NNA Track 1 – Collaborative Research: The climate impacts on Alaskan and Yukon rivers, fish, and communities as told through co-produced scenarios

2020 – 2024

National Science Foundation awards 1928189 (University of Colorado) and 1928078 (NCAR)

PROJECT DESCRIPTION

1. INTRODUCTION

Climate change is transforming Arctic hydrology. Rivers that rarely flowed in winter are rising in response to unprecedented winter melt events. Geochemical river loads are increasing as permafrost degrades and groundwater mobilizes (Striegl et al., 2005; Drake et al., 2015; Toohey et al., 2016). Permafrost thaw has broad implications for biogeochemical cycling of carbon (Hugelius et al., 2014); and mercury (Schuster et al., 2018), and is impacting aquatic ecosystems through the release of nutrients (Bowden et al., 2008; Frey and McClelland 2009). However, we have limited observations of these changes or how trends vary across regions. Many indigenous communities rely upon rivers for subsistence fishing and the transportation of fuel and supplies by barge during ice-free seasons and by river-ice roads in winter. Trends toward less reliable winter ice-cover (Sharma et al., 2019) put these communities at risk. Climate warming is also increasing pan-Arctic river temperatures (Park et al., 2017) and altering the physical habit of fish species (Reist et al., 2006). The impacts of this Arctic river transformation on people, their fisheries, and their winter travel corridors remain deeply uncertain.

The goal of this project is to converge Indigenous Knowledge and western science to strengthen collective understanding of terrestrial hydrologic change in the Arctic and the potential impacts on rivers, fish and Indigenous communities. Strong collaboration with Tribal and First Nation communities, community-based science networks, and environmental professionals will guide the science and facilitate monitoring and modeling. We will advance river monitoring networks and promising modeling techniques to assess how climate change will alter groundwater, river hydrology, geochemistry, river ice and temperatures, and fish habitat. Indigenous Knowledge and observations will support numerical modeling of climate change impacts on hydrology and fish biology to co-produce *storylines* of Arctic change. These changes have implications for global water and biogeochemical cycles, fisheries, and Arctic communities.

We will assess climate change impacts on hydrology, rivers, fish, and Indigenous communities in Alaska and upstream western Canada. Proposed specific conductance and temperature measurements of major rivers will innovate the monitoring capacity of Indigenous community-based monitoring networks and the USGS gage network, directly serving Research Focus Area (RFA) #1 of this call. Through ethnographic methods and a proposed Arctic Rivers Summit we will collectively identify vulnerabilities of fish and river ice to climate change. Participatory mapping of fish habitat and river-transport corridors will be used to merge existing spatial information into a common geofabric of Indigenous Knowledge (IK) and Western Science (WS), directly addressing RFA #4. A physically based model chain consisting of the Regional Arctic System Model (RASM) including the Community Terrestrial System Model (CTSM) and a dynamic streamflow routing model (mizuRoute), a river ice and temperature (RIVICE) model, and a fish bioenergetics model (FB4) will be used to assess historical hydrologic conditions and possible climate vulnerabilities of river ice and fish species. The co-development of IK and WS storylines of past and plausible future conditions (Clark et al., 2016) addresses RFA #2. The convergent assessment of physical, ecological, and societal climate vulnerabilities directly addresses three of the five NNA Research Focus Areas.

An exciting collaboration is proposed among the Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado Boulder (CU), the U S Geological Survey (USGS), the National Center for Atmospheric Research (NCAR), the Yukon River Inter-Tribal Watershed Council (YRITWC), the Institute for Tribal Environmental Professionals (ITEP) at North Arizona University (NAU), University of Saskatchewan, and University of Waterloo. The study domain spans a gradient of climate, permafrost extent, ecosystems, and Indigenous communities and cultures in Alaska, Yukon Territory and British Columbia, Canada. The geographic range includes rivers of various fish habitat, climate sensitivity, and states of ongoing and future hydrologic change. The project will support three Indigenous interns at the USGS Alaska Science Center and YRITWC; a Ph.D. student, a postdoctoral associate, and numerous undergraduate researchers at INSTAAR-CU; and one postdoctoral researcher based at NCAR.

2. HYPOTHESES & OBJECTIVES

The overarching research question of this proposal is: *How will societally important fish habitat and river-ice transportation corridors along Arctic rivers be impacted by hydrologic response to climate change including permafrost degradation, transformed groundwater dynamics, shifts in streamflow, and altered river temperatures?*

We hypothesize that:

H.1 Hydrologic response of the Arctic landscape to climate change will present as shifts in precipitation, snow-cover, permafrost, and the groundwater contribution to rivers. The relative and counteracting effects of each change mechanism on the integrated response of Arctic rivers will vary geographically and will depend on the future climate as realized by diverse climate models.

H.2 Hydrologic transformation will alter river temperatures with direct impacts (ranging in effect from positive to negative) on fish habitat of high value to communities and fisheries.

H.3 A convergence of Indigenous narratives, community-based monitoring, and physically-based modeling will permit unprecedented, co-produced climate change impact assessments of the habitat of river-run Arctic fish and the reliability of river ice transportation corridors.

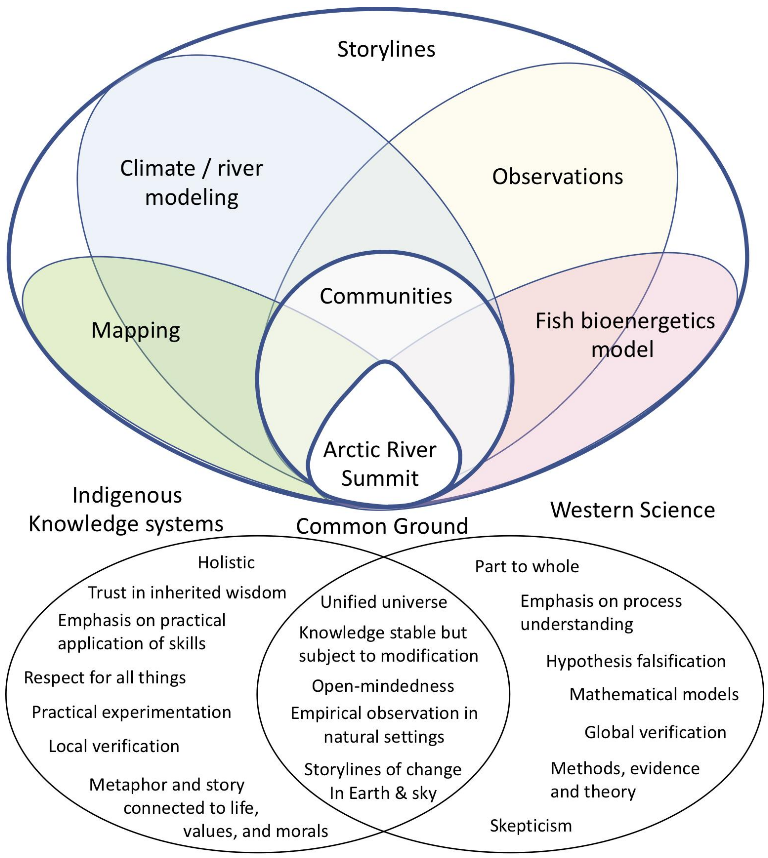

Fig. 1 | Proposed project components, common ground of social and physical systems; indigenous knowledge and western science (modified from Barnhardt and Kawagley, 2005).

These hypotheses will be tested across a climatic gradient of boreal-to-arctic river systems. Using a combination of participatory mapping, community-based observations, and physically based climate, hydrologic, river ice, river temperature, and fish bioenergetics models (Figure 1) we will achieve our overarching goal:

Co-develop descriptive and quantitative narratives, or storylines, of past and plausible future hydroclimatic, river ice, and fish conditions jointly based on Indigenous baseline knowledge and physical principles / western science.

Five key project objectives will be used to complete our goal.

O.1 Expand and enhance river geochemistry and temperature monitoring by the U.S. Geological Survey (USGS) and the community-based Indigenous Observation Network (ION). Use the data to assess variations in the relative groundwater contribution to streamflow, monitor long-term conditions, and validate / calibrate river simulations.

O.2 Conduct a historical (1979-2019) high-resolution reanalysis of weather, snow, permafrost, streamflow, and river ice and temperature, verified against and/or calibrated on a suite of existing and proposed Community-based observations.

