earth system processes (Lovecraft and Eicken 2011, Jones et al. 2013, Schneider et al. 2013b, 2013c). The value of incorporating local knowledge into science has been discussed as problematic because of its variability, lack of reliability, and questionable applicability in the scientific process (Agrawal 1995). Yet, oral history and local knowledge provides an important linkage between the concerns, observations, and experiences of rural peoples and the expertise, interests, and scientific curiosity of environmental scientists (Agrawal 1995, Huntington 2000, 2005, Cruikshank 2001, Carmack and Macdonald 2008, Bohensky and Maru 2011, Huntington et al. 2011). It can be challenging to incorporate local knowledge into the scientific process, but this dissertation contains three examples that built upon participatory research to investigate phenomena that were scientifically interesting and relevant to rural peoples, while providing opportunities for cross-team learning between scientists and non-academic local experts.

Because of the collaborative and multidisciplinary nature of this research, disciplinarians may question the cohesiveness of this central thesis. This dissertation examines the integrated hydrologic and societal impacts of a warming climate in Interior Alaska at both small and large scales in winter and in summer conditions, while building upon the knowledge, concerns, and curiosities of local experts and advancing ecohydrological science in northern latitudes. The key findings, conclusions, and implications of the dissertation are discussed below.

5.1. SUMMARY OF KEY FINDINGS

5.1.1. Chapter 2

The consensus among the villagers in Tanana, Alaska was that in recent decades the driftwood harvest had been less reliable than it had been historically. We used personal anecdotes, calendar records of subsistence activities, USGS gauging station data, and numerical modeling to investigate the relationships between flooding, driftwood mobilization, driftwood harvesting, and the temporal and economic costs associated with fuel alternatives. Research results indicated that:

1. The annual peak discharge of the early phase (1977 to 1993) for the USGS Stevens Village gauging station was significantly higher than the late phase (1994-2012).
2. The timing of the June Rise has been more variable in the late phase relative to the early phase, but the timing of the spring break-up flooding has not been different or more variable.
3. Analyses of local knowledge and subsistence calendar records combined with USGS gauging station data support the concept of a driftwood mobilization threshold. The driftwood mobilization threshold was estimated to be approximately 10,000 m^3/s (355,000 ft^3/s) at the Stevens Village gauging station on the Yukon River in Alaska.
4. According the model results, variations in river hydrology lowered the potential driftwood harvest in the late phase, but increased municipal demand has had a much greater impact on the annual wood deficit in Tanana.
5. Prior to installation of municipal wood-fired boilers, 42% of wood demand was met by harvesting mobilized driftwood. With a reduced number of households in the city (100 compared to 113) and increased demand from the village’s wood-fired boilers, the average annual harvest was only 21% of city’s total wood demand.
6. The harvest of standing deadwood requires the least amount of money, but more time relative to driftwood. The use of only fuel oil saves time (10,800 – 18,000 hours annually

for the entire village of Tanana), but requires substantial costs (approximately $533,000). A mix of fuel alternatives balances the required investments in time and money.

5.1.2. Chapter 3

Winter travelers in interior Alaska suggested that the Tanana River had become more dangerous for traveling relative to the past. After being led to areas of hazardous ice, most of the areas were associated with zones of groundwater upwelling. To characterize surface and ground water processes, a selection of these sites were instrumented and monitored over several winters. Field data were used to calibrate a numerical model to estimate the potential melt of river ice by groundwater in shallow sloughs of the Tanana River. The model was also used to evaluate ice melt under cooler and warmer environmental conditions. The field monitoring and modeling results suggest that:

1. The vertical hydraulic conductivity in Hot Cake Slough was 4.0 m/day. The vertical groundwater flow rate averaged 1.1 m/day. Average horizontal groundwater velocities were 0.4 m/day at 1.6 m depth.
2. In the absence of snow at air temperatures less than -12°C, ice thickness increases despite the groundwater heat flux.
3. At snow depths greater than 25 cm, the amount of ice melted by groundwater is independent from oscillations in air temperature.
4. Under field conditions, the calculated ice melt rate had decreasing sensitivity to changes in the groundwater temperature, vertical upwelling rate, water depth, snow depth, and air temperature, respectively.
5. In a cooler climate, the potential rate of ice melt by groundwater was modeled to be 5.2 mm/day, while in a moderate or warming climate the ice melt rates were estimated to be 9.3 or 13.0 mm/day respectively. Under each of these scenarios, it would take 19, 10.7, and 7.9 days (respectively) to melt 10 cm of ice.

