Summary of Results of AR(CI)^2 Stakeholder Workshop 1

April 20-21st 2021

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Acknowledgments and Disclosures

The AR(CI)^2 project is funded by the National Science Foundation (NSF) through grants ICER-2022562, ICER-2022568, and ICER-2022583. The opinions, findings, and conclusions or recommendations expressed are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

This is a collaborative research study by Virginia Tech under IRB-20-541, the University of North Carolina at Chapel Hill under IRB-21-0148, and Brigham Young University under IRB-2021-031.

The workshop organizers would like to thank all participants for their time and contributions. Your opinions and feedback are greatly appreciated and valued.

Affiliations of Workshop Participants

1. Introduction and Project Overview

1.1 Project Motivation and Overview

Civil engineering and community infrastructure are key for community health, functionality, and long-term sustainability in coastal Alaska. Uncertain impacts of climate-driven environmental changes are expected to affect infrastructure and the “built environment,” e.g., roads, homes, and utility structures. Planning and climate adaptation for Arctic communities thus requires an in-depth understanding not only of the impacts of these processes on local infrastructure, but also the impacts of infrastructure and engineering solutions on the surrounding environment and natural processes. However, current gaps in datasets and lack of thorough understanding of climate, cryosphere, natural processes, and the interaction with infrastructure in a given region restrict the advancement of this knowledge. Therefore, there is a strong need to identify the most pressing research questions, expand monitoring, and implement new tools as well as indigenous knowledge to understand natural processes and infrastructure in partnership with local stakeholders and communities. These efforts will increase the length and spatial coverage of available data, and provide new data types that are relevant to community planning.

To address the above gaps in knowledge, this project aims to:

1) Develop research hypotheses and questions that will lead to an improved understanding of the relationship between natural coastal and riverine processes and the Arctic built environment in the context of climate change;

2) Identify data collection and monitoring strategies that enable continuous/frequent monitoring over longer periods and at more locations to yield meaningful datasets about natural processes and to contribute to long-term community adaptation;

3) Identify the specific expertise and needs required to investigate the hypotheses and research questions related to environmental impacts on the coastal built environment, and assemble a diverse and interdisciplinary research team to pursue new research efforts; and

4) Engage Arctic coastal communities and stakeholders in goals 1-3, and to set the pathway for community and stakeholder engagement in future data collections and projects.

This project is designed to pursue these goals through (1) exploration and synthesis of existing knowledge, (2) two workshops that will enable new insights from expert and stakeholder opinions, and (3) local site visits to regions, communities, and infrastructure features of concern. **This report represents the synthesis of the first workshop held in April 2021 that focused on project aims 1 and 4**.

1.2 Workshop Goals and Overview

This workshop consisted of a survey that was distributed to participants two weeks prior and a virtual two-day workshop in April 2021. The workshop was attended by 20 topic experts from local stakeholder organizations and corporations, state and federal agencies, and academic institutions.

The following questions were asked in the pre-distributed survey:

1) Please choose the stakeholder group you feel most affiliated with.
2) When you hear about climate change (or general environment changes) in your community, what do you think about?
3) Please list the three most severe impacts that you expect climate change (or environmental change) to have on infrastructure in Arctic Alaskan communities. (text entry with three entries or verbal answer)
4) Has the way you use the landscape been impacted by past coastal and riverine hazards and processes? If so, please describe the environmental changes, and how they impacted you. (text entry or verbal answer)
5) Are any new coastal or riverine changes occurring which are impacting how you use the landscape or infrastructure? If so, please describe.
6) What do you want to understand better about how Arctic landscapes and environments are changing?
7) What do you think will be significantly different about the local environment in 5-10 years? What do you wish you could change?
8) What do you think scientists might not understand about how the environment is changing, and what infrastructure will be impacted in the next 5-10 years?
9) What would you like to share with scientists about your experience with riverine and coastal changes, and problems related to community infrastructure?

Thirteen of the workshop attendees responded to the survey. The results of the survey are summarized in Section 3 of this report.

The virtual workshop was organized into presentations and breakout discussion sessions. The team presentations focused on the introduction of the project to the workshop participants and the review of the survey results. The breakout discussion sessions focused on the following topics:

1) Changes in natural Arctic coastal and riverine processes in response to climate change;
2) Current and future vulnerability of infrastructure and the built environment in Arctic communities;
3) Relationships between natural coastal and riverine processes and the Arctic built environment; and
4) Current knowledge gaps and associated research needs.

The results of the breakout discussion sessions were synthesized, reported to all workshop attendees, and are summarized in this report in Section 3.

Some of the workshop attendees and invitees provided additional resources in terms of public reports and websites to the research team. The research team reviewed the materials provided and created a synthesis of the results relevant to this project (see Section 2 of this report).

The research team drew preliminary conclusions regarding key research topics needed to enhance the understanding of the interaction between natural processes and infrastructure in coastal and riverine Arctic coastal communities. Those are provided as concluding remarks in Section 4 of this report.