O.3 Through engagement (Arctic Rivers Summit), communication (formal community engagement calls), and ethnographic methods, unite Alaska Native and First Nation communities, researchers, and resource managers to coproduce an understanding of river ice and fish habitat vulnerabilities.

O.4 Guided in part by Community input (see O.3), select future climate scenarios as estimated by different climate models, downscale scenarios with a chain of process models, and assess projected changes in the terrestrial hydrology, river temperature, and river ice.

O.5 Guided by Community input (see O.3), select fish species to simulate metabolic conditions using an energy-budget based bioenergetics model. Assess potential changes in metabolic conditions by forcing the model with future projections of climate and simulated river temperatures.

3. SCIENTIFIC CONTEXT & BACKGROUND

The Arctic is rich in freshwater. Large areas of the Arctic are seasonally frozen, snow-covered, underlain by permafrost and/or affected by frozen soils. The seasonal variations in the phase and distribution of Arctic water impart unique physical and biogeochemical signatures on freshwater runoff. People and ecosystems structure on this seasonal cycle. For example, many communities off the road system in Alaska and Canada rely on river ice both for subsistence fishing and for vehicular transport. In recent years, river ice has been slow to form and disturbed by mid-winter flow events (Hori et al., 2018), isolating communities and posing risks to travel, fishery access, and hunting grounds with unknown socioeconomic impacts. Safety issues have been raised by hunters and fishers in interior Alaska regarding the rapidly changing weather, water levels, and landscape (Loring et al. 2011). As an example, the drowning rate in rural Alaska has been as high as ten-times the national average, with the highest rates attributed to Alaska Native males ages 30 to 39 – the group most likely to be hunting and fishing (Lincoln et al., 1996).

When mobilized by spring and summer melt, runoff in arctic and boreal regions feeds some of Earth's largest rivers, supports fish species of great value to northern communities and commercial ventures, and permits river passage by barge and boat. Rapid warming of the Arctic climate (Hinzman et al., 2005) is transforming this unique and sensitive natural (Liljedahl et al., 2016; Walvoord and Kurylyk, 2016), built (Hjort et al. 2018), and social (Ford et al. 2015; Herman-Mercer et al., 2016) environment. The changes are increasing the groundwater contribution to rivers and transforming the water cycle with deep connections among climate, land, water, fish, and communities. Groundwater inflows greatly modify river temperatures (Bolduc et al., 2018) and provide fish habitat and passage. As groundwater contributions to rivers change, so do river ice and fish habitat.

Groundwater changes have been especially pronounced in the boreal Yukon River basin of interior Alaska, which may serve as a regional indicator of future Pan-Arctic response to climate change. Here, river mineral and nutrient loads have significantly increased over the last 30 yrs., coincident with increasing river baseflow (Striegl et al., 2005; Walvoord and Striegl, 2007; Toohey et al., 2016) despite negligible changes in annual river discharge or precipitation. The changes are explained by weathering of minerals previously locked in permafrost and made increasingly accessible as permafrost degrades, exposing new subsurface flow pathways and altering groundwater residence time (Lamontagne-Hallé et al., 2018). *As groundwater and rivers transform, the ultimate impacts on fish survival (Carey and Zimmerman, 2014) and the reliability of winter river transport corridors (Loring et al. 2011) are unknown. There is great need to assess future possibilities for river travel, arctic fish species, fisheries, and Indigenous communities*.

Water temperature exerts a critical influence on water chemistry, aquatic metabolism, river ice, and anadromous fish. For example, water and air temperatures are first-order controls on the formation and break-up of river ice and fish behaviorally select water temperatures that are optimal for life. Thus, energy- and mass-budget approaches are regularly used to simulate both river ice and fish. Fish bioenergetics models have long been used to quantify energy allocation by partitioning consumed energy into metabolism, wastes, and growth (Winberg, 1956; Kitchell et al., 1977). River ice models simulate the thermal energy exchange between the water and air to represent the physics of ice generation, transport, progression, and jamming (Lindenschmidt, 2017). While the models provide robust frameworks to test hypotheses about climate change impacts on rivers and fish (Carey and Zimmerman, 2014), they have not been combined in a top-down model chain that links high-resolution (<5 km grid spacing) climate and weather model output with simulations of hydraulic river conditions, ice formation, and fish bioenergetics.

Climate change will affect Arctic rivers through a cascade of compounding and counteracting climatic, hydrologic and ecologic effects, which have challenged previous efforts to assess climate change impacts on northern fish populations (Reist et al., 2006). The complex system dynamics and unusually high uncertainty limits use of probabilistic methods in which multiple models (i.e., climate model ensembles) are used to quantify future change. For example, probabilistic averages can dampen responses, fail to correspond to any model simulation, and can lack physical consistency. Further, equally weighting all model projections may be suboptimal (Eyring et al., 2019). Instead, we propose to develop descriptive narratives, or *storylines*, of past and plausible future conditions and events. This emerging approach to climate impact assessment and adaptation strategy (Shepard et al., 2018) offers a powerful way to link processes with ecologic and human aspects of climate change.

Climate change literature is replete with references to narratives and scenarios. Narratives are often used in social science to characterize peoples' views or understandings. Scenarios are most associated with science-based socioeconomic pathways and resulting climate futures (Shepard et al., 2018). We will merge the definitions of social narratives and physically-based scenarios by developing *storylines* based jointly on Indigenous Knowledge and Western Science. Understanding of climate change is generally either semantic (fact-based) or episodic (experiential and event-based). Typically, semantic knowledge is held by climate scientists while the public is more likely to have episodic knowledge, e.g., memory of an impactful storm or drought event. Indigenous Knowledge is unique because it encompasses **both** episodic knowledge (i.e., past stories and qualitative observations) and semantic knowledge (i.e., quantitative observations of climate change impacts; Herman-Mercer et al., 2018). Thus, Indigenous communities hold powerful knowledge and ability to: 1) Meaningfully contribute to qualitative and quantitative storylines of Arctic change; 2) Comprehend the storylines in the context of impact to nature, livelihood and culture; and 3) Use the storylines to guide adaptation strategies and preparedness.

Indigenous observers are often the best source of baseline information in data poor regions like the arctic (Danielsen et al., 2014). We propose to leverage and supplement existing federal and community-based observations of river hydrology with high-resolution, physically based climate and hydrologic modeling, a river ice and temperature model, and a fish bioenergetics model. The *storylines* approach will merge advanced climate modeling with western and Indigenous scientific observations and knowledge to assess how permafrost, groundwater, and river conditions may respond to future climate scenarios, and how the changes may impact local and regional fisheries, river ice, and communities. The proposed project will be overseen by a Native Advisory Council to foster inclusive, respectful, and transparent coproduction of knowledge by Indigenous Peoples and western researchers.

Together, we will address several convergent social and scientific challenges in the arctic including climate change impacts on freshwater and groundwater transformation, the sustainability of arctic fish populations, the reliability of winter river ice travel, and the integrated impacts on communities dependent upon the land and its resources. The proposed project – characterized by open-data and meaningful community participation – will transform knowledge of interdependent baseline conditions informed by western and indigenous observations as well as changes in climatological, geophysical, geochemical, hydrological, biological, ecological, and social processes occurring in the Arctic.

4. STUDY DOMAIN

The study will be focused on a 1.25 million km^2 region of interior and northern Alaska and western Canada (Fig. 2). Rivers in the northern part of the domain drain north to the Arctic Ocean, while the southern portion of the domain includes the Yukon River, which flows east-west to the Bering Sea and is the fourth-largest river in North America. Glaciers in some headwater basins comprise a small percentage of total land area and annual streamflow, but contribute substantially to local river reaches. Permafrost is found beneath ~90% of the domain; it is thickest and most extensive in the north and thinner and more discontinuous in the south. Vegetation varies from tundra with short grasses and shrubs in the northern Arctic region to spruce forests in the southern boreal region.

