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Arctic geohazard mapping tools for civil infrastructure planning: A systematic review

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ABSTRACT

Civil engineers design buildings, roads, and utility pipelines in the Arctic to rest on firm frozen ground. But as permafrost thaws due to increased air temperature, the ground subsides and infrastructure fails. This paper assesses the current tools used for mapping Arctic geohazard for civil infrastructure planning in the warming Arctic. We formulate an integrated framework to inform science-based decisions and policymaking in response to the ongoing environmental changes. This study first conducts a systematic review of the Arctic geohazard mapping tools. Tools used for Arctic geohazard mapping fall into three categories: analytical or statistical equations for geohazard assessment, modeling approaches for predicting the extent of permafrost degradation, and remote and in-situ sensing for monitoring the natural and built environments and data collection. A description of these tools, along with their limitations and applicability, is provided. Co-production of knowledge is important in developing a robust geohazard assessment tool. Based on the scientific and gray literature, however, we find that the literature of the use of knowledge co-production in the development of evaluation tools outside of health care and public governance is highly sparse. Through the review of Arctic geohazard mapping tools, we provide an integrated framework for Arctic high spatial-resolution multi-geohazards evaluation for civil infrastructure planning. Indigenous knowledge and local observations are included in the proposed framework.

1. Introduction

The Arctic is on the front line of global climate change and is warming up to four times of the rest of the planet (Rantanen et al., 2022). Short-term climate variability and long-term climate change have already induced irreversible damages to Arctic civil infrastructure, threatening Indigenous Arctic communities and the pan-Arctic economy (Romanovsky and Osterkamp, 1997; Nelson et al., 2001, 2002; Lawrence et al., 2008; Romanovsky et al., 2010, 2017; Slater and Lawrence, 2013; Nicolsky et al., 2017; Hjort et al., 2018; Yang et al., 2021). Permafrost, any soil that stays frozen for at least two consecutive years, serves as a foundation material of civil infrastructure in the Arctic. Due to the warming air temperature, permafrost warmed up to 0.39 ± 0.15 °C from 2007 to 2016 (Biskaborn et al., 2019). Climate events in recent years have offered insight into what continued changes might mean for civil infrastructure: permafrost thaw caused ground subsidence

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and threated the foundation of civil infrastructure, coastal erosion induced land loss and forced a coastal retreat, coastal floods inundated coastal regions and affected the road system (Mills and Andrey, 2002; Boyle et al., 2013; Schweikert et al., 2014; Arctic Council, 2015; Marcer et al., 2019; Thaduri et al., 2021). Civil infrastructure damages due to permafrost warming and thawing have been well documented in Canada (L'Hérault et al., 2012; Calmels et al., 2015; Calmels et al., 2018; Levitt, 2019; De Guzman et al., 2021), Alaska (Kettle et al., 2017), Russia (Kronik, 2001; Khrustalev et al., 2011; Grebenets et al., 2012; Streletskiy et al., 2012a, 2012b), Greenland, and Svalbard (Harris et al., 2009; Daanen et al., 2011; Duvillard et al., 2021). Many Arctic regions are experiencing increasing coastal erosion and flooding, resulting in a catastrophic impact on civil infrastructure (Mittal, 2009; Bronen and Chapin III, 2013; Kritsuk et al., 2014; Lemmen, 2016; Denali Commission, 2019; Irrgang et al., 2022). While the damages to civil infrastructure due to climate change may sometimes be gradual, the interactions among permafrost thaw, coastal erosion, and flooding may combine to have significant and rapid impacts on Arctic communities.

The amount of thaw settlement and frost heaving is primarily related to ground ice content. If permafrost is ice-rich, ice melt can result in thermokarst development and uneven terrain. Thermokarst is defined as ground surface subsidence caused by the melting of buried massive ice or abundant ice lenses, which can impact hydrological and ecological processes (Farquharson et al., 2016; Kokelj and Jorgenson, 2013). Warming and thawing permafrost reduces the bearing capacity of piles and footings of civil infrastructure such as residences, public buildings, and elevated utility lines and affects roads and runways. Uneven surfaces created by differential thaw settlement can affect the functionality and serviceability of power lines and pipeline systems for water, sewage, and fuel (Williams, 1995).

The Arctic coast often has relatively high ground ice content, which increases the vulnerability of civil infrastructure to coastal erosion and thawing permafrost. Fig. 1 shows the pan-Arctic ground ice condition and the communities located in the Arctic permafrost region. The yellow points in Fig. 1 illustrate inland communities; the red points indicate coastal communities. A large proportion of coastal communities reside in ice-rich permafrost regions. Mean coastal erosion rates vary from one area to another between 0.00 m per year (Svalbard) to 1.15 m per year (U.S. Beaufort coast) (Lantuit et al., 2012; Irrgang et al., 2022). However, on a more localized scale, erosion rates can be many times higher, with much of the erosion occurred in brief periods (up to 25.1 m per year) (Kinsman and DeRaps, 2012; Gibbs and Richmond, 1978). Such high coastal erosion rates place coastal communities at risk when coastal land loss causes a retreat of the shoreline or riverbank toward infrastructure (Overduin et al., 2014). When a shoreline or riverbank reaches infrastructure, it undermines the foundation material, causing structural failure of buildings, utilities, and transportation facilities (Denali Commission, 2019). Arctic coastal erosion is typically caused by a combined thermal denudation and thermal abrasion (Aré, 1988; Lantuit and Pollard, 2008), which act together to thaw permafrost, melt ground ice, abrade and transport coastal materials offshore (Nielsen et al., 2022).

