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Indigenous Knowledge of Hydrologic Change in the Yukon River Basin: A Case Study of Ruby, Alaska

Nicole J. Wilson,[1] M. Todd Walter[2] and Jon Waterhouse[3]

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ABSTRACT. In the Arctic and Subarctic, the contribution of Indigenous knowledge to understanding environmental change has been established over the last several decades. This paper explores the role of Indigenous knowledge of water in understanding hydrologic change within complex social-ecological systems. Observations of hydrology in the Yukon River Basin, contributed by 20 community experts from Ruby Village, Alaska, in semi-structured interviews, are compared with findings from scientific literature to illustrate the commonalities and differences. Research findings reveal the contribution of Indigenous knowledge to understandings of hydrologic change in the Yukon River and its tributaries, which includes insights regarding alterations in sediment and river ice regimes. Recommendations for future research that incorporates Indigenous knowledge of water to gain insight into hydrologic changes in the watershed include combining multiple case studies that are distributed geographically. Our findings suggest 1) that using participatory research approaches to research will help ensure that it benefits the communities whose livelihoods are affected by hydrologic changes, and 2) that a multidisciplinary approach that combines qualitative and quantitative methods from the social and biophysical sciences would be most effective to help us understand and respond to hydrologic changes.

Key words: climate change; Indigenous knowledge of water; socio-hydrology; river dynamics; water resources

RÉSUMÉ. Dans l'Arctique et la région subarctique, l'apport des connaissances indigènes à l'égard de la compréhension de l'altération de l'environnement a été mis au clair au cours des dernières décennies. Cette communication explore le rôle des connaissances indigènes relativement à l'eau dans la compréhension des changements hydrologiques touchant les systèmes socioécologiques complexes. Les observations hydrologiques dans le bassin du fleuve Yukon, émanant de 20 experts communautaires de Ruby Village, en Alaska et prélevées dans le cadre d'entrevues semi-structurées, sont comparées aux constatations publiées dans des documents scientifiques pour illustrer les points communs et les différences. Les résultats de recherche révèlent l'apport des connaissances indigènes en matière de compréhension des changements hydrologiques caractérisant le fleuve Yukon et ses affluents, ce qui comprend un aperçu de l'altération des sédiments et des régimes de glaces fluviales. Les recommandations de recherches futures faisant appel aux connaissances indigènes de l'eau afin de mieux comprendre les changements hydrologiques du bassin hydrographique préconisent le fait de combiner de nombreuses études de cas géographiquement réparties. Nos constatations suggèrent 1) que le recours à des méthodes de recherche participative aidera à faire en sorte que les collectivités dont le mode de vie est touché par les changements hydrologiques bénéficient des travaux de recherche, et 2) qu'une approche multidisciplinaire dans les domaines des sciences sociales et biophysiques faisant appel à la fois à des méthodes qualitatives et à des méthodes quantitatives s'avérerait plus efficace, et nous aiderait à comprendre les changements hydrologiques puis à y réagir.

Mots clés : changement climatique; connaissances indigènes de l'eau; sociohydrologie; dynamique fluviale; ressources hydriques

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INTRODUCTION

Arctic and Subarctic watersheds are disproportionately affected by climate change (Semali and Kincheloe, 1999; Battiste and Henderson, 2000; Berkes, 2008; Pierotti, 2010). Freshwater ecosystems located in these geographical areas are sensitive to climatic changes because they depend on complex interactions between temperature, precipitation, and permafrost (Huntington et al., 2005). Increasing temperature, variations in precipitation, thawing permafrost, and a deepening of the soil active layer have been observed (Hinzman et al., 2005; Osterkamp, 2007). These changes

[1] Department of Natural Resources, Cornell University, Ithaca, New York 14853, USA; present address: Institute for Resources, Environment and Sustainability, 2220 Main Mall, University of British Columbia, Vancouver, British Columbia V6D 1Z4; n.wilson@alumni.ubc.ca
[2] Department of Biological and Environmental Engineering, Cornell University, Ithaca, New York 14853, USA
[3] Yukon River Inter-Tribal Watershed Council, 725 Christensen Drive, Anchorage, Alaska 99501, USA

are projected to result in alterations to water and sediment chemistry and discharge in upcoming decades (Schuster, 2007).

Little is known about the long-term effects of these changes in Arctic and Subarctic watersheds such as the Yukon River Basin (YRB). Indigenous peoples whose livelihood strategies are closely connected to their local ecology are among the first to observe and formulate responses to these changes (Berkes et al., 1995; Nyong et al., 2007; Turner and Clifton, 2009). In this paper, through a case study of the Koyukon Athabascan village of Ruby, Alaska, in the YRB (Fig. 1), we examine the contribution of Indigenous knowledge of water to understanding the impacts of climate change on the hydrology of Arctic and Subarctic watersheds.

INDIGENOUS KNOWLEDGE OF WATER

The value of Indigenous knowledge for perceiving and responding to changes in water resources has been acknowledged in a number of contexts (Blackstock, 2001; Toussaint et al., 2005; Singh, 2006; Alessa et al., 2008; ICIMOD, 2009; Singh and Singh, 2009; McGregor, 2012). For the purpose of this paper, we define Indigenous knowledge as "a cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes, 2008:7).

The value of local and Indigenous observations to research on climatic variation during the past several decades has been well acknowledged (Magnuson et al., 2000; Krupnik and Jolly, 2002; Nichols et al., 2004; Turner and Clifton, 2009). Given that Indigenous knowledge is passed down through oral history over generations, these observations also provide a long-term record of environmental change that extends well beyond the scale of the scientific record (Cruikshank, 2001; Reidlinger and Berkes, 2001; Krupnik and Jolly, 2002); an example is oral history of the impacts of climatic change on glaciers during the Little Ice Age (Cruikshank, 2001).