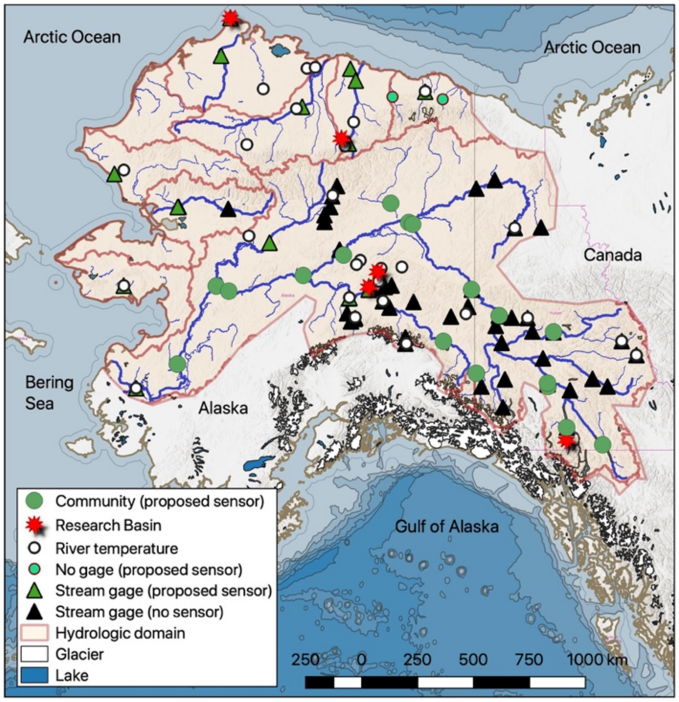

Fig. 2 | Hydrologic domain, infrastructure, and proposed sensor locations (green markers).

5. METHODS

We will assess climate change impacts on hydrology, river ice, fish, and Indigenous communities in Alaska and upstream western Canada using co-developed climate change storylines. This will be accomplished using co-led observation networks to validate and inform a chain of physically based models. Proposed specific conductance and temperature sensors deployed in main-stem rivers will innovate the observation capacity of Indigenous community-based monitoring networks and the USGS. An Arctic River Summit, ethnographic methods, and frequent community engagement calls will unite researchers and Indigenous community members to collectively identify climate vulnerabilities of rivers and fish. Finally, a chain of climate, hydrologic, river ice and temperature, and fish bioenergetics models will permit an unprecedented climate change impact assessment of the physical habitat of river-run Arctic fish and the reliability of river ice transportation corridors. In this section, our proposed methods are described.

5.1. Coproduce knowledge of river ice and fish habitat vulnerabilities

Knowledge of river ice, fish biology and habitat and the associated climate vulnerabilities will be co-produced by Indigenous experts and western researchers through continual engagement following both the *Principles for Conducting Research in the Arctic* (IARPC, 2018) and the *Guidelines for Considering Traditional Knowledges in Climate Change Initiatives* (Chief et al., 2015) produced by Indigenous persons and traditional knowledge experts. Further, our efforts are founded on an Indigenous Research Paradigm, which holds that research should be conducted *in partnership* through a knowledge coproduction process designed to respond to the needs of, and benefit Indigenous peoples (Wilson, 2009) as opposed to research done *on* Indigenous peoples. NSF defines knowledge coproduction as, “Research in which local and Indigenous people and organizations fully engage in the complete research process from the development of questions, to the collection, use and stewardship of data, and interpretation and application of results” (NSF, NNA 2018). Close community partnership is essential (Pearce, 2009) to conduct ethical research and to ensure meaningful outcomes (Kofinas, et al., 2016). Our research questions and proposed methods have been developed with Indigenous organizations (YRITWC, ITEP) with unique expertise and long histories of Indigenous community engagement. Research methods and questions will be further refined and revisited throughout the project through engagement and oversight by Indigenous communities, governments, and stakeholders as described in the subsections that follow.

5.1.1 Community Engagement & Oversight

Engagement calls with communities and interested parties will be hosted and facilitated by ITEP on a semi-annual basis in project years 1 and 2, ramping up to a quarterly basis in project years 3-5. The calls will provide a dialogue forum for Indigenous Peoples and researchers. In project Years 1 and 2, engagement calls will focus on introducing the project to communities and other stakeholders, exchanging the state of knowledge on Arctic rivers, listening to community concerns, allowing for input into research questions, building interest in the Arctic Rivers Summit (5.3.2), and soliciting feedback on Project goals and preliminary results. The calls will be used to educate researchers and Indigenous community members about protection of IK, Free, Prior, and Informed Consent (FPIC), potential risks in sharing IK, and data sharing agreements. After the Summit, quarterly calls will provide an opportunity for input on ethnographic methods (see section 5.3.3) and precursory information to guide the Storylines (see Section 5.2). The calls will allow the researchers to share newly processed data, and receive guidance on preferred data content and formatting methods.

A Native Advisory Council (hereafter Council) formed in project year 1 will provide oversight and feedback on the progress of the project. Representatives from Tribal and First Nation organizations within the study domain will be invited to join the Council including, but not limited to, the Alaska Native Regional Corporations, the Tanana Chiefs Conference, the Inuit Circumpolar Council, Council of Yukon First Nations, Association of Village Council Presidents, Alaska Federation of Natives, and Council of Athabascan Tribal Governments. The Council will meet by phone or teleconference on a semi-annual basis and will provide more formal and in-depth input and oversight of project objectives and research directions than might be possible during the quarterly engagement calls.

5.1.2 Arctic Rivers Summit

An Arctic Rivers Summit is proposed to bring together Tribal and First Nation resource managers, Arctic and Boreal community members, and academic, federal, state, and provincial researchers. Key areas for Summit discussion and activities will be co-identified through Community engagement calls and direction from the Council and may include: river ice, permafrost thaw, freezing temperatures, snowfall and rainfall patterns, fish biology and habitat of species relevant to subsistence and commercial fishing. The Summit will be held in Anchorage, AK, in winter of project Year 3 with the objective of unifying the state of knowledge on Arctic Rivers as a community of observers, investigators, knowledge holders, and stewards. The Summit will include targeted activities to: 1) facilitate discussions on the current state of knowledge of Arctic Rivers from western and Indigenous science perspectives; 2) identify important areas of concern with respect to Indigenous livelihoods, river transportation, and fish species shifts and survival; 3) identify key data and research gaps; and 4) brainstorm and exchange information on solutions for communities and species to survive while Navigating a New Arctic.

Targeted activities will include a combination of large group presentations, large and small group discussions, and activities designed to foster the sharing of information and ideas. Preliminary sensor data and modeling results and plans will be presented and discussed.

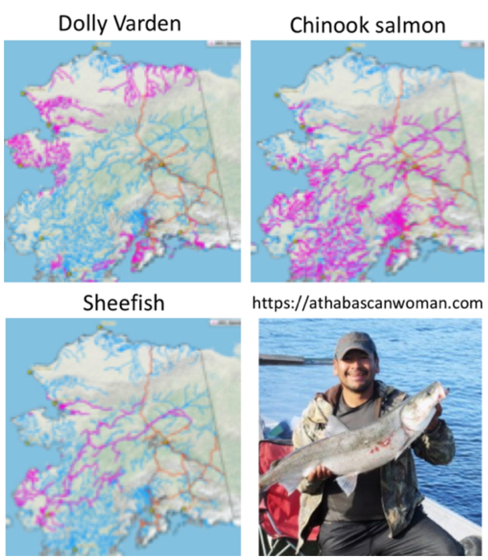

Fig. 3 | Fish resource monitor maps from the Alaska Department of Fish and Game.

Indigenous participants including environmental professionals, community members, Tribal and First Nation government representatives, youth, and elders are vital to the success of the Summit. In this spirit, members of Alaska Native Villages and First Nation Communities will be invited to apply for a scholarship to support travel and lodging to attend the Summit. Forty-two scholarships will be supported by the project and invitations to apply will be extended through engagement calls, various Tribal and First Nation targeted listservs, and word of mouth. Applicant selection by YRITWC and ITEP will consider equitable representation of gender, age, Arctic and Boreal regions, and perspective. Prior to the meeting, data management and transparency agreements between Indigenous participants, researchers, and managers will be obtained. An IRB review of the project by CU Boulder will occur. The results of the Summit will be disseminated through a white paper, fact sheets, presentations during quarterly engagement calls, through ITEP's monthly newsletter, and through short videos featuring Summit attendees who wish to participate. The videos may cover a variety of topics including how climate change affects the participant and how they/their communities are adapting.