Flooding can impact civil infrastructure (Mackay, 1986; Mason et al., 2012). Flooding hazards are defined as the inundation of infrastructure or the impassibility of airstrips and roads due to elevated water levels (Denali Commission, 2019). Coastal flooding can be caused by storm surge (Wratt et al., 2004,) and river flooding can be caused by large rain events or aufeis formation and ice jams (Turcotte and Morse, 2013). Flooding becomes a risk to the viability of a community when it threatens the use of and access to critical infrastructure. It also threatens lives when inhabited areas become inundated with moving water, possibly carrying residents downstream or offshore. In addition, waves can wash up over a beach and into developed areas, causing inundation. These events may carry debris into communities, posing a threat to critical infrastructure, housing, and human health (Denali Commission, 2019).

Vulnerable peoples at the heart of the negative impacts play active roles in influencing decision-making, selecting appropriate tools to limit and manage the effects of permafrost degradation, coastal erosion, and flooding, and revealing the human-environmental interdependency in climate adaptation (Berkes and Jolly, 2002; Berkes and Armitage, 2010). In 2021, it was estimated that there were 4,942,685 residents in the pan-Arctic permafrost region, residing in 1162 communities (Ramage et al., 2021; Bartsch et al., 2021). Fig. 2a depicts the proportions of pan-Arctic and coastal communities and the population residing in different types of permafrost regions. Most Arctic communities reside in the sporadic permafrost because most communities and people choose to live in the low-latitude Arctic. However, 42% Arctic communities, and 25% coastal communities reside in continuous permafrost, where the warming rate of permafrost is the highest. In addition, the distribution of communities living on permafrost has significant regional

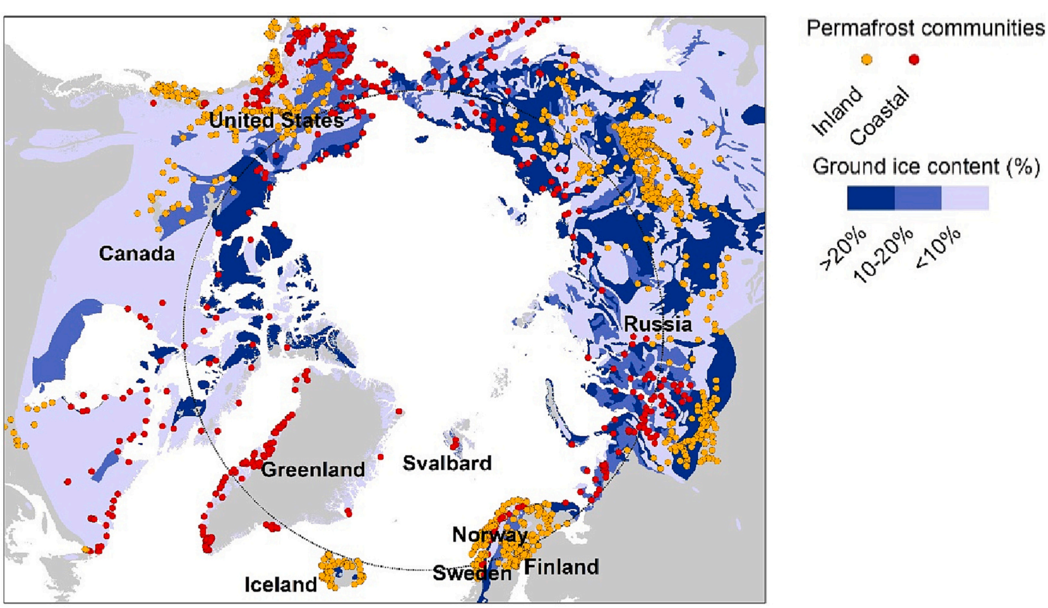

Fig. 1. Pan-Arctic ground ice condition (adapted from Brown et al., 1997); the yellow points illustrate inland communities; the red points are coastal communities (adapted from Wang et al., 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