2. Data Availability & Existing Efforts

2.1 Statewide Threat Assessment

The "Statewide Threat Assessment: Identification of Threats from Erosion, Flooding, and Thawing Permafrost in Remote Alaska Communities" (2019) is a report funded by the Denali Commission and prepared by the UAF Institute of Northern Engineering, USACE AK District, and USACE CRREL. The report summarizes a study on the vulnerability of communities and their infrastructure against the hazards of erosion, flooding, and permafrost thaw. Over 180 rural Alaskan communities are evaluated and organized into three groupings of high, medium, and low risk for each environmental threat. A combined threat ranking of the communities is also provided in the document. The report outlines data collection plans that aim to provide site-specific information to quantify one of the three aforementioned threats to a community to inform decision-making. The results of this report reveal that 29 communities are at high risk for erosion, 38 communities are at high risk for flooding, and 35 communities are at high risk for thawing permafrost. Altogether, there are 149 communities that are at either medium or high risk for at least one of the three hazards of erosion, flooding, and permafrost thaw, which signifies that these 149 communities are likely to be impacted by one or more of these threats in the short-term.

2.2 Recent Efforts from the Alaska Division of Geological & Geophysical Surveys (DGGS)

In recent years, the Alaska Division of Geological & Geophysical Surveys (DGGS) Coastal Hazards Program has led several projects that aim to increase the understanding of coastal and riverine processes in Alaska. Here, we highlight three of their recent publications. Please note that this list is not meant to be an exhaustive list of ongoing studies at the DGGS.

In 2018, the DGGS published "Alaska Coastal Mapping Gaps & Priorities." The document includes several figures that demonstrate the uniqueness of coastal processes in Alaska, including the different types of shorelines in Alaska, the distribution of permafrost, sea ice concentration and extent, and relative sea-level change. The report also features several maps that show where coastal data such as orthoimagery, elevation data, coastal elevation profiles, t-sheets, and bathymetric data have been collected, and wherein Alaska the data is lacking. Sites of water-level monitoring and GPS systems are also noted.

In the report on "Shoreline Change at Alaska Coastal Communities" (2020), the DGGS uses historical shoreline datasets and aerial images to analyze long-term shoreline change in Alaska at every 25 meters. Their results show that over half of the communities analyzed in their study have had average erosion rates greater than 1.0 meter per year over the past 60 years. The report on "Coastal Flood Impact Assessments for Alaska Communities" (2021) by DGGS describes a methodology for communities to assess flood impacts on their local community infrastructure. The method requires historical storm data, specifically the heights of previous floods relative to infrastructure in the community. An approach to estimate previous flood heights is also included in the report.

2.3 Promoting Resilience and Adaptation in Coastal Arctic Alaska

"Promoting Resilience and Adaptation in Coastal Arctic Alaska" is a report synthesizing the results from workshops held in 2016 in Nome, Unalaska, King Salmon, and Kotzebue, where local participants discussed risks and vulnerabilities related to climate change for their coastal communities. Discussion topics included climate change adaptation strategies, food & subsistence concerns, and infrastructure vulnerability. The report highlights several quotes from local participants that demonstrate concerns about climate change-related issues. One of the products from this report was the www.adaptalaska.org homepage, which features a long list of resources to help guide community decision-making.

2.4 Alaska Division of Community and Regional Affairs (DCRA) Community Database Online

The Alaska Division of Community and Regional Affairs (DCRA) Community Database (https://dcra-cdo-dcced.opendata.arcgis.com/) is an online portal that features community plans and resources such as hazard mitigation plans, photos, and profile maps for communities in Alaska.

2.5 Alaska Water Level Watch

The Alaska DGGS Coastal Hazards Program, in collaboration with the National Oceanic and Atmospheric Administration's (NOAA) National Water Level Observation Network (NWLON), the Alaska Ocean Observing System (AOOS), and other organizations have created a water level data program called the Alaska Water Level Watch (AWLW, https://water-level-watch.portal.aoos.org/). This project addresses gaps in water level data for

Alaska by increasing the number of water level sensors and tidal datums across coastal regions of the state.

3. Workshop Outcomes in the Context of Previous Efforts

The participants engaged in several breakout group discussions during the workshop and in a survey distributed prior to the workshop. The research team synthesized the survey results and the discussions from the breakout groups into several key research and community topics. A summary of the discussions and survey results is provided below in sections 3.1 and 3.2 of this report.

3.1 Research Topics

3.1.1 Natural Processes

Climate

Climate change is impacting natural processes in the Arctic in diverse ways, including warming water temperatures and shifts in typical seasonal weather patterns. Storm timing, intensity, and frequency are changing, creating new issues and concerns (e.g., storms arriving earlier in the year in certain regions). Participants noted changes in precipitation patterns, rising temperatures, thawing permafrost, earlier snowmelts, and water levels as main areas of concern. The variability in these changes was also discussed because weather events can be unpredictable. Another concern was the challenge of understanding scientific predictions of climatic changes that have an uncertain magnitude and frequency (i.e., can a community prepare for event(s) that cannot be accurately predicted or a climate with no discernible pattern?).

These shifts in the climate have been linked to changes in rates of coastal erosion, sea ice extent, and flood frequency. Many participants expressed how these changes are increasing uncertainty in both community planning and forecasting because historical patterns are no longer being observed.

Ocean

For coastal communities, topics of note included changes in sea ice and waves. The decrease in sea ice extent and duration has impacts on the natural, economic and cultural realms. Concerns were raised about sea mammal migration, commercial operations, and subsistence fishing. Participants discussed how the decrease in sea ice can be seen as an advantage for economic development through increased ship traffic including cruise ships, fishing vessels, and refueling tankers. However, such an increase in ship traffic could also be a disadvantage for the ecosystem.

Sea mammals are already migrating north to colder waters, and the potential for oil spills and overfishing as ship traffic increases could further hinder these populations. The decrease in sea ice also leads to an increase in fetch, which allows for an increase in wave energy and the potential for storm erosion of coastal dunes, permafrost bluffs, and infrastructure.