5.1.3 Codeveloped Storylines for Arctic Rivers, Fish, and Communities

We will co-develop descriptive and quantitative narratives, or *storylines*, of past and plausible future hydroclimatic, permafrost, river ice, and fish conditions based jointly on Indigenous baseline knowledge and physical principles / western science. Scientific guidance predicts a future climate fundamentally different from the past. Even those who are aware of the science have difficulty prioritizing actions due to the unfamiliarity of that future (Weber, 2006). Jointly constructed Indigenous and scientific storylines will be a novel and complementary approach to raise global risk awareness, by incorporating experiential information to make the predicted future more tangible with regard to potential impacts (Matthews et al., 2016; Shepard et al., 2018). Through ethnographic methods (see Section 5.5) we will document traditional and experiential accounts of impactful historical events, seasons, or years, in the context of climate impacts on Arctic river, fish, and communities. For example, expert Fisher and Hunter accounts may describe seasonal or annual abnormalities in climate, fish, or river ice and what impacts the events have on the Experts and/or Communities. Elders may choose to share Traditional stories with strong relevance to the climate and natural world. This information will be dovetailed with community-based and federal research observations (Section 5.3) and historical model reanalysis (Section 5.4) to form robust storylines of historical events and associated impacts.

We will use RASM to create an ensemble of downscaled future climate scenarios using a robust subset of climate model simulations from the Coupled Model Intercomparison Project Phase 6 (CMPI6; Eyring et al., 2016). Output from the ensemble of RASM future climate scenarios will be propagated down the chain of models to produce diverse, domain-wide estimates of future hydrologic conditions including precipitation, snowfall, soil ice, groundwater, streamflow, river ice, stream temperature, and the vulnerabilities and possibilities of different fish species and populations. These elements of future conditions will be appended to the storylines of historical change guided by Indigenous knowledge, measurements and historical model reanalysis. Finally, we will map historical events and Traditional storylines onto model-projected future climate conditions. Such ‘simulated experience’ is likely to be more effective at conveying impact and adaptation possibilities than statistical characterizations (Shepard et al., 2018). The storylines will allow Indigenous Knowledge of climate change to be set within the context of western science, with tremendous mutual benefits. The deliverable forms of the storylines will be determined in the coproduction process and could vary from fact sheets, maps, white papers, and scientific publications and will include descriptive and quantitative historical conditions and multiple future projections each with associated Community impacts. Thus, we will co-develop descriptive and quantitative narratives of past and plausible future hydroclimatic, river ice, fish conditions, and societal impacts based jointly on Indigenous baseline knowledge and physical principles / western science.

5.3. Expand & Enhance River Monitoring

5.3.1. Continuous Specific Conductance and Temperature

Continuous monitoring of river specific conductance (SC) and temperature will allow us to monitor changes related to warming and increased groundwater-surface water interactions. Specific conductance of river water correlates strongly to the total dissolved ion load of water and has been increasing in major Alaskan rivers on decadal timescales related to increased input of groundwater to rivers as permafrost thaws (Toohey et al., 2016). Seasonal variations in SC correlate with the spring freshet, thawing of the active layer, and the transition from flow in shallow organic soils to deeper mineral soils (Petrone et al., 2007; Koch et al., 2014). SC and major ions have been used to discern the contribution of runoff and stored water during individual storms in arctic (McNamara et al., 1997) and boreal (Koch et al., 2014) basins. Annually, maximum SC occurs in dry conditions in late summer or winter, when streams are most strongly influenced by groundwater (McNamara et al., 1997; Maclean et al., 1999; Koch et al., 2013; 2014). Thus, SC can be used to develop end-member mixing models on annual to decadal timescales, permitting the estimation of the proportion of river water derived from groundwater and terrestrial water input (Fig. 3).

New instrumentation is proposed to enhance existing USGS gages and to advance and support ION, a community-based water-quality monitoring project collaboratively facilitated by the USGS and the YRITWC (subcontract). Forty new In-Situ Aqua TROLL® 100 sensors will be installed on main-stem rivers to permit continuous (15 minute) measurements of SC and water temperature. The YRITWC staff will deploy 20 sensors in Indigenous communities participating in ION in Alaska and Yukon Territory (Fig. 2). The USGS and CU students will deploy and maintain another 20 sensors at USGS gage and research sites (Fig. 2; see Letter of Commitment (LoC), USGS AK Water Office Chief). Independent measurements of SC will be made during site visits to calibrate the sensors. The sensors will be deployed during the ice-free season and retracted before ice-up for each year of the five-year study, giving an unprecedented continuous perspective of river hydrology across Alaska. End-member models from SC measurements will 1) characterize surface- and ground-water connections and 2) provide a calibration target for hydrologic simulations. The water temperature data will augment existing sensors (Fig. 2) to validate the river ice model and inform the fish bioenergetics model. The proposed sensors mirror the USGS Next Generation Water Observing System (NGWOS) pilot study, Delaware River basin (Dillow et al., 2018).

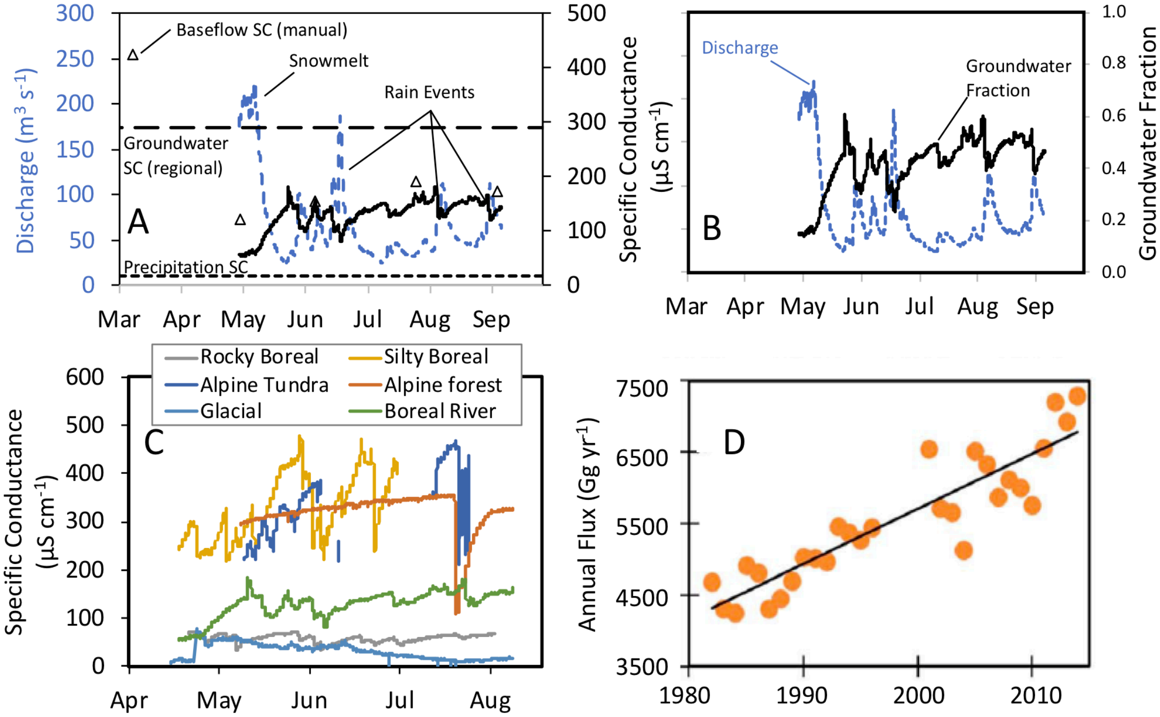

Fig. 4 | A) Seasonal changes in SC of a boreal river can be related to hydrologic events, including winter baseflow (maximum EC), early summer snowmelt (minimum SC), mid-season rainfall (SC dilution and recovery), and mid-summer dry periods (rising SC). River SC varies inversely to discharge, because low-SC precipitation dilutes the river's baseflow, which is primarily composed of high-SC groundwater. B) SC data can be used to create a two end-member mixing model based on regional average precipitation and groundwater signatures (horizontal dashed lines). C) SC trends vary in Alaskan rivers due to differences in climate, soil texture and ice (permafrost and glaciers). D) SC is primarily controlled by dissolved ions in river water, and so will also respond to decadal-scale increases in solute-rich groundwater upwelling related to permafrost thaw (Toohey et al., 2016).