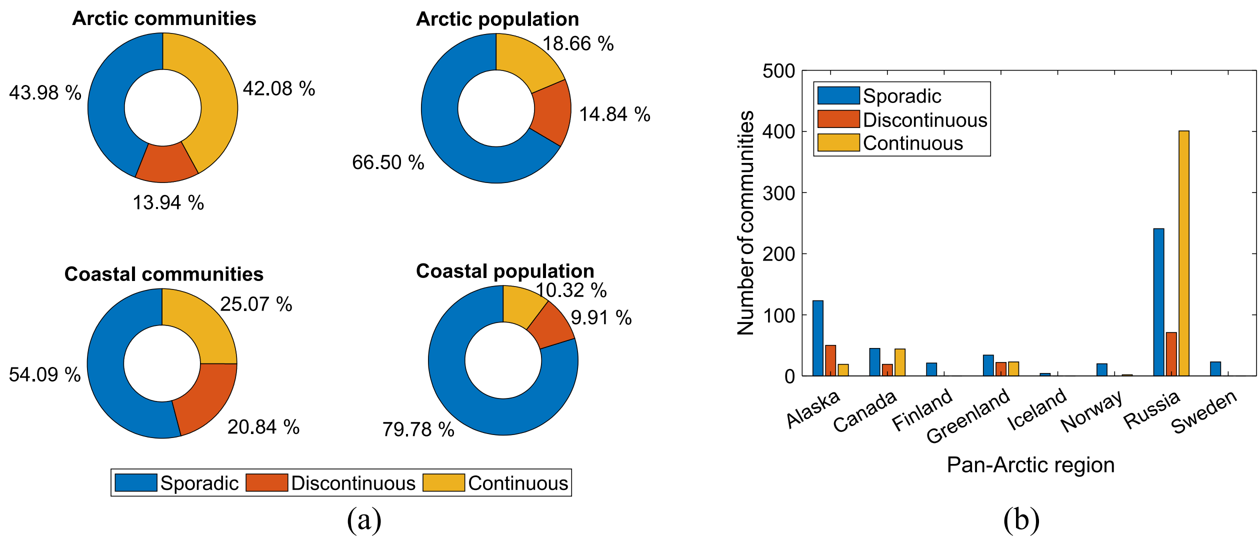

Fig. 2. (a) Proportions of pan-Arctic and coastal communities and populations in different types of permafrost regions in, 2017; (b) the number of communities living in different types of permafrost regions per country in 2017 (data adapted from Ramage et al., 2021).

differences, as shown in Fig. 2b, making the prediction of Arctic geohazards more complex. Therefore, co-producing knowledge with Indigenous communities is vital to aid the adaptation to climate change.

It is essential to predict the rates of permafrost thawing, the magnitude of coastal-erosion-induced land loss, the frequency and intensity of flooding, and their impacts on the performance of civil infrastructures to mitigate potentially catastrophic impacts for Arctic communities. Geohazard maps for monitoring and categorizing risk areas are crucial to adapting to climate change in the Arctic. To date, Arctic geohazard mapping has only been conducted at a relatively coarse spatial resolution (Hjort et al., 2018; Suter et al., 2019; Streletskiy et al., 2023). Due to ongoing and rapid landscape changes across the Arctic, there is an urgent need for mapping geohazard risks at a high spatial resolution to support civil infrastructure planning and design (AMAP, 2017; Obu et al., 2021). Owing to the increasing economic and environmental relevance of the Arctic (Larsen et al., 2014), it is of vital importance to gain detailed knowledge about risk exposure in areas of current and future infrastructure (Melvin et al., 2017). In recent years, several tools have been developed to evaluate the risks and life-cycle costs of Arctic civil infrastructure under various climate scenarios. Hazard-risk modeling of climate change impacts has been successfully applied to inform policymakers and the public about potential future environmental conditions (Arndt, 2003; Monmonier, 2008; Tol, 2018; Ayyub, 2018). However, across the Arctic, infrastructure developers currently rely on sparse data and do not include convergent approaches for high spatial resolution geohazard mapping. Developing integrated tools for Arctic civil infrastructure planning and understanding society's capacity to adapt and transform are crucial for effectively preparing for the continued climate change.

This study reviews the Arctic geohazard mapping tools for civil infrastructure planning. Within this paper, we (1) synthesize the tools used for geohazard mapping in the Arctic; (2) present the role of co-production of knowledge in developing a robust tool for mapping Arctic geohazards; (3) develop an integrated framework for high spatial-resolution, multi-geohazards mapping for Arctic civil infrastructure planning; and (4) present the challenges and limitations of the proposed integrated evaluation framework. This review may be used as a reference for future planning and adaptation of social systems and the built environment to the unprecedented changes in the natural environment of the Arctic.

2. Tools used for mapping Arctic geohazard

2.1. Risk definition and tools selection

Civil infrastructure risks in this study are defined as the multiplication of the following three components: (1) hazard: the probability of occurrence of geohazards induced by Arctic infrastructure threats (i.e., permafrost thaw, coastal erosion, and flooding); (2) vulnerability: the consequences of these events when considering the vulnerability of the site and foundation of civil infrastructure; and (3) exposure: the presence of civil infrastructure's site and foundation in a specific region that could be adversely affected. Predicting and mapping the probability of Arctic geohazards are essential to address the "hazard" component of Arctic civil infrastructure risks.