5.1.3. Chapter 4

After traveling extensively and mapping hazardous areas on Interior Rivers in Alaska for several years, subtle visual cues were used as indicators of dangerous ice in field environmental conditions. Hazardous areas of the Tanana River between Fairbanks and Nenana, Alaska were mapped using field efforts in spring. Unsupervised classification of high-resolution satellite images was used to identify hazardous ice and open water on the Tanana. The results demonstrated that:

1. The unsupervised iso-cluster classification generated maps that realistically represented on-the-ground field conditions.
2. When mapped by pixel-based efforts, 95% of the river channel was occupied by undegraded snow mapped as “safe” for river travel. Degraded ice covered 4% of the river channel and less than 1% of the channel was open water.
3. Due to differences in the field-based and pixel-based mapping efforts, remotely sensed safe conditions are often found in close proximity to areas mapped as dangerous. In a practical sense, these areas are best avoided.
4. Most of the remote sensing errors were associated with shadowing; however, several approaches were discussed to minimize shadowing errors.

5.2. CONCLUSIONS AND IMPLICATIONS

These dissertation results are applicable to communities throughout the North. Variations in the magnitude and frequency of summer flood events were found to affect people’s ability to harvest driftwood to use as fuelwood; however, increases in demand for wood (through the installation of municipal wood-fired boilers) had a much greater impact on the village’s wood deficit. Yet, people are adaptable. If additional wood is required, they can invest more time in the collection of wood or they can spend more financial resources to purchase alternatives to driftwood. We illustrated how USGS gauging station records can be monitored to help Alaskans determine when a river exceeds its driftwood harvest threshold to predict when mobilized driftwood might be expected to pass by a particular village. The specific flood recurrence interval or lag time after the threshold is reached will vary for each river and / or village along a river. The utility of this type of tool is that it provides some predictability to unpredictable processes and helps rural people to prepare for driftwood harvests. These efforts may not provide advance notification of driftwood flows, but could inform a user whether a driftwood run is likely in the near future.

In northern environments, winter travel on rivers is not only common, but also an important aspect of subsistence lifestyles and recreational activities. Predictable and reliable environmental conditions help maintain an enjoyable quality of life for subsistence peoples. As discussed in chapters 3 and 4, rural Alaskans have observed that winter travel conditions have become more dangerous due to thin or open ice (Herman-Mercer et al. 2011, Jones et al. 2013, Schneider et al. 2013a, 2013c).

Modeling results from chapter 3 present a potential mechanism to explain small-scale changes in travel conditions on the Tanana River and other rivers in interior Alaska. Degrading permafrost in distant recharge areas may allow for enhanced infiltration and greater fluxes in groundwater upwelling areas, which degrades ice from below and generates hazardous ice conditions on river channels. The combination of local knowledge of rural Alaskans and hydrological modeling coupled to climate projections suggest that permafrost degradation, forest fires, and associated increases in groundwater upwelling may elevate the dangers related to winter travel on river ice in areas with discontinuous permafrost. Research results from chapter 3 also show that relatively small changes in upwelling, groundwater temperature, or snow depth could have substantial impacts on ice thickness. Because snow depth can change very quickly, winter travel conditions on river ice can also change very quickly.

In chapter 4, groundwater discharge was shown to have larger scale impacts on river ice between Fairbanks and Nenana. High-resolution satellite imagery was used in conjunction with simple spatial classification systems to evaluate the potential safety of travel on ice-covered water bodies. Due to its relatively simple implementation, its quick analysis time, its low costs, and robustness across satellites and images, these types of products could be provided as an online service by local, state, or federal agencies and may be applicable to industry, transportation authorities, specialized groups (adventure race organizers), field researchers, and other winter river travelers.

This dissertation explored the ecohydrological linkages between hydrology, climate, and people in the North by examining hydrological processes at both small and large scales in both winter and summer. In Alaska, rural and native subsistence users validated the concerns of climate scientists regarding the potential impacts of a rapidly changing Arctic. Based upon this research, I conclude that the participatory research process adds relevance to scientific investigations, can be mutually beneficial for scientists and the subsistence users, and promotes the importance and applicability of science to the general public. In addition, environmental variability is the primary threat to subsistence lifestyles and may serve to accelerate the migration of rural peoples to cash-based economies in city environments. However, regional-scale adaptations and technological development (such as modeling and remote sensing tools) may help to moderate the effects of environmental variability (e.g. flood frequency or magnitude) or unexpected environmental conditions (such as thin or hazardous ice conditions in the winter) driven by climatic or related impacts (e.g. permafrost degradation, increased wildfire frequency, or increased wildfire intensity). These adaptations and technological developments also provide important economic opportunities and increase the adaptive capacity of society to changing social-ecological conditions in the North.

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