5.3.2. Streamflow

River discharge is measured at approximately 40 locations across the domain (Fig. 2). Data from these stations date to as early as the 1950s and are publicly available from the USGS and the Water Survey of Canada. Historical streamflow data (1979-2019) will be used to calibrate and validate model reanalysis of weather and hydrology. Streamflow data will also be used to validate SC-based hydrograph separations.

5.3.3. Permafrost, Meteorological and Snow Observations

We will use comprehensive near-surface permafrost and active layer data from hundreds of monitoring stations in Alaska (Wang et al., 2018). The dataset includes collections by the USGS, the National Park Service, and the University of Alaska - Fairbanks permafrost monitoring networks and is freely available. An additional dataset co-produced by the USGS, the YRITWC, and Yukon River communities includes gridded manual measurements of active layer thickness and automated measurements of air temperature, soil moisture and soil temperature (Herman-Mercer et al., 2017). The data will be used to validate historical land surface model simulations. Hourly and daily summary observations of meteorology including air temperature, relative humidity, precipitation, wind speed, snow depth, and snow water equivalent are available from diverse, publicly available networks across Alaska and Yukon Territory. The data will be used to verify historical climate model reanalysis, both at the point-scale and against gridded ensemble-based interpolations currently in development at NCAR (Collaboration PI Newman) to expand upon existing products across the U.S. (Newman et al., 2015, 2019). Additionally, five major research basins are located within the study domain (Fig. 2). This includes four Long-Term Ecological Research

(LTER) sites: Bonanza Creek, Caribou-Poker Creek Research Watershed, Arctic, and the Beaufort Lagoon Ecosystem. Additionally, the Wolf Creek Research Basin located near Whitehorse, Yukon Territory is managed by Global Water Futures and the University of Saskatchewan (LoC; GWF).

5.4. Physically based model systems

We propose to build upon the recent success of high-resolution (4 km) Weather Research and Forecasting (WRF) model runs over Alaska and western Canada conducted at NCAR by Collaboration PI Newman and colleagues (Monaghan et al., 2018). The domain-wide WRF runs better simulate snowpack than an offline model forced with local meteorological observations (Fig 4). We propose to use the Regional Arctic System Model (RASM) at unprecedented high-resolution and regional configuration to drive a chain of physically based hydrology, river ice, stream temperature, and fish bioenergetics models. This will be done for both a historical reanalysis and an ensemble of future climate scenarios.

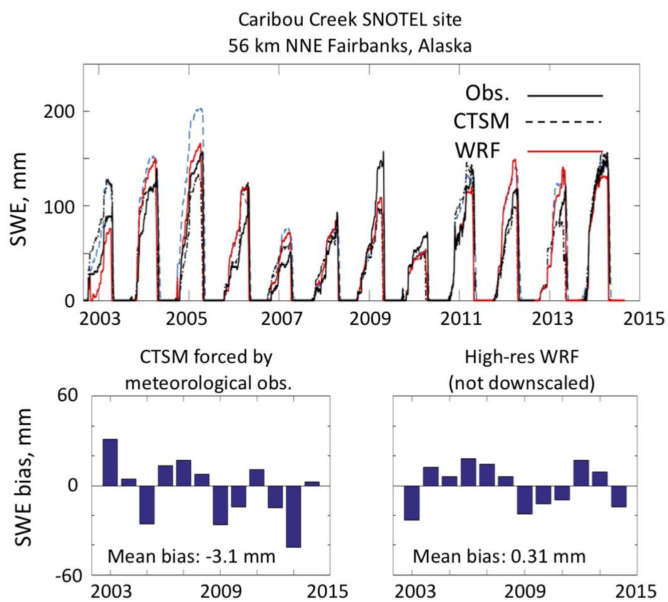

Fig. 5 | Snow water equivalent (SWE) measured at a SNOTEL site and annual biases from CTSM forced by station data and WRF at 4 km resolution. Musselman and Clark (unpublished).

5.4.1. Regional Arctic System Model

The Regional Arctic System Model (RASM) is a fully-coupled regional Earth system model (ESM), developed with support from the US Department of Energy, the US Department of Defense, and the National Science Foundation. RASM's development was motivated by the need to improve multi-decadal simulations of high-latitude climate and to advance understanding of the coupled interactions between systems and processes within the Arctic climate system. When applied over the pan-Arctic domain in fully-coupled mode, RASM combines the WRF atmospheric model (Cassano et al., 2017), the Variable Infiltration Capacity (VIC) hydrology model (Hamman et al., 2016), the RVIC streamflow routing model (Hamman et al., 2017), the Parallel Ocean Program (POP) model (Smith et al., 2010), and the Los Alamos Sea Ice (CICE) model (Roberts et al., 2015) using Community Earth System Model (CESM) coupling (CPL7; Craig et al., 2012).

Although RASM is most-commonly applied over the pan-Arctic, alternative model configurations and spatial domains are possible. We propose to modify the model configuration to improve detailed representation of terrestrial rivers necessary to assess fish habitat. Namely, RASM will be configured for a regional, high-resolution domain. A grid spacing of 4 km is chosen based on previous regional climate studies in complex terrain (Ikeda et al. 2010; Liu et al. 2017; Monaghan et al. 2018). This resolution gives optimal simulation of convection (Prein et al. 2017), mountain snowpack (Musselman et al., 2017), and rain-on-snow dynamics (Musselman et al., 2018) while remaining computationally tractable. We will modify the typical RASM coupling configuration (Fig. 5) by replacing the VIC land surface model and the RVIC streamflow routing model with the Community Terrestrial Systems Model (CTSM) and the mizuRoute routing model, respectively. Both CTSM and mizuRoute are next-generation community models currently in use and development at NCAR within CESM. The coupling will improve RASM capacity to simulate global permafrost and serve to advance the RASM model infrastructure (see LoC Wieslaw). Prescribed sea-surface temperatures and sea-ice cover from GCM model output will be used to focus on land-atmosphere processes and terrestrial hydrology. We will iteratively configure and test RASM loosely following recent high-resolution WRF simulations in this domain (Monaghan et al., 2018).

<u>HISTORICAL CLIMATE REANALYSIS</u> – Historical (1979-2019) reanalysis will be run over the domain (Fig. 5b) forced by ERA5 global reanalysis. Reanalysis will form a critical baseline against which to evaluate future climate scenarios and to assess historical trends and patterns. Simulations will be verified in detail using all available observational datasets. Bias correction may be applied to RASM output using

processes to identify if bias correction is necessary and the appropriate correction methods (Ehret et al. 2012; Maraun et al. 2016).

FUTURE CLIMATE SIMULATIONS – With the goal of developing a set of quantitative storylines representing multiple, equally feasible Arctic hydrologic futures, we will select four climate model simulations from CMIP6. One option is to select GCMs that cover a range of possible future climates: e.g., warm/wet; warm/dry; cool/wet; cool/dry, as each scenario will have diverse impacts on the downstream model chain and associated impacts. The ultimate selection of models, emissions scenarios, and future time horizons will be based on a combination of factors including: input from Indigenous Community members (see Brinkman et al. 2016) in a discussion facilitated by NCAR climate model experts (our collaborators) and co-PI Herman-Mercer at the Arctic River Summit, and these experts' consideration of model climate sensitivity, fidelity, and diversity (Rupp et al. 2013).