Various analytical and statistical equations have been developed to predict and map permafrost thawing rates, the magnitude of coastal-erosion-induced land loss, and the frequency and intensity of flooding. These analytical and statistical equations need various physical and environmental properties as inputs. Under such circumstances, permafrost degradation modeling can provide physics-based ground thermal properties, and remote or in-situ sensing can collect high spatial resolution data. To provide an integrated framework for high spatial resolution and physics-based geohazard mapping, we reviewed three main categories of tools for Arctic geohazard mapping: (1) analytical and statistical equations for geohazards assessment, (2) modeling approaches for predicting the extent of permafrost degradation, and (3) remote and in-situ sensing for monitoring the natural and built environments and data collection.

2.2. Analytical and statistical equations for geohazards assessment

We evaluated 11 analytical and statistical equations that have been designed to assess the potential of permafrost thaw, coastal erosion, and flooding for Arctic civil infrastructure. Table 1 and Table 2 review the analytical and statistical equations used for evaluating thawing permafrost and coastal vulnerability, respectively. Description of the equations and their previous applications in Arctic geohazard assessment are included.

Table 1 summarize eight analytical and statistical equations for evaluating thawing permafrost hazards. The formulations and variables used in each equation are shown in Table S1. Each equation considers different sets of hazard-affecting factors. Settlement and bearing capacity are two essential factors that affect civil infrastructure

Table 1
Current analytical and statistical equations evaluating thawing permafrost hazards.

Equations	Applications in Arctic geohazard assessment	Description
Settlement index (Nelson et al., 2001)	Applied to pan-Arctic (Nelson et al., 2001; Hjort et al., 2018; Karjalainen et al., 2019) and local region - Qinghai Tibet Plateau (Ni et al., 2021) risk assessment.	A dimensionless indicator based on the multiplication of two factors: relative changes in the active layer thickness (ALT) (%) and the volumetric ground ice content.
Thaw subsidence model (Streletskiy et al., 2019)	Used for both pan-Arctic (Suter et al., 2019) and local region - Russian Arctic (Streletskiy et al., 2019) risk assessment.	To predict the thaw subsidence of permafrost based on two factors: ALT changes (m) and ground ice content.
Allowable bearing capacity model (Xu and Wu, 2019)	Applied to local region - Qinghai Tibet Plateau (Xu and Wu, 2019; Ni et al., 2021).	Uses empirically derived equations to calculate the changes in permafrost allowable bearing capacity. The empirical equations were established from experimental data with two variables: soil type and mean annual ground temperature.
Bearing capacity model (Streletskiy et al., 2012a)	Used for pan-Arctic (Suter et al., 2019) and local regions, including North Slope of Alaska (Streletskiy et al., 2012b), Northwest Siberia (Streletskiy et al., 2012a, 2012b), and Russian Arctic (Streletskiy et al., 2015; Streletskiy et al., 2019).	Estimates the ultimate bearing capacity of a specific region. The bearing capacity model's input consists of spatially and temporally variable permafrost conditions (maximum ground temperature, soil texture, ice content, and volumetric fraction of peat in mineral ground) and standard pile dimensions.
Risk zonation index (Daanen et al., 2011)	Applied in both circumpolar (Hjort et al., 2018; Karjalainen et al., 2019; Ni et al., 2021) and regional scales- Greenland (Daanen et al., 2011).	A risk assessment procedure based on a classification flow diagram that considers four factors: surface properties, grain size distribution, ice content, and permafrost thaw potential (PTP).
Permafrost settlement hazard index (PSHI) (Hong et al., 2014)	Developed for Alaska geohazard risk assessment (Hong et al., 2014). It has been expanded for pan-Arctic region (Shahabi and Hashim, 2015; Hjort et al., 2018; Karjalainen et al., 2019; Ni et al., 2021).	Identifies thaw subsidence risks in Alaska and considers six factors: ground ice volume, air temperature, soil texture, snow depth, vegetation type, and organic content of the soil.
Analytic hierarchy process (AHP)-based index (Hjort et al., 2018)	Applied to pan-Arctic (Hjort et al., 2018; Karjalainen et al., 2019) and local region – Qinghai Tibet Plateau (Ni et al., 2021) risk assessment.	Based on the AHP, including five variables: ground temperature, ground ice content, relative increase of ALT, fine grained sediment content, and slope gradient.
Destabilization risk index (Duvillard et al., 2015)	Developed for the French Alps permafrost region geohazard risk assessment (Duvillard et al., 2015, 2021).	Assesses local permafrost conditions in the French Alps to identify and rank at-risk infrastructure elements with hazard characterization. Four factors are considered: the passive factors, potential level for destabilization, the potential level of damage according to the infrastructure type, and the index of unitary economic value for an infrastructure element exposure.

Table 2
Current statistical equations for evaluating coastal vulnerability.