Previous studies of Indigenous observations of environmental change provide a precedent for using these observations to study water resources. It has been noted that Arctic climate science is constrained by insufficient scientific understanding of biophysical processes in this region and the limited availability of long-term scientific data that could act as a baseline for measuring change (Reidlinger and Berkes, 2001). However, the value of Indigenous knowledge is not only established through the incompleteness of science, but also driven by the ethical objective to prioritize the research agendas of Indigenous communities (Kassam, 2009). The failure to incorporate the latter perspective can reinforce problematic power inequalities, largely the consequence of historic colonialism (Smith, 1999; Battiste and Henderson, 2000), which influence research so that Indigenous knowledge is made to conform to Western scientific ways of knowing (Nadasdy, 1999, 2005; Cruikshank, 2001). This bias often results in "cherry picking" or prioritizing the elements of Indigenous knowledge that are compatible with a Western scientific worldview (Nadasdy, 1999, 2005) and a failure to consider the Indigenous practices and beliefs that are fundamental aspects of these knowledge systems (Berkes, 2008). For example, hydrologic changes in the YRB are intimately connected to all aspects of Indigenous peoples' subsistence livelihoods and culture (Wilson, 2014a). Therefore, this study is not motivated solely by the value of Indigenous observations of hydrologic changes to science; it also seeks to understand and respond to the impacts of these changes on Indigenous peoples and their livelihoods.

Several bodies of literature inform the analysis of Indigenous knowledge of water. First, the subfield of socio-hydrology, or the science of the interface between people and water, is based on the assumption that social, ecological, and physical sciences are essential to understanding the dynamic interactions within coupled human-hydrologic systems (Sivapalan et al., 2011). In the study of socio-hydrology, it has been asserted that human-hydrologic interactions should be studied using exclusively quantitative social science methods (Sivapalan et al., 2011). However, qualitative research has the potential to provide rich narratives that can contribute to holistic understanding of how people negotiate human-hydrologic interactions. We suggest that the focus solely on quantitative methods is a limitation to the study of socio-hydrology, which would benefit from a mixed-method approach that combines these perspectives. Second, Indigenous knowledge of water has been referred to as "ethnohydrology" (Back, 1981; Gartin et al., 2010). Ethnohydrology "is concerned with the science of hydrology in the broadest sense, to include both the observation and interpretation of phenomena and the application of knowledge so gained to the practical problems of water use and management by ancient peoples" (Back, 1981: 258). Ethnohydrology can be understood as a subset of socio-hydrology that emphasizes the importance of Indigenous knowledge of water. Third, the relationships between people and water occur within coupled social and ecological systems (Gunderson et al., 2006; Olsson et al., 2006). The term "coupled systems" refers to a theoretical perspective that views social and ecological systems as linked within a dynamic, complex, and adaptive system (Gunderson and Holling, 2002; Berkes et al., 2003). The coupled systems literature examines the role of social learning in responding to changes in water within these complex systems (Mostert et al., 2007; Pahl-Wostl et al., 2008). The value of Indigenous knowledge for understanding and responding to change within coupled social and ecological systems has been well established (Berkes and Folke, 1998; Berkes et al., 2003). Therefore, we adopt a coupled systems approach to the study of Indigenous knowledge of water in our case study of Ruby Village in the YRB.