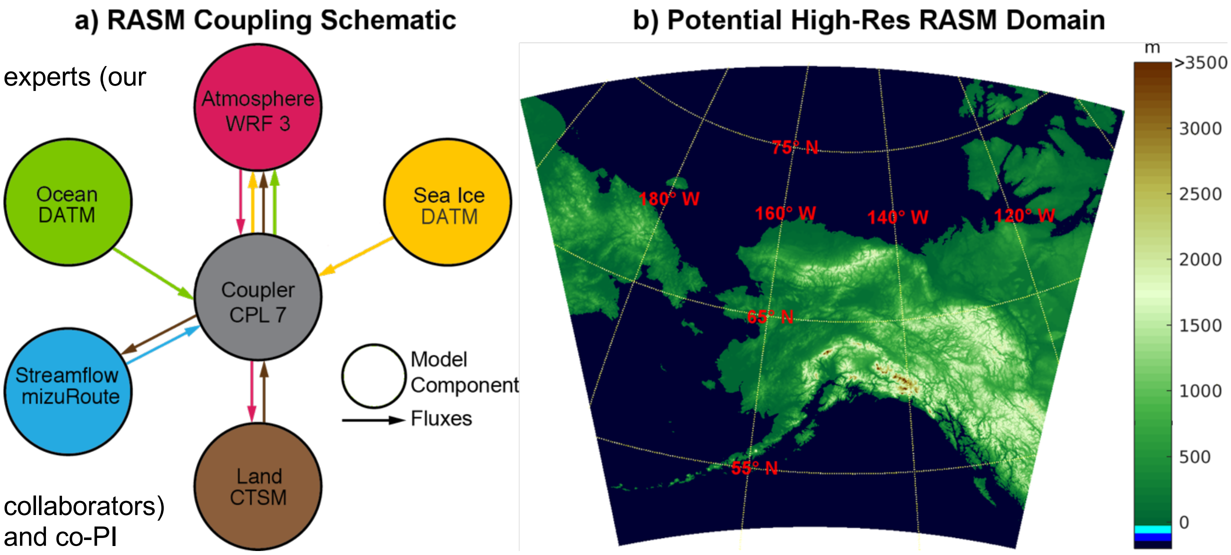

Fig. 6 | a) RASM coupling schematic where arrows indicate flux interactions, with ocean SSTs and sea ice coverage prescribed as a specified data model (DATM). b) Potential 4-km grid spacing domain topography with resolved elevations up to 4900 m around Mt. Denali.

5.4.2. Community Terrestrial Systems Model

The Community Terrestrial Systems Model (CTSM) is a unified land model for simulating climate, weather, hydrology, and ecology. The CTSM project is a recent extension of the Community Land Model (CLM) version 5.0 with development focusing on improving model structure, modularity, and tools and datasets for regional applications. Examples of initiatives under the CTSM banner include improving the flexibility of CTSM to be coupled to regional atmosphere models and regional and irregular spatial configurations. CLM 5.0 is the current model version used in CESM 2.0 and has undergone comprehensive validation (Lawrence et al, In review). CLM has been extensively used to study high-latitude terrestrial processes including permafrost, streamflow, snow cover, and the carbon cycle.

Under the proposed work, CTSM will be coupled to RASM as the land surface component. New soil and vegetation parameters will be developed to support the model's application in the smaller high-resolution model domain. We will leverage large-domain parameter estimation methodologies developed at NCAR (Mizukami et al. 2017) that are undergoing further domain specific refinement via Collaboration PI Newman. Key to our application of CTSM will be the use of optional model features for simulating hydrologic processes including representative hillslope hydrology and sub-grid glaciers. Representative hillslopes may improve simulations of discontinuous permafrost and river-groundwater exchange.

5.4.3. MizuRoute Streamflow Routing Model

Runoff simulated by CTSM will be routed to streams and river networks with the mizuRoute model (Mizukami et al., 2016). The model was developed at NCAR to enable continental-scale evaluation of water resource assessments including the impacts of climate change on streamflow. MizuRoute will be fully coupled with CTSM in 2019 as part of an ongoing NASA project. We propose to use MizuRoute for two reasons: 1) parallelized code facilitates large ensembles of multi-decadal runoff, and 2) the required parameters are similar to those required by the river ice model (see Section 5.2.4). Runoff is routed to rivers in two steps. First, runoff is routed from each hillslope to river channels. This allows for the representation of ephemeral or small channels. Second, channel routing delays and passes flow from grid cells to river network segments. Thus, streamflow estimates at any river location can be extracted.

For hillslope routing, a two-parameter Gamma distribution (i.e., unit-hydrograph) is used to route runoff from CTSM to the stream network (Bhunya et al., 2007). The parameters in the gamma distribution that affect the peak time and flashiness will be estimated based on river geometry information (Kumar et al., 2007). For river channel routing, kinematic wave tracking (KWT) will be used to compute the wave speed (i.e., celerity) of the flow that enters river segments (Goring, 1994). Runoff is propagated through the river network based on travel time (the celerity divided by segment length). Wave celerity is calculated as a function of channel width, Manning's coefficient, channel slope, and discharge. Channel width will be informed from satellite-derived estimates (Allen and Pavelsky, 2015). Manning's coefficient may require a transfer function, sensitivity analysis and/or calibration (Mizukami et al., 2016). Historical discharge simulations at USGS gage locations will be compared to observations and model skill will be assessed using multiple objective functions. Continuous SC data collected as part of this project will provide a second line of evidence of storm peak flow timing, which will be used as a calibration target.

5.4.4. RIVICE river temperature and ice model

We will use a one-dimensional, open-source, dynamic river-ice model (RIVICE; Lindenschmidt, 2017). When a river is ice-free, the model solves the momentum and continuity equations that describe channel flow in a manner similar to mizuRoute. Water temperature is simulated through heat transfer with the atmosphere. Notably, when streamflow and atmospheric conditions permit, RIVICE simulates the formation of river ice. Key ice processes such as ice generation, ice transport, ice cover formation and progression, hanging dam formation, and ice cover melting and ablation are simulated. Parameters include many of the same hydraulic river geometries required by mizuRoute. The US Army Cold Region Research and Engineering Lab (CRREL) in Fairbanks, AK, will provide data on river structure and ice-road transport corridors (see LoC, CRREL), but has cautioned that existing information is limited to regions with petroleum or defense interests. We will work with YRITWC and Indigenous Community members at the Arctic Rivers Summit and through ethnographic methods (see section 5.3.3) solicit local knowledge and observations (e.g., ice-on, break-up dates; river geometry and high-water level heights) to guide/improve large-scale parameter estimation efforts.

Model developer and senior personnel Lindenschmidt at Global Water Futures, University of Saskatchewan (see LoC, GWF) will provide important parameter guidance. Energy-budget based stream temperature models are highly sensitive to the representation of river flow path-lengths, which are poorly resolved at coarse spatial scales used in global simulations (Wu et al., 2012). For example, Park et al., (2016) reported a negative bias in summer river temperature of 2 to 5°C for large Arctic rivers. VanVliet et al. (2012) reported that water temperature estimates were highly sensitive to boundary conditions (i.e., groundwater fluxes and air temperatures), which were improved with higher model resolution. The high-resolution and large-scale simulations proposed here will advance Arctic streamflow, river ice, and river temperature model accuracy. Model biases will be evaluated against temperature measurements and temperature bias correction options will be considered. River ice validation will use diverse observations from the USGS and Indigenous communities. Future efforts will investigate the use of commercial satellite imagery to monitor river ice and validate simulations.

5.4.5. Fish Bioenergetics Model

Water temperature is a main factor directly governing the biology of fish and ultimately determining their production and survival (Christie and Regier, 1988; Magnuson et al., 1990; Sharma et al., 2007; Busch et al. 2012; Carey and Zimmerman 2014). As ectotherms, the body temperature of fish is determined by the local water temperature thereby influencing their physiology and behavior (Magnusson et al. 1990). Many fish species are at their physiological limits due to the harsh environment of Arctic and Subarctic ecosystems; thus, even small changes in hydrology and temperature may alter the structure of fish communities in Arctic and Subarctic rivers. Moreover, temperature may indirectly influence fish by governing primary production in streams and shifting food resources. The bottom-up changes in the food web and direct streamflow and temperature effects together will determine fish performance. To explore these consequences, we will use a bioenergetics model to simulate historical conditions and future changes in fish growth under different climate scenarios as represented by the proposed model chain.

Bioenergetic models provide a framework to test hypotheses about climate change by linking physiological and ecological factors (Kitchell et al., 1977; Hanson et al., 1997; Beauchamp 2009; Shuter et al., 2012). We plan to assess the metabolic response of fish to predicted changes in temperature using the Wisconsin bioenergetics model (Hanson et al., 1997). The model was recently revisioned in the R computing environment (Fish Bioenergetics 4.0 (FB4) model; Deslauriers et al. 2017). It is a mass-balance equation where consumption (C) equals growth (G) minus the energy cost of respiration (M) and waste (W), C = G + M + W. Growth is determined by somatic growth and gonad production. We will use growth estimates for Dolly varden and Arctic grayling from data collected in watersheds of the Noatak River, AK and Canning River, AK (M. Carey, unpublished data). For species identified by Community members as important and for those without direct measures of growth, we will estimate annual growth using a von Bertalanffy growth function (length (1-e-0.16(age)). Using a von Bertalanffy growth function with a bioenergetics model has been insightful for many fish species (Essington et al. 2001). Metabolism involves respiration, active metabolism, and specific dynamic action whereas waste includes egestion and excretion. The parameters for metabolism and waste will be taken from the literature for all fish species. We will assess historical and future conditions under which fish are metabolically stressed.