Coasts

In the coastal realm, participants expressed interest in better understanding coastal retreat and changes in water levels. Some discussions focused on retreat of thermally sensitive permafrost bluffs under the influence of rising sea level and increasing wave climate (see above), and associated land loss (with recognition that in other areas, accretion leads to land gain). Questions were also raised about the contributions of subsidence to sea-level change - i.e., will subsidence of thawing permafrost accelerate land loss and exacerbate flooding? Other discussions focused on the impacts of storms on protective dune systems. Some communities reportedly re-build dunes after major storms. One participant noted that natural dunes tend to be a preferred defense system, especially after boulders/rip-rap were placed in one region but were displaced during a storm, leading to hazards on the beach for operators of off-road vehicles. Some interest was expressed in planting efforts aimed at helping dunes develop stabilizing vegetation. Participants also expressed interest in understanding how other coastal revetments (e.g., jetties) are impacted by changes in water level and shoreline erosion and accretion.

Figure 1. Actively eroding permafrost bluff on Barter Island Alaska. Image courtesy of U.S. Geological Survey from https://www.usgs.gov/media/images/eroding-bluffs-kaktovik.

Seawater intrusion at the coast was also identified as a threat to freshwater supplies and infrastructure. For example, one workshop participant reported that a recent storm event in Utqiaġvik caused overtopping of dunes and saltwater contamination of a surficial freshwater supply. Another participant suggested that dunes could be raised prior to storms to prevent such problems. Others noted that saltwater intrusion into the ground is a corrosion concern for buried infrastructure (e.g., foundations and buried utility facilities).

Perhaps the most common concern expressed by participants regarding the coast focused on increased coastal flooding from diverse sources including storm surge, persistently higher water levels related to sea-level rise, and changes in upstream hydrology. One participant expressed interest in understanding how river flooding and river ice dynamics interact with coastal ice dynamics (i.e., is there a feedback between rivers and coastal waters during flooding events and/or when ice is present in both systems?).

Rivers

Upstream of the coast, changes in river dynamics are of concern. River hydrologic cycles may be impacted by long-term changes in precipitation, periods of drought, and changes in the timing of events. For example, a lengthening summer season may mean there will be less river ice, which intuitively could suggest less risk for flooding. However, if changes in precipitation trends bring late-season rain-on-snow events, high discharge during periods when ice is forming may lead to substantial flood events. In other words, feedbacks between different parts of the hydrologic system - and changes in timing - should be considered when assessing changes in processes and hazards to infrastructure.

Figure 2. Landslide north of Rabbit Creek outside of Anchorage Alaska. Image courtesy of U.S. Geological Survey from https://www.usgs.gov/media/images/2018-potter-hill-landslide-2-anchorage-ak.

Riverbank erosion, whether driven by floods or more gradual processes, is a topic of critical concern for many communities. Communities are commonly located along riverbanks for ready access to transportation of goods and resources. Participants shared several examples of Arctic communities that have needed to relocate due to rapid riverine erosion. Riverbank erosion processes are less understood in the Arctic, due both to the presence of permafrost soils in many areas and seasons of ice cover (and ice-jam floods during spring breakup). Sedimentation dynamics are also of concern. Rivers may see increased sediment loads related to increased forest fires, and/or changing sediment loads due to changing precipitation patterns and different timing of the hydrologic cycle. Participants were also concerned about how dredging may impact sedimentation and channel cross-sections.

Participants expressed interest in better understanding the estuarine portion of rivers as well, where rivers meet the coast. Many communities are located at the land-ocean boundary, and participants were interested in better understanding these systems individually and understanding their interactions in the context of how communities will be affected (e.g., by compound flooding).

Terrestrial Impacts

Participants expressed many concerns about terrestrial changes in permafrost, snowpacks, fires, and ecosystems. Permafrost thaw has led to accelerating erosion and subsidence in many communities represented in this workshop. Roads and houses are sinking due to the thawing ground, and in fact accelerate the subsidence by acting as heat sinks. Climate shifts have also led to decreased snowpack, which is problematic because the snow cover acts as a natural insulator, and its attrition means that utilities are more likely to freeze. More concerns regarding similar scenarios affecting Alaskan communities are addressed in section 3.1.2 (Infrastructure & Built Environment).

Variability in precipitation patterns has led to drought in some areas, which impacts natural vegetation and farming, as well as flooding. Vegetation can offer erosion protection for the landscape, but the droughts and subsequent wildfires destabilize those areas, leading to more erosion during flood events and sediment delivery to streams. The need for better understanding the impacts of flooding and wildfires on permafrost was expressed by participants, especially because of the feedbacks between processes. The compound effects of thawing permafrost, erosion, and flooding may also be impacting salinity intrusion for coastal communities, which presents a risk of contamination for some community water supplies (see above, *Coasts*).

Other Concerns

Participants also expressed concern about topics related to habitats, ecology, and species. These included increases in the number of threatened and endangered species; loss of some already endangered species; arrival and/or expansion of invasive species ranges; and changes in fish and wildlife presence, abundance, and migration pathways. Concern over habitat degradation which can alter subsidence strategies of coastal communities as well as the health of the coastal ecosystem was also expressed. Another cause for the alteration of ecosystems is the potential release of sequestered hazardous materials from thawing permafrost; carbon, radioactive chemicals, and waste, were included in a list generated by a concerned participant. While these concerns are valid, they are not within the scope of the proposed research or engineering solutions.