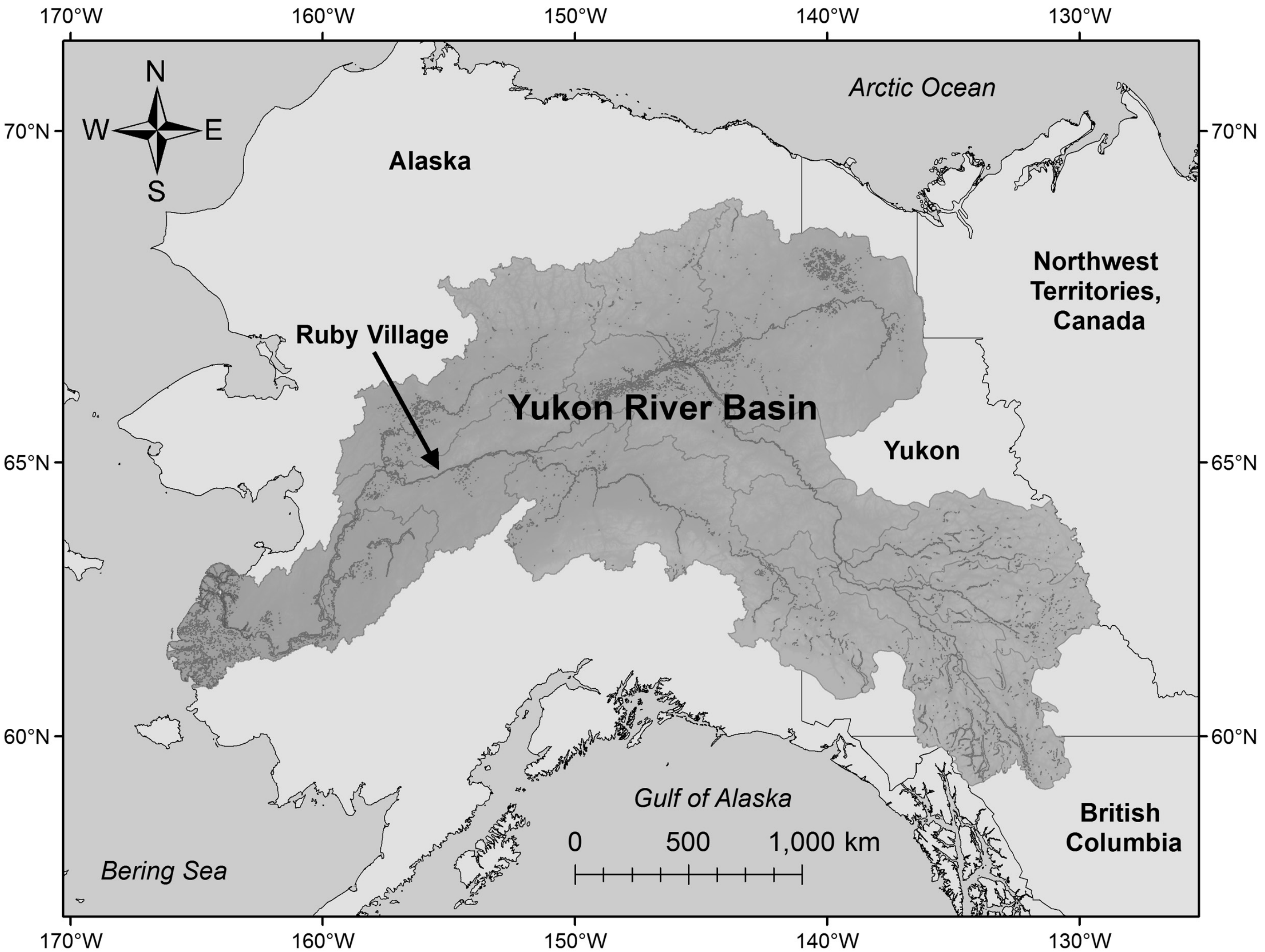

FIG. 1. Map of the Yukon River Basin showing the location of Ruby Village.

CONTEXT

Ruby Village is situated in the middle river region of the Yukon River in the traditional territory of the Koyukon Athabascans (64˚44′22″ N, 155˚29′13″ W). Ruby is located on the south bank of the Yukon River between the villages of Tanana and Galena, adjacent to the Nowitna National Wildlife Refuge. The current population of Ruby is 166 persons, living in 62 households. The residents are 88.6% American Indian or Alaska Native (U.S. Census, 2010).

The Yukon River and its tributaries are defining features of the landscape in the interior of Alaska and are interconnected with all aspects of the lives and livelihoods of its Indigenous residents. This region has plentiful wetlands, streams, lakes and sloughs, open spruce forests, and shrubs that provide habitat for a rich variety of fish and wildlife including salmon, moose, diverse species of migratory waterfowl, beaver and other small mammals, bears, and wolves (YRITWC, 2002). The people of Ruby are actively engaged with their local ecology through subsistence livelihoods; harvesting activities include hunting, trapping, and fishing for a wide variety of species (Sullivan, 1942; Clark, 1974, 1975; VanStone, 1974; Nelson, 1986). The significance of subsistence livelihoods as part of a traditional way of life for Alaska Natives has been well documented (e.g., Nelson, 1986; Thornton, 2001; Andersen et al., 2004; Wolfe, 2004; Wheeler and Thornton, 2005).

Water is connected to all aspects of these subsistence livelihoods—for example, as habitat for fish, an important food source. Villages and towns in the watershed obtain their water for drinking and other domestic uses from the Yukon River, and more often from smaller tributaries of the Yukon River and related aquifers (Wilson, 2014a). The Indigenous people of Ruby are engaged in a multifaceted reciprocal relationship with the Yukon River, in which the river is not only seen as a means to meet their subsistence needs, but also understood to have consciousness and a need to be treated with respect (Nelson, 1986). Yukon, Canada, and Alaska, USA, have been described as a "Republic of Rivers," acknowledging the fundamentality of hydrologic connectivity to social interaction in the region both before European colonization and afterwards (Murray, 1990). For example, river networks were and continue to be an important transportation corridor for the villages that are not located on the road system. Water is used for transportation year round. People travel by boat during the ice-free season and by snowmobile or dog sled when the rivers are frozen. The multifaceted relationship between the people of Ruby and the Yukon River, through long-term engagement and observation, has given them detailed knowledge of the river and its hydrology. In this paper, we examine the contribution of Indigenous knowledge of water to understanding hydrologic change in the YRB and some of the implications of such change for the subsistence livelihoods of the people of Ruby.

METHODS

This study is based on participatory methods (Greenwood and Levin, 2008) and was designed and conducted in partnership with the Ruby Tribal Council (RTC) and the Yukon River Inter-Tribal Watershed Council (YRITWC), a grassroots organization that works with 70 Indigenous governments from Yukon and British Columbia, Canada, and Alaska. All research data and outputs were shared with and validated by the community of Ruby Village, the RTC, and the YRITWC.

Research was conducted during two field seasons (June to October 2010 and July and August 2011). Semi-structured interviews were conducted with 20 community experts, including Elders, subsistence harvesters, and tribal administrators. The community experts were eight women and 12 men, whose ages ranged from 49 to 92. Community experts were recruited using a snowball method: contacts at the RTC and other community members were asked to make a list of the individuals who could contribute to the research (Patton, 2002). Community experts were added to the initial list when referred by individuals who had already participated in the study. All of the community experts were selected because they were considered knowledgeable about subsistence practices and had lived in Ruby for a long time, if not their whole lives. Although the definition of an Elder differs between communities (Stiegelbauer, 1996), for this study Elders were identified by their age—approximately 60 years or older—and the extent to which others considered them knowledgeable and respected community members.