Methods	Applications in Arctic geohazard risk assessment	Description
Coastal vulnerability index (CVI) (Gornitz et al., 1994)	Jaskólski et al. (2018) applied CVI for calculating the shoreline changes over the 1990–2009 period in Svalbard.	The input variables include geomorphology, coastal slope, rate of relative sea-level rise, shoreline erosion, mean tide range, and mean wave height.
Coastal sensitivity index (CSI) (Shaw et al., 1998)	Used to calculate the vulnerability of Canadian Arctic coasts (Shaw et al., 1998).	This index combines seven variables: relief, rock type, coastal landform, sea-level tendency, shoreline displacement rate, mean tidal range, and mean annual maximum significant wave height.
Coastal hazard index (CHI) (Arkema et al., 2013)	Arkema et al. (2013) applied CHI for calculating coastal hazard of Alaska.	The index combines seven variables: habitats, shorelinetype, relief, wind, wave, surge potential, sea level rise.

serviceability and foundation performance. As shown in Table 1, the settlement index and the thaw settlement model are two settlement-related tools. Settlement calculation is based on the assumption that the liquid water produced by the thawing of ground ice is drained from the affected sites, and thaw settlement is proportional to the thickness of ice lost. The increase of active layer thickness (ALT) is usually followed by the development of talik, which is defined as a perennially unfrozen zone above or within permafrost (Ferrians et al., 1969). Only considering the changes of ALT without talik may result in underestimates of thaw subsidence (Farquharson et al., 2022). Eq. (1) shows permafrost thaw subsidence considering talik:

$$S = dZ_{ALT+TT} \times V_{ice} \tag{1}$$

where S is the thaw subsidence (cm); $dZ_{ALT+TT} = d(Z_{ALT} + Z_{TT})$ is the change of combination of ALT and talik thickness (TT) (cm); V_{ice} is the volumetric ground ice content (%).

The thaw subsidence predictions for North Slope Borough (NSB) of Alaska in the 2060s under RCP8.5 are shown in Fig. 3. Higher thaw subsidence occurs in the low-latitude upland regions of NSB when compared with the thaw subsidence model without considering talik. We used the Geophysical Institute's Permafrost Laboratory (GIPL-2) model (Nicolsky et al., 2017) to predict ALT and TT (in Supplementary Fig. S1). The ground ice map is adopted from Karjalainen et al. (2022) (Fig. S2).

Table 1 lists: the ultimate bearing capacity model and the allowable bearing capacity model. The ultimate bearing capacity model estimates the maximum structural load that can be carried by a foundation at a given reference depth (10 m) into permafrost (Streletskiy et al., 2019). The ultimate bearing capacity of a vertically loaded friction pile can be approximated as the sum of normal stress at the base of the pile and shear stress on the pile sides in contact with permafrost. The normal stress and the shear stress can be determined by a series of empirically derived equations, depending on the maximum ground temperature, soil texture, ice content, and volumetric fraction of peat in mineral ground (Russian Construction Norms and Regulations (CNR), 1990). The allowable bearing capacity model (q_a) proposed by Xu and Wu (2019) also uses a series of statistical equations related to mean annual ground temperature (MAGT) for different soil types (Eq. 2).

$$q_a = -0.3959MAGT + 0.6092 \quad \text{(gravel)}$$

$$q_a = -0.3021MAGT + 0.4954 \text{ (coarse sand).}$$
$$q_a = -0.3021MAGT + 0.3454 \text{ (fine sand, silt).}$$

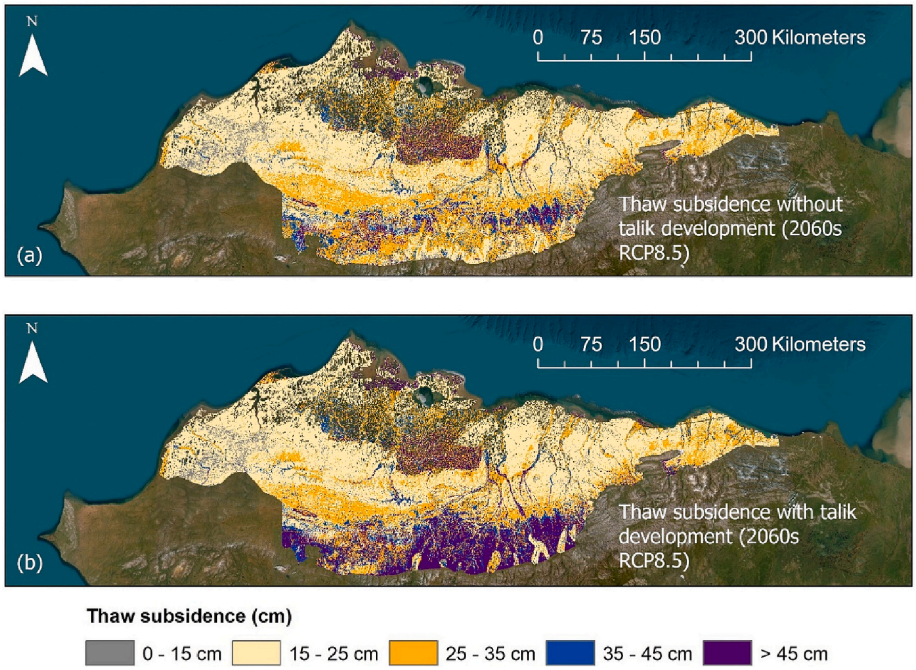

Fig. 3. Ground thaw subsidence (cm) of Alaska North Slope Borough from 2020s to 2060s under RCP8.5. (a) without talik development; (b) with talik development.