5.5. Ethnogenic Methods

Indigenous Knowledge has long been recognized as a source of contextual ecological information and insight that cannot be obtained from other sources (Huntington, 1998). Additionally, observations of environmental change made by Indigenous residents of Arctic and boreal regions of Alaska and Canada are important sources of baseline information in a region where data is particularly scarce (Danielsen et al. 2014). This rich understanding of local ecology is due to strong multigenerational ancestral ties to the environment through subsistence, cultural, and spiritual practices. Furthermore, there is evidence of widespread consensus among residents of Alaska Native villages regarding change to river ice (Herman-Mercer et al. 2011, Wilson, 2015) and fish populations (Loring & Gerlach, 2010). Thus, we propose to identify vulnerabilities of fish and river ice through Indigenous observations and knowledge using semi-structured interviews and participatory mapping designed to complement modeling and aid the development of climate change storylines. Additionally, the ethnographic component of this project will work to understand the community's, and individual's, economic, social, and spiritual activities to provide context and elucidate the cultural perspectives each participant brings to the topic (Fienup-Riordan, et al., 2013). This will be accomplished through secondary historical information and documents as well as participant observation methods.

Interviews will be conducted by Indigenous students in self-selected villages as expressed during the Arctic Rivers Summit and/or engagement calls. Interview respondents will be chosen by Tribal Councils and First Nation governments representing participating communities and will be confined to elders (as defined by Tribes) and experts on fish and fish habitat, the river, river ice, and transportation corridors. Experts are defined as community members that have been active subsistence hunters and fishers in their community for at least ten years. Interviews will be conducted by undergraduate student summer interns with the YRITWC and an Alaska Native Science and Engineering Program (ANSEP) summer bridge internship with the USGS Alaska Science Center. Intern training will be held in Anchorage, AK, at the Climate Adaptation Science Center office and provided by Co-PI Herman-Mercer (USGS - Social Scientist) in interviewing and participatory mapping techniques. Other training participants will include senior personnel Carey (USGS - fish biologist), Toohey (USGS - Science Applications Coordinator; hydrologist), and Brooks (CU - professor; environmental governance and policy) who will lecture on fish biology, hydrology, river temperature, and outreach techniques. These lectures and trainings will help form the research protocol including a standard question guide and methods for participatory mapping. This 'semi-structured' approach ensures that while the interviews are open to guidance by respondents' knowledge (Huntington, 1998), topics covered remain standardized to permit comparability of results.

Results from Methods in ***Section 5*** *will be used to codevelop* storylines *of past and plausible future river ice and fish conditions jointly based on Indigenous knowledge and physical principles / western science.*

6. DELIVERABLES & EXPECTED OUTCOMES

This project will converge and advance Indigenous Knowledge and Western Science to transform collective understanding of how terrestrial hydrology has and will continue to change and the potential impacts of these changes on rivers, fish and communities in Arctic and boreal regions of Alaska and western Canada. This will be accomplished through two primary goals and our project objectives, each with specific deliverables and expected outcomes described below. At least 10 publications are expected.

Co-produce knowledge of river ice and fish habitat vulnerabilities – Outcomes from the Arctic Rivers Summit will be disseminated through a white paper, fact sheets, presentations during quarterly engagement calls, through ITEP's monthly newsletter, and through short videos featuring Summit attendees who wish to participate. Interviews will be audio-recorded and transcribed. Participatory mapping will be combined with monitoring and modeling results to create a plain language reports for distribution to participants, participating communities, Native organizations, and other stakeholders across Alaska, Canada and beyond. A common geofabric of spatial IK and existing spatial information on fish habitat and ice-road corridors will be used to create Community-specific maps of historical and feasible future conditions. Maps will be distributed to Tribal Councils and First Nation governments for display in their offices and community centers. One publication will be co-authored with indigenous interns and community representatives. The sensitive nature of IK will be diligently navigated to protect sensitive IK and ensure privacy considerations such as *free, prior, and informed consent*.

Climate change storylines – Co-developed descriptive and quantitative narratives, or *storylines*, of past and plausible future hydroclimatic, river ice, and fish conditions jointly based on Indigenous baseline knowledge and western science will be reported as a white paper, fact sheet, and at least one publication.

River Monitoring – Continuous sensing of SC and river temperature will be used to produce quantitative assessments of spatiotemporal variations, patterns and trends in the relative groundwater contribution to streamflow using end-member models. This information will be used to characterize surface- and ground-water connections across the diverse northern domain. Two publications and a publicly accessible USGS data release will result from the River Monitoring during the five-year project.

Historical Reanalysis – High-resolution simulations with the RASM climate model for the period 1979-2019 and subsequent forcing of the RIVICE model will produce an immense, publicly available dataset of weather, snow, permafrost, streamflow, river ice, and river temperature. Hourly output of RASM/CTSM states and fluxes will be carefully chosen to include those necessary to constrain the surface water and energy budget and to promote future hydrologic and atmospheric analyses. Deliverables will include publicly available, high-resolution climatology and hourly reanalysis of weather for the full domain and improved Arctic-specific parameter estimates for the cutting-edge, NSF-sponsored community model CTSM. Two publications are expected to result from the historical reanalysis during the 5-year project.

Future Climate/River Simulations – For the future climate, we will produce detailed analyses of how and why terrestrial hydrology and river conditions of the boreal and arctic environment may change. Simulated shifts and changes in surface- ground-water connections will be a critical research focal point. At least one paper will present an assessment of how, why and where climate change alters hydrologic connectivity in Arctic and boreal regions. A second outcome will be an assessment of the climate sensitivity of river temperatures in the context of groundwater contribution and shifts in terrestrial water input. A third outcome will be an assessment of future permafrost and the future reliability of river ice for Indigenous winter travel, fisheries access, and transport, along with an assessment of western infrastructure and transportation impacts (LoC ADOT&PF). Four papers are expected to result from the future climate/river simulations during the 5-year project.

Fish Bioenergetics Simulations – We will report, for various fish species, life cycles and river reaches, the conditions under which historical and future simulated river temperatures cause metabolic stress. Vulnerabilities and possibilities of co-identified river-run fish will be reported including culturally significant salmon and transboundary Arctic Ocean species such as Dolly Varden. Streamflow simulations will also be assessed to examine potential future limitations to safe fish passage (e.g., during low flow), and overwintering. This will result in at least one publication during the 5-year project.

7. BROADER IMPACTS

Through a subcontract with the Yukon River Inter-Tribal Watershed Council (YRITWC), we will interface with Indigenous communities participating in river monitoring, including K-12 education. The YRITWC is an Indigenous, grassroots, non-profit organization consisting of 74 First Nations and Tribes dedicated to the protection and preservation of the Yukon River Watershed. K-12 student interaction will include traveling lectures and an 'ask scientists' website. The YRITWC will hire an Indigenous youth intern who will be trained on hydrologic monitoring methods and the science behind the measurements. They will travel to Indigenous communities with YRITWC staff to form Community connections, learn to deploy the sensors, take manual geochemical river samples, and manage data and equipment. Advisors consisting of Tribal Councils and First Nation governments will help guide researchers as they conduct their investigations and will facilitate community scholarships to attend the Arctic River Summit.

Two Indigenous summer interns and recent high school graduates will work on the project in Year 3. The USGS is a strategic partner for the Alaska Native Science and Engineering Program (ANSEP) summer bridge program, which provides opportunities to graduating high school seniors to complete an internship before beginning college. After the summer bridge program, students are eligible for scholarship funding to attend the University of Alaska Anchorage. This program introduces Alaska Native students to careers in the fields of science and engineering with a focus on professional and social development. Interns will be trained by project investigators and will travel with USGS scientists and YRITWC staff to rural Communities to conduct semi-structured interviews of Elders and Indigenous experts in fisheries and hunting regarding their challenges, adaptive successes, and perceived changes in Earth, Sky, and Life.