At least three interviews were held with each community expert. During the first interview, they were asked to describe their subsistence livelihoods and any changes in the environment they had observed. To avoid potential influence, they were never asked directly about "climate change." Specific follow-up questions were asked to clarify responses. For example, only after community experts had mentioned that temperatures had increased were they asked about when the largest increases had been observed and how these increases had affected them. Interviews were documented using written field notes rather than audio recordings. The lead author wrote a narrative essay for each community expert based on interview field notes. A typed version of each interview narrative was validated during a second interview, when it was read out loud to the community expert and changes were made to correct data or to add important information that had been left out during the initial interview. During a third visit, a printed version of the final interview narrative was shared with each participant.

Interview narratives were coded for observations of change using Text Analysis Markup System (TAMS) Analyzer, a qualitative data analysis tool. All observations that could be linked to the impact of climate change on hydrology were included. The number of community experts who observed a given phenomenon is also noted in parentheses throughout the remainder of this paper. It is important to note that the use of semi-structured interviews means that community experts were not asked the same questions. The summary of observations should therefore be interpreted with caution, as it is not intended to imply that these numbers have quantitative relevance beyond the context of this paper. The interpretation of this research was shared with the community for validation during a public presentation in Ruby Village in July 2011. Community experts consented to having their names used in this research. Their names are used in the acknowledgement section of this paper as a form of citation and to recognize the contribution their knowledge has made to this research.

RESULTS AND DISCUSSION

The impacts of climate change on water are already being observed in the YRB. Community experts' observations of hydrologic change are analyzed in relation to findings from Western scientific literature on climate change in Arctic and Subarctic freshwater systems in an effort to understand hydrologic change in the YRB (See Table 1).

Hydrometeorological Variability

While one Elder noted that the behaviour of the Yukon River and the weather have always been highly variable (1/20), two other community experts noted that these were now more difficult to predict (2/20). As one Elder stated, these days "we can't predict what the heck [the Yukon River] will do." Observations about the inability to predict change may be linked to increases in hydrometeorological variability. The subfield of hydrometeorology combines meteorology and hydrology to provide insight into the interactions between weather, including temperature and precipitation, and hydrologic cycles (Wiesner, 1970). The study of hydrometeorological variability examines the influence of changes in climate (including human-induced climate change and other sources of variability) on hydrology. For example, the Pacific Decadal Oscillation (PDO) is a climate index that is associated with decadal shifts in climate averages (Salinger, 2005) and stream discharge dynamics (Neal et al., 2002). Unlike oscillating climate behaviour like the

TABLE 1. Observations of hydrologic change by community experts in Ruby Village, Alaska.

Type	Total times mentioned	Increase	Decrease	Earlier	Later	No change
Hydrometeorological variability	3	2				1
Air temperature	20	19				1
Fall	5	5				
Winter	10	10				
Summer	2		2			
Precipitation	15					
Rain	7	6	1			
Snow	8	2	6		2	2
Permafrost	5		5			
River ice breakup	10					
Timing	4					4
Sound	5		5			
Duration	3		3			
River ice freeze-up	15				15	
River ice coverage and thickness	16		16			
River ice crossing	7				7	
Annual hydrograph, and sediments	16					
Fall water level	3		3			
Summer water level	3	3				
Sediments and erosion	5	5				

PDO, human-induced climate change is a significant factor contributing to the loss of hydrologic stationarity (Milly et al., 2008), defined as the inability to predict future events from past trends (Khaliq et al., 2006). The loss of stationarity has significant implications for water management and planning processes (Pahl-Wostl, 2007; Milly et al., 2008). The relatively long record represented by the Elders' observations suggests that the changes in weather and the Yukon River are due in part to long-term climate change.

Air Temperature

All community experts noted a marked increase in temperatures during their lifetimes, with greater increases in recent decades (19/20). They observed that they rarely see temperatures that fall below −45˚C anymore. Some of the largest temperature increases were observed to be occurring during the fall season (5/20). It was noted that winters are generally getting warmer. One participant noted that "it doesn't stay as cold anymore. We have started seeing rain in November. It only stays cold for two weeks at a time." While temperatures are generally understood to be increasing, a number of community experts noted that they thought that the summers were cooler now than in the past (2/20).

Temperature is a major driver of hydrologic change, as it interacts with precipitation, evaporation, and other hydrologic processes to alter water temperature, river ice, and factors such as snowpack and permafrost regimes that can affect annual streamflow (Bates et al., 2008). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) concluded that 11 of the preceding 12 years were the warmest on record since instrumental observation began in 1850, and that the average temperature of the earth had increased by 0.74˚C over the past 100 years. Mean temperature increases demonstrate that Arctic regions of Alaska and western Canada are among the fastest-warming regions in recent decades (ACIA, 2005; Hansen et al., 2006). Larger changes are projected over the next century (ACIA, 2005). The change in mean temperatures in the Arctic is significant for human populations, but extreme temperatures such as those seen during winter warming events have a more significant impact on hydrology (Gilbert and Neuman, 1988). While community experts discussed the general pattern of warming, none noted specific winter warming events.

Precipitation

Many community experts perceived changes in precipitation in the form of rain and snowfall (15/20). While one community expert observed that rainfall was decreasing, leading to an overall drying of the landscape (1/20), others noted an overall increase in rainfall (6/20). The same community experts observed changes in the timing of rainfall, which normally falls in August. Snow arrives later in the fall (2/20), and snowfall has decreased during the fall and winter months (6/20). One Elder commented as follows:

> There seems to be a lot of rain, it is raining off and on, and the snow is unpredictable. Years ago we used to pretty much know how much we would get. The past 15 years we don't know what we will get, and this past winter we didn't get any.