$$q_a = -0.1979MAGT + 0.3046 \text{ (clay, sandy loam)} \tag{2}$$

We applied the allowable bearing capacity statistical model (Xu and Wu, 2019) to Alaska NSB as an example. The distribution of soil types and MAGT (Fig. S3) are derived from the GIPL-2 model. The results in Fig. 4 show that the coastal low-land has higher q_a compared with the inland region, primarily driven by lower MAGT in the coastal region. The q_a of NSB will significantly decrease in the 2060s because of increasing MAGT. The establishment of the empirical or statistical equations depends on limited data for specific regions (e.g., the Russian Arctic; Qinghai-Tibet Plateau). In-situ or laboratory testing is needed to determine bearing capacity for specific regions. Input data of finer spatial scale are also needed to produce a higher spatial resolution map to aid civil infrastructure planning.

Other tools exist for thawing permafrost hazard assessment. The risk zonation index determines the risk of permafrost degradation based on a flow diagram with relatively simple parameters. Its classification

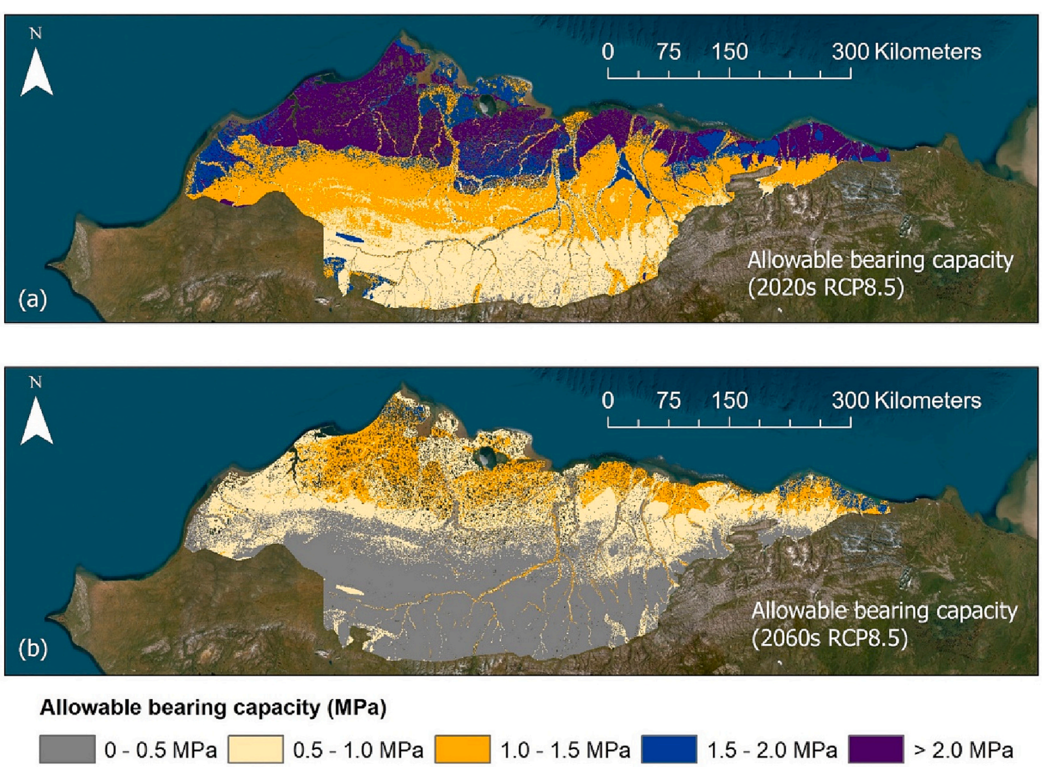

Fig. 4. Distribution of permafrost allowable bearing capacity (MPa) of Alaska North Slope Borough using RCP8.5. (a) the year 2020s; (b) the year 2060s.

process is based on Greenland permafrost. Site-dependent classification for any specific region is recommended for high-resolution hazard prediction. The analytic hierarchy process-based index and the permafrost settlement hazard index (PSHI) were developed based on the Analytic Hierarchy Process (AHP). AHP is an efficient decision-making approach to examining complex problems, such as the specification of the relative roles of factors affecting natural hazards (Saaty, 1977, 2008; Shahabi and Hashim, 2015). However, the judgment of the relative importance of each variable is subjective. The destabilization risk index includes the vulnerability of infrastructure in calculating the risks and provides a qualitative risk assessment for infrastructure on permafrost in regional scale. However, it has limitations due to scaling issues, where the data set does not consider the local disturbance due to human activities and infrastructure (Duvillard et al., 2021). It may be more significant to consider the effects of human activities and infrastructure than the effect of global warming in local scale (Duvillard et al., 2021).