3.1.2 Infrastructure & the Built Environment

In the pre-workshop survey, participants shared their perceptions regarding climate change impacts to infrastructure and the built environment in the Alaskan Arctic. Survey participants shared their levels of concern of climate change impacts for eight different infrastructure types. Figure 3 below summarizes the participants' responses regarding their perceived impacts to various types of infrastructure. Note from Figure 3 that houses, pipelines, and roads seemed to warrant the greatest concern among participants, though most other infrastructure elements were not ranked significantly lower.

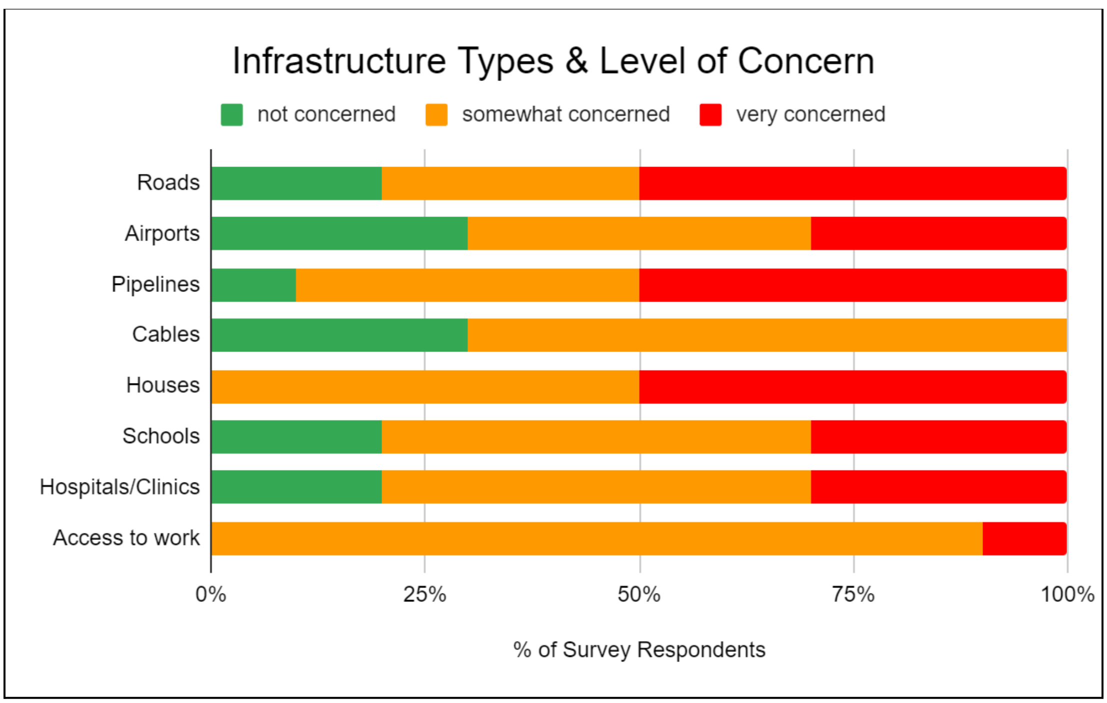

Figure 3. Summarized graphical responses to the pre-workshop survey question regarding which infrastructure elements were most at risk from climate and environmental changes.

Housing

Participants noted that increased storm frequency has negatively impacted permafrost, which has had the subsequent effect of damaging the foundations to many residential structures. The built environment itself may have a feedback effect, insomuch as anthropogenic structures act as heat sinks. Houses are built on gravel pads for stability, but, if the gravel pad is in direct contact with the permafrost, the permafrost can deteriorate. Attempts have been made to prevent contact between the gravel and permafrost by excavating the thawed area and laying a foam pad between the permafrost and gravel. This has had some success over short periods of time, but proves ineffective in the long-term. Permafrost thaw beneath homes has prompted residents to re-level their houses every 3 to 5 years as part of their maintenance routine.

Roads

Transportation infrastructure in the Arctic is also impacted by permafrost degradation. During long summer days, the roads absorb heat and warm the underlying permafrost. One participant noted that a local unnamed roadway was originally built 6 feet above the tundra. As the road warmed the permafrost, the road began to sink. Now, in some places, the roadbed is 15 feet below the tundra. This participant noted that many roads today are built on two feet of insulation to protect the permafrost. This additional fill makes building roads an expensive endeavor.
Another factor affecting the roads in Alaska is erosion and flooding. Alaskan highways are generally located inland and away from the coast. Coastal communities in western Alaska are inaccessible by roads or highways. It is not uncommon for these rural Alaskan communities to lack road systems or have only one or two local roads. The warmer spring seasons are leading to flooding of these roads. This flooding is alarming because some communities rely on a single bridge for lifelines/evacuation routes. Flooding has frequently caused these lifeline routes to become impassable, isolating the community from aid and potential escape if the need arose. For example, a participant recalled that two years ago, the Sagavanirktok River overflowed and cut off the Dalton Highway south of Dead Horse for 7 to 10 days. This cut off the entire North Slope from ground transportation.

Pipelines and Freshwater

Pipelines have been used to distribute oil and gas throughout the state. These pipelines are particularly vulnerable when it comes to permafrost degradation. The degradation of permafrost from erosion or warming causes subsidence, which can result in the pipes bursting and oil and gas spilling into the rivers and the landscape.

Because ground water availability is scarce in many communities, these regions rely on pipelines to deliver freshwater to the community. Some pipes, previously insulated from extreme temperatures by the snow pack, are now being exposed to colder conditions. These extreme cold temperatures are causing the pipes to burst and leaving communities without potable water, sometimes for months at a time. When the pipeline systems are down, drinking water must be flown in or boiled.