Trends in precipitation are more difficult to observe than temperature trends because of the limitations on measuring snow and rainfall in cold environments (McBean et al., 2005). Instrumental observations for Alaska show an overall increase in precipitation during the last century, with greater increases in the fall and winter (Serreze et al., 2000). However, the overall percentage of annual precipitation in the form of snowfall has decreased (Stone et al., 2002; McBean et al., 2005). Changes in annual snowfall have a significant effect on freshwater ecosystems in the

Arctic, where snowfall is the most important hydrological input (Wrona et al., 2006). Reduced snowfall could have long-term negative effects on the ecology of the YRB. The snowpack and spring freshet are critical to maintaining wetlands. Therefore, reduced snowfall has consequences for regions (like the interior of Alaska) dominated by wetlands, which provide wildlife habitat such as spawning grounds and migratory routes of fish, fowl, and macrofauna (McBean et al., 2005).

Permafrost

Several community experts (5/20) observed that permafrost appeared to be thawing, and some observed that permafrost thaw might be responsible for observed shifts in buildings and changes in the roads around the village. However, other factors such as substandard construction were also thought to contribute to shifting foundations. Further investigation of these observations should be completed to map the present and future impacts of changes in permafrost on Ruby Village and its infrastructure.

The permafrost temperature regime has been cited as a sensitive indicator of decadal to centennial climatic variability (Lachenbruch and Marshall, 1986; Osterkamp, 2005). Recent trends indicate that in the interior of Alaska, south of the Yukon River, permafrost surface temperatures, at a depth of 20 m, warmed by 0.3˚C to 1˚C from 1983 to 2003 (Osterkamp, 2005). The permafrost base thawed at an average rate of 0.04 m per year until 2000, when the thaw rate accelerated to 0.09 m per year (Osterkamp, 2003, 2005). Permafrost thaw contributes to changes in land surface characteristics and drainage systems (Lemke et al., 2007). Subsidence, a process of gradual sinking of the ground's surface, occurs as ice-rich ground thaws and forms thermokarst, or an uneven surface with sinkholes and mounds, and results in dramatic changes in ecosystems, landscape, and infrastructure (Lemke et al., 2007). While a significant portion of the YRB has continuous permafrost, Ruby is located in an area of discontinuous permafrost, and most subsistence harvesting takes place in areas of moderately thick to thin permafrost (Fig. 2). Regions of discontinuous or thin permafrost might be less affected by thawing of permafrost. However, changes in permafrost are significant for the formation and function of wetlands (McBean et al., 2005) throughout the interior of Alaska that are important wildlife habitats.

River Ice Breakup, Freeze-up, Coverage, and Thickness

Community experts observed changes in river ice regimes, including alterations in breakup, freeze-up, and the general characteristic of river ice coverage and thickness (10/20). They noted that breakup seems to be occurring at approximately the same time on the Yukon at Ruby Village (4/20), but two main qualities have changed: the sound of the event (5/20) and its duration (3/20). An Elder from Ruby stated, "There has been a change in spring breakup on the Yukon. It goes out at the same time in May, but the difference is in the ice. The sound it used to make was tremendous and now it doesn't make that noise." Other community experts also noted that breakup is happening faster and does not make the sound that it used to when the ice goes out.

The timing of freeze-up has always been variable. However, most community experts observed that freeze-up is occurring later on the Yukon River and its tributaries and that these rivers are taking longer to freeze solid (15/20). This change is likely due to warmer fall temperatures. They also noted that once the ice begins to freeze, it takes longer than it used to before the rivers are safe to cross either on foot or in a vehicle (typically a snowmobile) (7/20).

The majority of community experts observed decreased ice thickness on the Yukon River and consequently an increase in open leads, or places on the river that remain ice-free throughout the winter (16/20). The snow covers these open leads and makes it dangerous to travel on the frozen river. As another Elder from Ruby observed,

> Warmer weather can make it dangerous out on the river for travel early in the winter. The river melts and then it snows and covers the holes. Now we have to wait until early December to go out on the river to trap, to get wood, or just to cross the river. There is a lot of change in that. You used to be able to cross right after the ice stops. It will be moving along and then it all stops. It used to be two to three days after that you could cross. Now the ice is not that thick. There are more open spots and you have to work to get around them so you can't get over right away. You have to be really careful nowadays. You have to wait until it freezes all the way.

Two community experts noted that snowfall has an influence on ice formation, in that if snow falls on the ice before it has thickened, the ice remains thin because the snow insulates it. The combination of later freeze-up, thinner ice, and more open leads poses serious challenges to subsistence livelihoods, which require the river ice for travel and other activities.

Although lake ice has served as an indicator of environmental change, river ice has rarely been used in this way. This omission is likely due to the complexity of the hydroclimatic factors controlling river-ice processes. A number of recent studies have focused on the impacts of climate-induced change on river ice regimes (Janowicz, 2010; Prowse et al., 2010). Most of these studies pertain to ice-cover dates (freeze-up and breakup) rather than to complex variables such as ice thickness, or ice-jam frequency and severity (Beltaos and Prowse, 2009).