A subcontract to the Institute for Tribal Environmental Professionals (ITEP) at NAU will support this group to facilitate information exchange between Indigenous community members, the YRITWC, and investigators to enhance project operations and performance outcomes. ITEP will train investigators on cultural sensitivity of working with Tribes and First Nations, which will serve all investigators and students. Multimedia from the field and the Arctic River Summit will include interviews, a co-authored white paper, and a National Geographic Blog (Brooks) with more than 50,000 viewers. Collectively, the project will: 1) further co-production of knowledge, 2) support Indigenous interns, undergraduate and graduate students, and postdoctoral researchers, and 3) enhance public appreciation of the scientific process, the sensitivity of the Arctic environment, and vulnerabilities and adaptive capabilities of local communities.

8. PROJECT MANAGEMENT & WORK PLAN

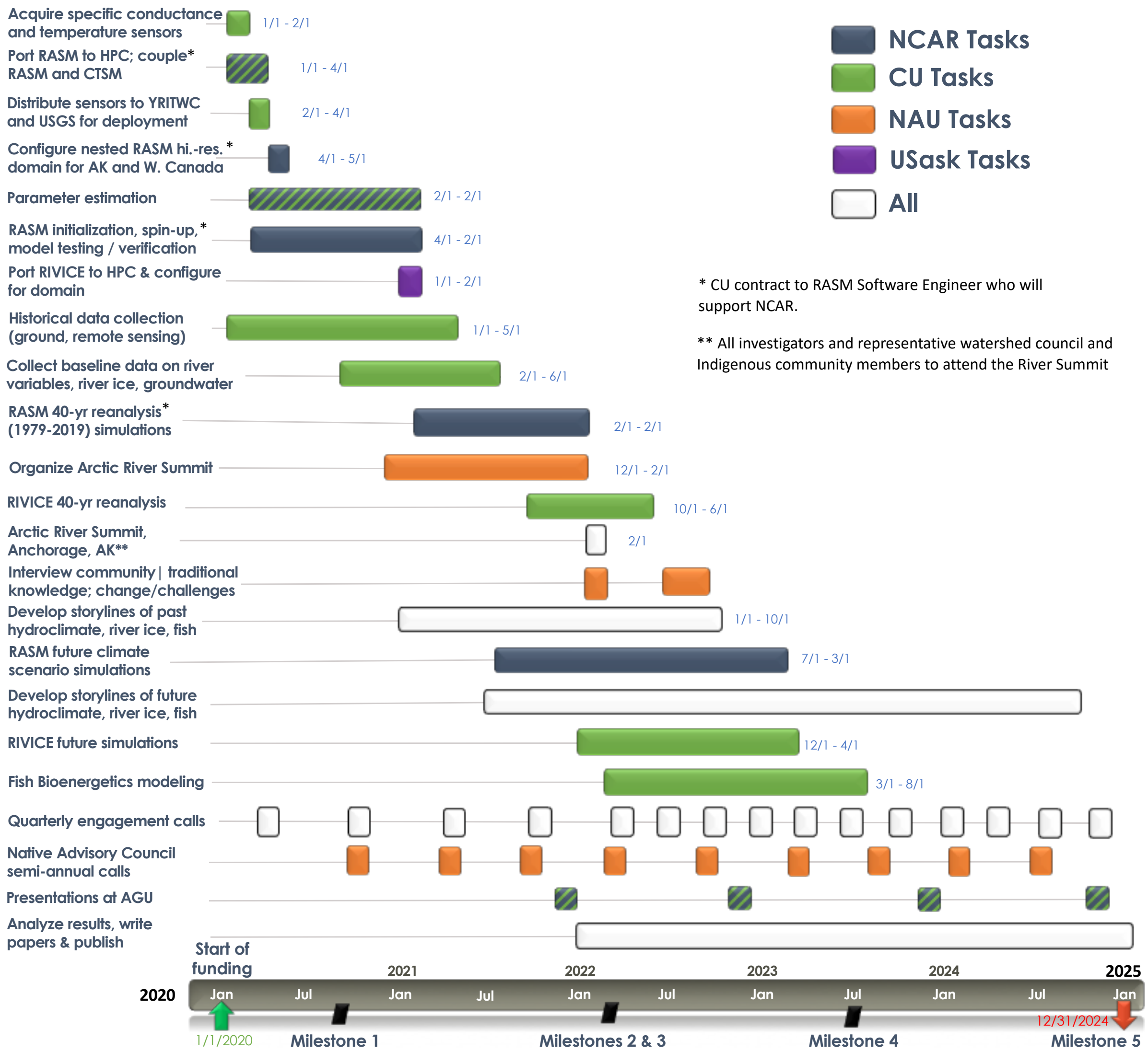

Fig 7 | Timeline of tasks and anticipated project milestones. 'USask' refers to the University of Saskatchewan. Please refer to the Management and Integration Plan for detailed Project tasks and integration efforts.

9. RESULTS FROM PRIOR NSF SUPPORT

PI Musselman NSF EAR Award #1824152: *Extending the vadose zone: characterizing the role of snow for liquid water storage and transmission in streamflow generation*: $166,480. 1/01/2019 - 12/31/2020.

Intellectual Merit: Dynamics of liquid water storage and the connectivity of flowpaths within a mountain snowpack are poorly understood. This project uses new techniques to understand the storage and transport of liquid water within snow. Improved understanding of water flow through snow will transform our conceptual and model representations of cold region hydrologic processes. This project leverages state-of-the-art approaches to understand the storage and transport of liquid water within a seasonal snowpack.

Broader Impacts: A community college undergraduate, supported for summer research experience, is developing conceptual understanding of water flow through snow and its application to hydrology.

Research Products & Their Availability: Data collection for this project will begin in March, 2019.

Collaborative PI Newman – none in the past 5 years

Collaborative co-PI Hamman – none in the past 5 years

Michael Gooseff (PI) NSF 1115245, Increased Connectivity in a Polar Desert Resulting from Climate Warming: McMurdo Dry Valley LTER Program (MCM4), $5.88M, 4/2011-3/2017. In this renewal of the MCM LTER program (begun 1993), we are testing hypotheses related to increased connectivity of the landscape due to regional warming, which would induce melt of ice at higher elevations than has been typical. We proposed that these new physical connections would serve as vectors for materials and biota and that the ecosystem would respond by increasing coupled biogeochemical cycles, increasing biodiversity, and that new wetted habitats would develop based on local geographic factors (slope, aspect, elevation, etc.).

Intellectual Merit: Our findings to date indicate that our working hypotheses were perhaps too optimistic in their positive changes in ecosystem structure and function. We have found increased moisture in soils, for example, to cause lowered biodiversity. Analyses of our long-term records of this polar desert ecosystem indicates that our austral summer climate has pivoted from a period of decadal cooling to a recent decade (since 2002) of steady, low cool air temperatures and high mean solar radiation. In response to this change, the ecosystem has responded with increasing lake and stream primary productivity and increasing soil secondary productivity.

Broader Impacts: Our scientific impact is definitive ecosystem studies of the largest ice-free area in Antarctica, providing new discoveries and advances in ecology from a relatively simplified, microbially-driven ecosystem. Our outreach and education efforts include TEDx talks and the development of teaching materials and several language translations of our children's book, The Lost Seal.

Research Products & Their Availability*:* We produced 157 papers in refereed journals, 20 book chapters, 2 books, and 27 theses/dissertations. We have involved over 43 graduate students, 8 postdoctoral fellows, 88 undergraduates, 22 K-12 students and teachers, and 34 collaborators. As a publicly-funded research program, the LTER Network makes data available online with as few restrictions as possible. A data manager works to ensure that data is reviewed for errors and inconsistencies and thoroughly documented so that it can be incorporated into broader comparative and synthetic studies. Data have also been made available through disciplinary or regional repositories such as the Biological and Chemical Oceanography Data Management Office (BCO-DMO), the Arctic Data Center, the Dryad Digital Repository, and others. The most comprehensive search of public data at this time is available via the DataONE Federation, LTER member node.

Co-PI Joshua Koch: none in the past 5 years

Co-PI Nicole Herman-Mercer: none in the past 5 years