For evaluating coastal erosion and flooding hazards, numerous statistical tools have been developed to assess coastal vulnerability. For example, Gutierrez et al. (2014) used the Bayesian network to predict shoreline-change vulnerability for the coasts of the United States. Nguyen et al. (2016) synthesized 53 vulnerability indices used for evaluating coastal vulnerability under the impact of climate change. However, most of these tools focus on non-Arctic coasts. As shown in Table 2, we reviewed three statistical methods that have been applied to evaluate the Arctic coastal vulnerability: the coastal vulnerability index (CVI), the coastal sensitivity index (CSI), and coastal hazard index (CHI). The formulations and variables used in each tool can be found in Supplementary Table S2. Calculations of CVI and CSI follow the same methodology as the square root of the product of the scored variables divided by the total number of variables. The CHI calculates the geometric mean of input variables to represent the potential coastal hazards. Despite recent efforts by applying CVI for coastal vulnerability assessment in Longyearbyen, Svalbard, and CHI for Alaska coastline hazard assessment, statistical tools have received little attention in assessing Arctic coastal vulnerability. Current coastal vulnerability indices lack permafrost-related variables such as ground ice content, ground temperature, and ALT. There is a need for future work on the development of CVI, CHI, or other statistical tools incorporating Arctic-related variables to improve the applicability.

2.3. Modeling approaches for permafrost degradation

The modeling approaches reviewed in this study are physics-based and use physical mechanisms to simulate permafrost degradation. The physics-based models have the potential to determine the timing and extent of future Arctic civil infrastructure damage. Existing modeling approaches for evaluating Arctic civil infrastructure risks under permafrost degradation are summarized in Table 3. The analysis of each model includes: applicable spatial scale, advantages, limitations, and examples of specific models.

Existing thawing permafrost models generally fall into three groups, i.e., geotechnical models, land surface models, and process-based tiling models (Schneider von Deimling et al., 2021). The geotechnical models are subsurface heat and mass transfer models that can simulate freeze-thaw processes and are based on mathematical, physical laws and constitutive equations. These models couple phase change with fluid flow, i.e., thermo-hydro (TH) modeling. More complex thermo-hydro-mechanical (THM) models can be used to understand the responses of civil infrastructure, considering site-specific conditions in fine spatial scale and the relationships between various physical mechanisms. Examples of TH and THM models are summarized in Table 3. A strength of the THM models is the coupling of mechanical process and the thermohydraulic process and the capability to provide site-specific condition diagnostics in the form of stability and deformation measures, failure modes, and quantification of time to failure. These advantages of thermo-hydro or thermo-hydro-mechanical models allow them to become an essential tool for predicting the civil infrastructure performances in the Arctic. However, owing to the complexity of the modeling of highly coupled physical processes, these modeling tools are limited to fine scales with high computational costs. And the impact of civil infrastructure on permafrost thaw has rarely been considered in existing geotechnical models in Arctic.

The second group of models is the land surface models, which is the land component of earth system models. Land surface models can be used to describe the exchange processes of water and energy fluxes at the land surface-atmosphere interface and ultimately enable the feedback from land to the climate system (Aas et al., 2019). Examples of land surface models are shown in Table 3. These modeling tools are computationally efficient and can be applied globally. The development of these models is based on large-scale physical thaw processes and biogeochemical cycles of soil carbon release. However, the permafrost thawing processes represented in the current land surface models tend to be rather simplistic because of the significant uncertainties of the dynamics of permafrost, mainly due to a lack of observational knowledge (Alexeev et al., 2007; Nicolsky et al., 2007; Burke et al., 2020). The projections of permafrost thaw vary substantially in distribution and magnitude depending on the model used (Yokohata et al., 2020). The land surface models also have not incorporated the impact of civil infrastructure on the permafrost thawing processes.

The process-based tiling model is the third group of models to model the interactions between climate warming, permafrost degradation, and civil infrastructure (Schneider von Deimling et al., 2021). The term "process-based tiling" means the consideration of the dynamic interactions among the tiles modeling; tiles are defined as spatially

Table 3
Analysis of existing modeling tools for evaluating permafrost degradation.