Because breakup and freeze-up are important to human activities, long-term records of these dates been kept in many locations. These records can provide important climatic data but must be interpreted with care because myriad factors, including the occurrence of heavy rains upstream, influence both breakup and freeze-up dates

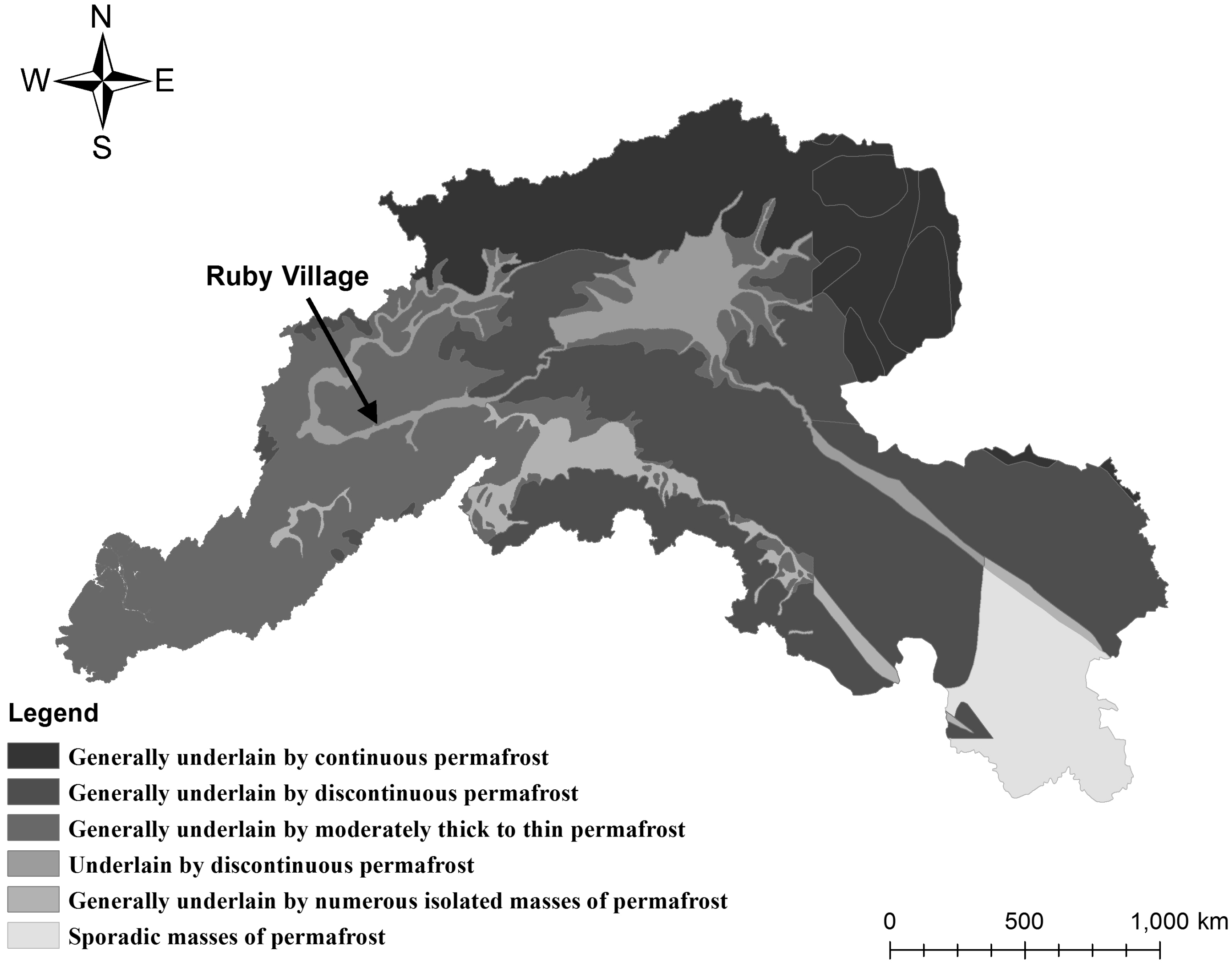

FIG. 2. Map of permafrost characteristics of Alaska. Ruby Village is located in an area of discontinuous permafrost, and the traditional territory of its people is characterized primarily by moderately thick to thin permafrost (Long and Brabets, 2013).

(Lemke et al., 2007). The most comprehensive study of freshwater-ice dates for the Northern Hemisphere indicates that significant changes in river ice have occurred in the last 150 years (Magnuson et al., 2000): freeze-up dates became later by 5.8 days per 100 years, and breakup dates became earlier by 6.5 days per 100 years. The same study found a similarly clear change in interannual variability of river ice dates after 1950. Studies of the Yukon River at Dawson City, Yukon (1898–1998, Jasek, 1998), and the Tanana River at Nenana, Alaska, a major tributary of the Yukon (1917–2000, Sagarin and Micheli, 2001), indicated that while long-term trends were characterized by various interdecadal cycles, breakup dates had advanced approximately five days per century. Our literature review did not find specific studies of freeze-up dates on the Yukon River. Breakup and freeze-up records starting in the early 1900s are available for many locations on the Yukon River from the National Weather Service, Alaska. Ice thickness data are also available for some locations on the Yukon River. While the analysis of thickness data is not within the scope of this paper, we recommend that a comprehensive study of these data be completed in the future.

The timing and severity of breakup and resulting ice-jam flooding depend on many factors, primarily those driven by climate (Prowse and Beltaos, 2002). These factors and processes vary greatly over spatial and temporal scales (Prowse et al., 2007). As a result, these hydroclimatic controls are complex and cannot be understood as a simple observed relationship between air temperature and the timing of breakup (Prowse et al., 2010). Although ice thickness has not been studied so extensively, research shows that there is a general trend towards decreasing ice thickness, which results in more open leads (ACIA, 2004).

It is predicted that the trends observed in breakup, freeze-up, and river ice thickness and coverage will become more pronounced as Arctic and Subarctic regions experience further impacts of climate change (ACIA, 2004). The projected changes in river ice regimes have a number of potential impacts on the physical, biological, and chemical composition of water in the YRB. Changes in the timing of freeze-up and breakup and the severity of breakup can alter the natural hydrologic extremes, including floods and low flows. For example, changes in spring breakup are projected to result in reduced flooding. Changes in the intensity of breakup and associated flooding could alter the formation of river channels and the amount of suspended sediment carried to the ocean (ACIA, 2004). Biological and chemical changes are also predicted. A change in breakup intensity would affect the supply to riparian zones and river deltas, through flood water, of critical organic carbon and nutrients (ACIA, 2004) that support biochemical processes vital to in-stream and riparian ecosystems (Hauer and Lamberti, 2011) that form the habitat of a wide variety of fish and animals.