Communities that do not rely on pipes for water rely on rivers or glacial meltwater. Changes in precipitation and warmer springtimes could have impacts on water availability. In regions where groundwater is available such as Hooper Bay and the surrounding area, significant amounts of well water is being affected by saltwater intrusion. Other participants remarked that saltwater is even contaminating their fresh water tanks.

Schools, Hospitals & Clinics

Schools, hospitals and clinics are of particular concern because of their societal necessity and the expenses of rebuilding and relocating. Many of the same fore-mentioned problems facing housing and roads are also problems for schools, hospitals, and clinics. Educational and healthcare buildings may experience significant settlement due to permafrost thaw. Foundations are becoming compromised and are requiring creative approaches to remain functional. Unlike houses, which are much smaller, schools, hospitals and clinics are much more difficult to level. The relocation of hospitals and clinics is an expense that many smaller communities and villages are unable to afford.

Airports

Similar to schools, hospitals and clinics, airports are very vulnerable to the effects of climate change. Because of a lack of roads, airports are built adjacent to communities—and thus adjacent to rivers and coasts. This proximity leads to flooding, wave runup, and erosion and debris deposition on the runway. In some areas respondents have noted that you could drive a boat across the runway. The flooding of airport runways can have catastrophic effects on a community, because many communities rely on airports for food delivery and communication.

Figure 4. Flooded airport on Barter Island Alaska. Because of the frequency of flooding, the airport had to be moved. Image courtesy of U.S. Geological Survey from https://www.usgs.gov/media/images/flooded-airport-runway-barter-island-alaska.

Tank Farms

Many Alaskan communities get their energy from diesel fuel that is stored in large, above-ground tank farms. Permafrost thaw and coastal erosion are threatening tank farms in coastal communities. As the ground continues to destabilize due to climate-driven warming, the risk of oil spills and leaks is increasing. Relocating oil storage facilities is difficult because they need to be close to the coast and rivers. Ships delivering the fuel pump it directly into the tanks because they are inaccessible by roads, making transport by other methods difficult and prone to spills.

Currently, these tank farms are of particular interest to the Coast Guard, which performs tank farm inspections in many of the Alaskan communities. A participant noted that the Coast Guard is interested in using UAVs to perform both tank inspections and coastal erosion inspections in these communities.

Barge Landings, Marinas, & Beach Access

Coastal erosion has affected barge landings, marinas, and beach access. Seawalls have been constructed to hinder the erosion. Participants noted that seawalls may protect coasts from erosion at their installation sites but may increase erosion along other segments of the beach. Some communities are now opting to rebuild dunes after storm events instead of building seawalls. Erosion of riverbanks has impacted the fishing camps, significantly affecting the communities built around them.

3.1.3 Interaction and Feedbacks Between Natural Processes & the Built Environment

A key topic of interest of this research is the interaction and feedbacks between natural processes and the built environment, in Arctic coastal and riverine environments and communities. While those interactions and feedbacks are manifold and complex, the purpose of the survey questions and workshop sessions targeted these issues. A primary goal was to assess what key interactions stakeholders are concerned with. The issues listed below reflect the survey results and discussion sessions, but must not be considered a complete list of interactions and feedbacks between natural processes and the built environment of concern to Arctic coastal and riverine communities.

The issues raised can be grouped into the following categories: (1) impacts of natural processes on the built environment; (2) anthropogenic impacts on natural processes that further may affect the built environment; and (3) community and infrastructure management in response to changing natural processes.

Regarding *impacts of natural processes on the built environment*, participants voiced concerns about oil spills and contamination from different types of spills, related to permafrost degradation and flood events. Specifically, pipeline ruptures due to slumps, erosion, and general permafrost degradation were mentioned. Such events may affect the local and larger economy, utility services, and local mobility, and may also result in long-term environmental and health issues.

Another concern was increased vessel traffic, related to longer periods of no to little sea ice, and the reduction of ice in riverine waterways. Interestingly, this was mentioned as an environmental concern, for example, in relation to the increased risk for oil spills and pollution from the presence of more vessels. However, it was also mentioned as an economic opportunity for water-fringing communities, and some attendees were concerned that this is not recognized and that appropriate investment is not being made. Thus, attendees commented that changes in natural processes may bring new problems and uncertainties, but may also bring unique economic opportunities for the region. But these opportunities must be carefully assessed, in light of increasing risks and hazards in the same region—highlighting the need for investments into risk and opportunity assessment plans.

Other examples for impacts of changing natural processes on infrastructure and the built environment included impacts of river flooding on roadways, as noted in section 3.1.2. As a specific example, the flooding of the Dalton Highway was mentioned that led to a standstill of North Slope ground transportation for days, representing a significant interruption to North Slope economics and community services. Furthermore, the impact of river flooding on ice roads was mentioned, with the question of whether ice roads will continue to suffice as a transportation lifeline under increasing flood risks.

*Anthropogenic processes affecting natural processes and possibly posing increased hazards to infrastructur*e were also mentioned by participants. Specifically, dredging and mining may change sedimentation and sediment transport patterns in some rivers, which impacts river flooding and erosion risks for some communities. Participants felt that little knowledge was available to assess and predict the effects of dredging and mining on river dynamics, but they voiced concerns particularly regarding sedimentation and resulting increase of flooding.