As mentioned above, research findings highlight the need to investigate changes in two aspects of breakup: its timing and its acoustic dimensions. Community experts perceived that breakup is completed in less time than previously observed and no longer makes the "tremendous sound" that it used to. While the observation that breakup on the Yukon was not "as loud" as it used to be was noted in one other study (Herman-Mercer et al., 2011), these two observations have not been reported elsewhere in the literature and therefore merit further investigation. It is possible that these changes indicate an alteration in the morphology of the river ice at the time of breakup on the Yukon. A change in ice morphology could be due to an increase in thermal breakup prior to mechanical breakup. Thermal breakup takes place when warmer temperatures decay river ice so that it is weaker when mechanical breakup, through the physical force of ice and water rushing downstream, occurs. When thermal breakup is greater, the mechanical breakup event is less intense because the ice fractures into small pieces and no ice jams form (Rundquist, 2009). A change in ice morphology at the time of mechanical breakup arising from increased thermal breakup is one possible explanation for the changes observed in the timing and acoustic qualities of breakup. However, further research on this topic is required to confirm this speculation. While these changes in ice morphology and the acoustic dimensions of breakup were not reported to have specific negative impacts for subsistence livelihoods, these observations provide an example of how Indigenous observations can contribute to the study of complex hydrologic changes.

Annual Hydrograph and Sediments

Sixteen of 20 community experts observed changes in the annual hydrograph and sediments on the Yukon River at Ruby. Several observed higher water levels in summer, when salmon fishing takes place, and lower water levels in fall (August and September), during the moose season. Many community experts observed that the Yukon River is getting shallower in some areas and that sandbars are forming where none existed before (5/20). One Elder described some of the changes observed in the Yukon River over the course of his lifetime:

> The river is flatter and shallower, and sand bars are all over where they never used to be. The river is cutting the banks and some of the native allotments are losing their ground because of it. One of my native allotments has lost 50 feet or so in the past 20 years. There have been a lot of changes in the channels. The water is going odd ways, different ways. It never used to go those ways.

Although the annual hydrograph of the Yukon River (Brabets et al., 2000) and fluvial processes affecting sediment regimes (Gordon et al., 2004) are subject to a degree of natural variability, the observed changes in the annual hydrograph and sediment regimes may be linked to climate change in several ways.

First, changes in the annual hydrograph are revealed through studies of streamflow data. Streamflow trends in the YRB between 1944 and 2005 indicate that winter flows—and, in some cases, April flows—have increased in the Yukon River (Brabets and Walvoord, 2009). Streamflow records covering more than the last 30 years in the YRB also show increased groundwater contributions (Walvoord and Striegl, 2007). Increased winter streamflow is likely a consequence of thawing permafrost (Walvoord and Striegl, 2007). Earlier spring snowmelt, caused by contraction of the cold hydrologic season, generally results in reduced snowpack and contributes to reduced flows in summer and early fall (Brabets and Walvoord, 2009; Déry et al., 2009). Although existing streamflow data contribute to good records of changes in the annual hydrograph in the YRB over several decades, Indigenous observations of change can still contribute to analysis of long-term trends. Furthermore, the manner in which these observations are linked to subsistence livelihood activities such as fishing and hunting also indicate the various ways that alterations in streamflow affect harvesting. For example, community experts noted that when streamflow is particularly high during salmon fishing season it could be dangerous to travel on the river to set and check fishing nets (3/20). At the same time, lower flows in the fall might make it difficult to travel by boat into shallower side channels while hunting for moose (3/20).

Second, multiple interacting factors control erosion and deposition of sediments in rivers; therefore, several factors may be contributing to observed changes in sediments on the Yukon River. The quantity of sediment at any given point in a watershed is affected by both the amount of sediment input through erosion and contributed from upland areas and the capacity of a stream to carry sediments, including either washed-in sediments or material from riverbanks and beds (Gordon et al., 2004). All rivers are geomorphologically dynamic and undergo constant change in stream channels as a result of deposition (sandbars) and erosion (riverbank loss) (Gordon et al., 2004). Permafrost thaw affects surface hydrologic processes with decreased summer and increased winter streamflows, changes in stream water chemistry, and other fluvial geomorphologic processes (McNamara et al., 1998). There is evidence that permafrost thaw may contribute to increased erosion (ACIA, 2005). However, the dynamic nature of high-energy river systems such as the YRB makes it difficult to distinguish climate change from other drivers.

Several community experts observed increases in riverbank erosion (5/20). Similar observations of changes in sandbars and sediments were also found in an Indigenous knowledge study conducted in the lower river region of the Yukon River (Herman-Mercer et al., 2011). While community experts noted changes in sediment regimes, these observations are not necessarily linked to climate change and may be driven by other factors within the complex of fluvial geomorphic processes. Furthermore, despite studies measuring sediment loads on the Yukon River, the limited availability of long-term scientific data makes it difficult to establish what might be occurring (Dornblaser and Striegl, 2009). Additional study of sediment regimes in the YRB is needed to understand the observed variation in sediment regimes. The study of sediment regimes may also be important for understanding the effect of hydrologic change on fish habitat, especially salmon spawning habitats, which are sensitive to sediment loads (Lloyd, 1987; Platts et al., 1989).