Participants also recognized the risk of warming roads affecting the underlying permafrost. While this issue is long known and different solutions are available to mitigate the issue, participants felt that some solutions are costly or even cost-prohibitive, and that other solutions are inefficient, tedious, and drain resources.

Finally, participants offered comments about the *interaction between natural processes and the built environment with regards to infrastructure management and investment*. Participants highlighted that interaction between natural processes and the built environment can force minor to severe planning and management decisions. One of the most prominent examples is community relocation and decisions to move infrastructure farther away from the water. While this appears to be a significant but effective management solution, it also brings many challenges. One challenge that was noted was access to water, which is often required for logistics, transportation, as well as economy and subsistence.

Increased coastal management was also mentioned by participants in response to this topic. Increased coastal management was found to be necessary to manage changes in natural processes. At the same time, participants voiced concerns related to impacts from coastal management solutions, and called for more detailed assessment of risks, and the impacts of coastal management solutions. Participants also called for more considerations of nature-based engineering solutions where feasible.

A participant also commented that climate change is leading to drastic changes in natural processes and impacts on the built environment, but community management adaptation and responses lag behind the rate of change in natural processes.

3.1.4 Tools, Measurements, Challenges, and Ideas

Data Type, Quality, & Modeling

Participants noted that Alaska presents new challenges for modeling. For example, in the coastal realm, many present models are optimized for sandy coastlines - but in Alaska, many coasts comprise ice-rich, thermally sensitive permafrost bluffs or other complex soil types. Modeling these types of systems will demand additional knowledge about erodibility, substrate types, and physical properties including thermal mechanics. In the river realm, a participant noted that many of the models available (and even applied to Alaska) were developed for systems like the Mississippi - i.e., larger systems without ice impacts. Many Alaskan rivers develop ice in the winter, are prone to ice-jam floods during spring breakup, and meander through permafrost landscapes (meaning processes of riverbank erosion differ from their temperate counterparts). Rivers are also supplied by snow melt, and the character of snowpacks and timing of snowmelt is changing.

It was also noted that processes which are complex and difficult to model in temperate systems, like compound flooding, are even more difficult to model in the Arctic. Compound flooding can occur, for example, when a river floods during a period of storm surge at the coast. In the Arctic, rapid snowmelt and rain-on-snow events may occur during periods when there is extensive ice cover or ice jams on the river, exacerbating the flooding beyond what a temperate-region model would predict. It is also unclear how these flooding processes would interact with adjacent permafrost soils. Compound flooding represents one of many superimposing natural processes as well as human impacts. Participants noted that there is little understanding of how different processes interact with each other and infrastructure, and thus, there are few tools to assess those impacts or provide actionable assessments or predictions. Therefore, compound disturbances were identified as a future key research topic.

One of the key limitations to modeling Alaskan systems (e.g., river hydrology and coastal retreat) is the scarcity of data in some regions, or low resolution of data. Participants noted that even where data resolution is sufficient, the scale and quality of data may be insufficient to justify computationally expensive and high-resolution modeling. For example, more topographic data, bathymetric data, and time series of water levels and wave energy are needed in some regions.

A lack of historical data about storms was also identified as a concern for modeling and projecting future scenarios. Without a robust historical record, it may be difficult to simulate extreme future events. Participants suggested using joint-probability approaches, i.e., simulating a range of possible storms, even if such storms do not appear in the sparse historical record.

Data Acquisition

Participants identified the lack of data as a major hindrance to understanding how climate change is impacting the communities. Two reasons for the lack of data are the short season wherein data can be collected, and the remote locations of the communities. Because of these barriers, few long-term studies have been conducted. Efforts have been made to leverage remote measurement techniques (for example, Coast Guard monitoring of tank farms using UAVs, as mentioned above), but additional data are still required.

Participants identified the historic riverbank surveys that were conducted before land ownership was transferred as a possible source of additional data. They also noted that the historical information that the elders in the communities know has often been overlooked. This first-hand experience may be beneficial. They also proposed coordinating with members of the communities to collect data. Community members are invested in the success of the community, and would be a good resource in establishing long-term, sustainable measurements.

Big Picture Research Goals and Unique Arctic Processes

While there are innumerable specific processes of interest for future study, several large-scale and overarching challenges and topics were identified for Arctic systems in general. Participants noted a need to *understand patterns and trends* in Arctic systems, while recognizing that *processes are changing in time and space*. For example, river flooding may be increasing in frequency, but severe ice-jam floods may also be migrating to different regions of the state in response to changing temperatures and timing of precipitation and snowmelt. Such environmental shifts present a challenge for choosing design lifetimes of new infrastructure (or planning for upgrades or replacements of existing infrastructure). This example also highlights the *unique riverine and coastal processes* at work in Alaska.

There was also much interest in understanding *feedbacks and linkages between processes and systems*. Examples include: do floods (riverine and/or coastal) impact the rate of permafrost thaw and subsidence? Does the timing of river ice breakup relative to coastal ice breakup impact the degree of river flooding? How does forest fire change plant communities, with impacts on sediment delivery to rivers and habitats available for wildlife? *Tipping points* were also highlighted - for example, at what point will increased sediment availability (e.g., from forest fire denudation, eroding riverbanks, increased river flooding) lead to the formation of aeolian dune fields in some regions? *Compound processes and sequential events* were also recognized as having key impacts on infrastructure. For instance, a rain-on-snow event which drives river flooding coincident with a coastal storm may lead to extreme flooding (not forecasted by analysis of sparse historical storm records), creating a compound event. Or, numerous sequential smaller storms or floods may trigger substantial changes in a given year.