Livelihood Impacts of Observed Changes in Hydrology

The people of Ruby are actively engaged with their local ecology through subsistence livelihoods (Sullivan, 1942; Clark, 1974, 1975; Nelson, 1986; McNeeley, 2009). The above-noted observations of hydrologic change are made possible by detailed knowledge of water maintained by the people of Ruby and other Indigenous peoples as they engage with their local ecology (Reidlinger and Berkes, 2001; Kassam, 2009). Research findings indicate that alterations in hydrology have cascading impacts on the livelihood security of the people of Ruby. The above discussion of observations of hydrologic change reveals that climate change is affecting the access people have to subsistence livelihoods, the predictability of weather, and the safety of subsistence activities (Berkes and Jolly, 2001) (Table 2).

While the vulnerability and adaptation of subsistence livelihoods to climate effects in Ruby Village have been explored in detail elsewhere (McNeeley, 2011; McNeeley and Shulski, 2011; Wilson, 2014b), it is important to note that the impacts of climatically induced changes on subsistence livelihoods in Ruby Village are significant. The influence of climatically induced hydrologic changes on subsistence livelihoods highlights the importance of using participatory methods in this kind of study, orienting research toward both furthering scientific knowledge and understanding the complex ways that social-ecological relations are being altered. Knowledge of biophysical processes and their impacts on subsistence livelihoods, such as those documented by this exploratory study, is essential to the formulation of adaptation and mitigation strategies.

CONCLUSION

This exploratory study of Indigenous knowledge of water in Ruby Village indicates that hydrologic changes are occurring in the YRB, including alterations in temperature, precipitation, permafrost, annual hydrograph, river ice, and sediment regimes. While our findings are based on only one case study, they are comparable to those of recent Indigenous knowledge studies conducted in other locations in the YRB (Herman-Mercer et al., 2011; McNeeley, 2011; McNeeley and Shulski, 2011). Many of the observed changes in water resources can be linked to complex processes that are not adequately explained by current hydrologic research.

Research findings highlight three possible topics for future investigations related to Indigenous knowledge of water. First, findings from Ruby Village indicate that while the shift towards earlier breakup due to increasing temperatures is certainly of interest, future studies of river ice breakup should also focus on changes in the speed at which the event occurs and the acoustic qualities of breakup. In particular, these studies should focus on the influence of thermal breakup on river ice morphology at the time of mechanical breakup (Rundquist, 2009). Second, observed changes in sediments and sandbars on the Yukon River remain unexplained because of the current lack of long-term data and the inherent complexity of geomorphologic processes. Changes in sediments can indicate other major hydrologic and ecological alterations in the watershed and may have serious implications for the local ecology. Indigenous observations of changes in sediments in this and other case studies highlight the need for further research.

Indigenous knowledge can contribute to the scientific understanding of hydrologic change in at least three ways. First, it can provide valuable data in the absence of substantive Western scientific observations related to specific areas of hydrologic change. Long-term data on Arctic and Subarctic watersheds are crucial to understanding the impacts of climate change on the hydrology of these river systems. Findings from Ruby Village indicate that in the absence of scientific data on river ice thickness, breakup and freeze-up, and river sediments, Indigenous observations are

TABLE 2. Livelihood impacts of changes in hydrology observed in Ruby Village, Alaska.

Impacts	Definition	Illustrative example
Access	Changes that alter access to important subsistence activities.	Later river ice freeze-up can change time periods in which people have access to certain key areas.
Predictability	Hydrologic changes that influence the ability to predict the weather.	Ability to predict the weather is reduced.
Safety	Changes that reduce the safety of subsistence harvesters.	Increased number of open leads (unfrozen spots) on the river make travel on the river ice dangerous.

important for understanding the changes that are occurring in the YRB. Second, Indigenous knowledge can indicate new areas of inquiry by contributing observations not previously considered by Western scientific studies. For example, observed changes in the acoustic qualities of river ice breakup or sediment regimes can contribute to the generation of new research questions. Third, Indigenous knowledge can be used simultaneously with Western scientific methods of observation in long-term monitoring projects.

Research on Indigenous knowledge of water is also valuable to Indigenous communities. Indigenous knowledge is essential to the formulation of adaptation and mitigation strategies that address the impacts of climate change on Indigenous communities and their livelihoods (Nyong et al., 2007; Turner and Clifton, 2009). Yet this unprecedented global climate change and Northern Hemisphere warming are resulting in change so rapid that Indigenous knowledge alone may not suffice to develop adaptation strategies, and a combination of Indigenous knowledge and Western science may be necessary to understand and adapt to climate change.

Hydrologic changes have cascading ecological impacts that affect subsistence species and their habitat. Since Indigenous peoples are among the most affected by climate change (Adger et al., 2006; Crate and Nuttall, 2009), researchers have an ethical responsibility to structure research so that it can help people develop strategies for mitigating or adapting to the impacts of climate change. A participatory research approach is essential to accomplishing this task because it provides a framework for addressing the power relations between the holders of Indigenous and Western scientific knowledge and facilitates the goal of holding researchers accountable to the communities where they work. Furthermore, the successful formulation and implementation of responses to climate change depend on the participation of Indigenous communities during all phases of research.

Future studies of Indigenous knowledge of water can be improved in at least two ways. First, the present research is limited to one case study. Deeper understandings of hydrologic changes require a watershed-scale perspective. Future studies should incorporate multiple case studies from other locations throughout the same watershed, for example, Yukon First Nation or Alaska Native communities from the headwaters to the mouth of the Yukon River where it drains into the Bering Sea. Second, this study is limited by its reliance on social science methods alone. Future research should be conducted using multidisciplinary research teams that incorporate qualitative and quantitative methods from the social and biophysical sciences in order to identify and investigate observed hydrologic changes more effectively.

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