Resilience was also discussed - how do we define it? The National Institute of Standards and Technology defines resilience as “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.” Although this definition was crafted in regard to cyber infrastructure, it is also applicable to our discussion on the resilience of community infrastructure. Infrastructure, such as roads and buildings, in the Arctic are impacted by many “disruptions” due to climate change and must be designed with resilience in mind. Time scales are critical in these discussions. How long should infrastructure be designed to last or be protected, and are those plans compatible with the spatial and temporal changes of processes in the natural environment? For example, should ice roads and winter trails continue to be used, or should more permanent infrastructure be constructed? Can creative engineering solutions be applied to maintain and protect permafrost, or should facilities be adapted to an environment where subsidence is anticipated?

3.2 Community Linkages

3.2.1 Management, Design, & Planning

Community management, design and planning is difficult given rapidly changing conditions, minimal data that can be difficult to locate or utilize, and complicated regulations. The questions “should infrastructure impacted by climate change be replaced or relocated?” and “how do we decide?” were presented in several of the groups. Adequate information and data are not easily accessible, which makes answering these questions extremely difficult. In addition to the rapidly changing conditions, mitigation attempts that are useful now, may not be useful in the future (e.g., as temperature zones shift across the state, some problems - like severe ice jam floods - change location).

Participants identified that they use a cost benefit analysis to manage their communities. If it is cheaper to repair a structure than to replace and relocate the structure, they will opt for repair - even knowing that they will have to repair it again later because funds are not available for replacement or relocation. It was also noted that some communities are frustrated with the government. Participants expressed frustration with the old regulations still in place, arguing that they do not do enough to help the communities. Grants and government funding are available, but the communities lack the resources to write competitive grant proposals, thus raising the important issue of social equity. In some cases, funding is reduced because of standards beyond the communities’ control. For example, access to FEMA’s funding is more difficult for the communities to obtain because the building codes of the area are not aligned with FEMA’s standards. To further compound the problem, relocation, which is frequently the recommended response, may not necessarily be a long-term solution. Villages in the past that have relocated are now experiencing erosion at their relocated areas, requiring further relocation in the future.

Participants remarked that some communities are feeling science fatigue. The communities have interacted with scientists who bring new technology to test. The communities will try it and continue using it for a short time if it works, but often these efforts stop because funding ends and the community does not have financial resources or incentive to continue the work. In other examples, scientists have brought ideas that are not feasible or will not work in the area. Participants noted that additional studies will do little without active community involvement and engagement.

3.2.2 Funding and Investment

Participants noted that in many cases, funding and investments are a major obstacle for community adaptation to climate change (and the resulting changes in natural processes). Overall, a lack of financial support on the community level was cited. However, if resources become available, decision-making about where resources should be invested was identified as an issue of concern. Risk and hazard assessment that could facilitate more informed decision-making about investments has been found to be costly in itself. If data and assessments are available, it is still challenging to translate those data into actions. Questions were raised about how to determine which investments are suitable and which projects will perform best long-term. The need for cost-benefit analyses was stated. However, even if available, it was noted that such data may not be easily accessible to community managers and decision makers.

Related to the issue of successful and efficient data acquisition to enable informed decisions, stakeholders mentioned that cost-share in funding opportunities represents a major obstacle for many organizations and communities. Furthermore, it was stated that there is a need for investments into trained technical local staff and accessible data management infrastructure to assist with the development of long-term data sets and data monitoring programs.

3.2.3 Community Wellbeing

Several concerns over the wellbeing of communities impacted by climate change were expressed by participants. Water scarcity and hunger were discussed in the context of saltwater intrusion (which can contaminate freshwater supplies) and changes to precipitation patterns (which are impacting both natural vegetation and agriculture). Subsistence concerns were also expressed because native communities are no longer able to fish, hunt, or collect food in the same locations that they could previously. People are forging new trails through the tundra and also having to move to higher elevations in an attempt to follow the vegetation.

Relocation of communities either through planned moves or emergency egress also has a direct impact on community wellbeing. People are leaving behind culturally or personally significant land because certain regions are no longer habitable. There are also significant economic impacts because many communities do not have the funding available to relocate and rebuild. Concerns were raised about the availability, accessibility, and allocation of funds when it comes to relocating rural villages who struggle to write competitive applications.

3.2.4 Noted Communities of Concern

Although many communities throughout Alaska are struggling to adapt to the significant changes to the Arctic climate, participants expressed specific concern about Western Alaska. Point Hope, Point Lay, and Y-K Delta communities were identified in the workshop as receiving less scientific attention. Participants also noted that several river communities were attempting to assess environmental threats, but not receiving necessary levels of support. These included Chefornak, Napakiak, Kotlik, Alakanuk, Newtok, Nunapitchuk, Tuntutuliak, Noatak, and Huslia. All of the listed communities were evaluated in the Alaska Statewide Threat Assessment (2019) for the threats of erosion, flood, and permafrost thaw on community infrastructure. In the Alaska Statewide Threat Assessment, communities were grouped based on the relative threat that each of the three processes imposed on the community (1 = high, 2 = medium, 3 = low). Table 1 summarizes the groupings of the communities. 10 out of the 11 noted communities fell in the highest risk grouping for at least one of the three environmental threats.

Table 1. The erosion, flood, and permafrost thaw groupings for the communities of concern identified in the workshop by participants. (Source: USACE 2019). The groups represent the relative threat level of erosion, flood, or permafrost thaw on the community's infrastructure.

Community	Erosion Group	Flood Group	Permafrost Thaw Group
Point Hope	Medium	Medium	Medium
Point Lay	Low	Low	High
Chefornak	High	Medium	High
Napakiak	High	High	Low
Kotlik	High	High	Medium
Alakanuk	High	High	Medium
Newtok	High	Medium	High
Nunapitchuk	Medium	Low	High
Tuntutuliak	Medium	High	High
Noatak	High	Medium	High
Huslia	High	Medium	High

3.2.5 Communication

Effective communication was consistently identified by participants as a necessary but lacking tool. Participants noted the presence of many communication barriers between the communities, scientists, and policy makers. Although science is being conducted and data is available online, data is not necessarily accessible to the communities and there is not a clear path for applying these data to hazard mitigation plans. Participants also discussed a disconnect between the research conducted and the community needs; while data is available, it may not necessarily be helpful to the community. This links to another interesting topic of discussion: the training of citizen scientists and community engagement in measurements. If members of the community were trained to collect or analyze data, it would be more useful to stakeholders and local representatives who are trying to assess threats to the community.

Participants noted that natural processes need to be understood not only by communities, but also by policy makers. Concerns were discussed regarding the local differences between communities and the pace of the changing environment. For the communities to gain adequate assistance, policy makers need to understand the scope of the environmental and structural issues each group is facing. An understanding of design life is also required - one participant described structures with design lives of 50 to 75 years are being used well past those design lives without proper maintenance. Another participant noted that one threatened community was relocated to an area that is now also under threat due to erosion. Participants feel that long-term solutions and future impacts of climate change need to be considered when making new policies and rebuilding structures.

Among community members, there is also an underlying perception of unequal attention, in the form of research and funding, to coastal rather than riverine communities. Improvements in communication could help shift these perceptions and strengthen relationships between communities. This issue was also noted more generally for rural communities and villages, who feel undervalued by scientists. Participants expressed concern over a communication barrier between local traditional knowledge and the science community.

4. Concluding Remarks and Path Forward

The 2021 AR(CI)^2 virtual workshop involved 20 stakeholders including Alaska Natives, researchers, and engineers that work in Arctic Alaska. The resulting discussion and the associated pre-workshop survey revealed valuable information, critical knowledge gaps, and several significant challenges regarding climate change effects on coastal and riverine communities and their associated infrastructure in the Alaskan Arctic. These effects were explored in the context of:

- Changes in natural Arctic coastal and riverine processes in response to climate change;
- Current and future vulnerability of infrastructure and the built environment in Arctic communities;
- Relationships between natural coastal and riverine processes and the Arctic built environment; and
- Current knowledge gaps and associated research needs.

Based on the group discussion, breakout sessions, and pre-workshop survey results, the following principal conclusions can be made:

1) The natural processes associated with climate change in the Alaskan Arctic including warming air and seas; precipitation changes; colder winters; increased flood events; changing vegetation and wildlife patterns; and accelerated coastal and riverine erosion are significantly affecting Alaskan communities and their infrastructure. Many of these effects tend to compound on each other, thus intensifying their effects and impacts.

2) While our understanding of coastal effects of climate change in the Alaskan Arctic is increasing substantially, we know nearly nothing about riverine effects of climate change.
3) Coastal and riverine Alaskan communities are significantly struggling to adapt to the effects of climate change in the Arctic. The substantial amount of uncertainty associated with a general lack of knowledge, lack of data, and lack of communication are exacerbating this struggle.
4) Assessing the risks associated with climate change and developing an effective, practical, and viable hazard mitigation plan is currently out of reach for most Alaskan communities due to social inequity, government inefficiency, and a lack of resources.
5) While there are numerous scientists attempting to study and understand the science behind climate change in the Alaskan Arctic and its natural effects on the local ecosystem, their methods, technology, and frequency/infrequency of study often create significant technical and social challenges. These scientists also have historically worked independent from the local communities that are directly being affected by the very climate change effects that are being studied, and generational and institutional knowledge of the locals is not being considered or incorporated to the extent that it could.
6) An apparent imbalance exists in multiple parts of this complex topic. Many communities are fatigued by research while some do not receive any attention at all. Most of the research performed in the Arctic is focused on increasing our scientific understanding of the natural processes at work, but does not impact or improve the lives and wellbeing of the local residents at all. What little research is focused on improving the lives and wellbeing of the local residents rarely sees community implementation. While government resources exist to assist Alaskan communities that are impacted by climate change, few of those communities have the resources and/or education to access them. Finally, in the few instances where risk assessments are performed and/or hazard mitigation plans are developed, community leaders rarely have the resources and/or training to implement them.
7) The bottom line is that local Alaskan residents in coastal and riverine communities are being significantly impacted by climate change in terms of infrastructure, culture, economy, and subsistence.

5. Acknowledgements

We wish to thank all of the participants in the first project workshop who gave generously of their time, enthusiasm, and thoughtful ideas and concerns pertaining to the Alaskan environment. We also thank NSF for supporting this work under projects ICER-2022562, ICER-2022568, and ICER-2022583.

The AR(CI)^2 project is funded by the National Science Foundation (NSF) through grants ICER-2022562, ICER-2022568, and ICER-2022583. The opinions, findings, and conclusions or recommendations expressed are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

This is a collaborative research study by Virginia Tech under IRB-20-541, the University of North Carolina at Chapel Hill under IRB-21-0148, and Brigham Young University under IRB-2021-031.

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