Tools	Applicable spatial scale	Advantages	Limitations	Examples
Geotechnical models	Site-specific, fine scale	Coupled mechanical processes in modeling	It has high computational costs; current models are only applied to fine spatial scale; the impact of civil infrastructure has rarely been included in current models in the Arctic	• Thermo-hydro (TH) model (Harlan, 1973; Hansson et al., 2004) • Thermo-hydro-mechanical (THM) model (Thomas et al., 2009; Nishimura et al., 2009; Yamamoto et al., 2013; Zhang and Michalowski, 2015)
Land surface models	Global, regional scale	Computational efficient in long-term, and large-scale modeling	Key processes for modeling permafrost thaw are not considered; it cannot capture localized permafrost thaw; the impact of civil infrastructure has rarely been included	• CCSM4.0 (Lawrence et al., 2011) • GFDL-ESM (Dunne et al., 2012) • MRI-CGCM3 (Yukimoto et al., 2012) • HadCM3 (Martens et al., 1999) • IPSL-CM5 (Dufresne et al., 2013)
Process-based tiling models	Both fine and regional scales	Reducing modeling complexity, resolving key processes for capturing civil infrastructure-affected permafrost thaw	It lacks sufficient applications on both small and large scales when incorporating the effect of civil infrastructure in the Arctic	• GIPL2.0 (Marchenko et al., 2008) • CryoGrids3 (Westermann et al., 2016)

implicit aggregations of the area within a grid cell in a particular land surface category, and they are used to represent landscape heterogeneity (Fisher and Koven, 2020). These modeling tools aim to reduce the complexity of modeling and resolve key processes for capturing infrastructure-affected permafrost thaw. Examples of process-based tiling models include GIPL2.0 (Marchenko et al., 2008) and CryoGrid3 (Westermann et al., 2016). Daanen et al. (2011) used GIPL2.0 to model the current and future states of permafrost in Greenland driven by large-scale climate projection. Nitzbon et al. (2019, 2020) used CryoGrid3 to capture the dynamic mechanism of tundra degradation. Schneider von Deimling et al. (2021) used CryoGrids3 to simulate the thermal regime of permafrost under a specific infrastructure in Prudhoe Bay, Alaska.

We show an application of the GIPL2.0 model to simulate the MAGT of NSB, Alaska in the 2020s and 2060s using RCP8.5 (Fig. 5). The model predicts the ground temperature by numerically solving the 1D quasi-linear heat conduction equation with phase change. Because of data deficiency, the current GIPL2.0 model with 1 km spatial resolution lacks the ability to be applied to community scale for civil infrastructure planning. In addition, it requires future studies to link these process-based tiling models with the THM models and land surface models to consider more mechanism of permafrost degradation.

2.4. Remote and in-situ sensing for monitoring and data collection

Remote sensing techniques are increasingly becoming a critical tool for monitoring landscape changes in remote Arctic circumpolar permafrost regions due to advances in technologies and an increase in the number of sensors providing suitable data (Jorgenson and Grosse, 2016; Grosse and Jones, 2018; Bartsch et al., 2020; Beamish et al., 2020). Remote sensing, including optical, thermal-infrared, and microwave remote sensing, has been used to monitor the near-surface soil freeze-thaw and permafrost state directly or indirectly in the Arctic circumpolar permafrost region. It is based on a growing array of satellite, airborne, and terrestrial platforms that cover a wide range of spatial and temporal scales and increasingly allow robust detection of changes in Arctic permafrost landscapes (Jorgenson et al., 2008; Nitze et al., 2018; Van der Sluijs et al., 2018; Parsekian et al., 2021).

A literature review was carried out to illustrate the development of remote sensing applications for monitoring permafrost thaw, coastal erosion, and flooding. As can be inferred from Fig. 6a, there has been rapid growth in the number of remote sensing studies. The applications of remote sensing in the Arctic can be grouped mainly into three categories: (1) identifying and mapping surface features and objects typical for permafrost areas (Jiang et al., 2020; Bergstedt et al., 2021; Philipp et al., 2021); (2) retrieving physical variables directly or indirectly relevant to subsurface thermal conditions (Tedesco et al., 2015; Pastick et al., 2015; Zwieback and Meyer, 2021); and (3) tracking permafrost region changes over time using remote sensing time series datasets (Nitze et al., 2018; Bartsch et al., 2021; Clark et al., 2021). The most applied remote sensing techniques relative to Arctic civil infrastructure geohazards are for permafrost thaw monitoring (Fig. 6a).

In-situ sensors can directly monitor and measure the geophysical and geomechanical properties of degrading permafrost. The in-situ properties can be used to forecast and map geohazards in the Arctic for building and maintaining civil infrastructure. There is a diverse spectrum of in-situ sensors. However, it is challenging to maintain in-situ instrument safety, power supply, communications, and data transfer due to the extreme climatic conditions in cold regions. Fiber-optic distributed sensing is an in-situ sensing technique with a fast-growing number of applications in all latitudes (Fig. 6b). We provide a literature review of the number of publications using fiber-optic distributed sensing including distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) in the Arctic (Fig. 6b). In contrast to conventional geophysical testing using spatially discrete geophones, distributed sensing utilizes a single optoelectronic interrogator unit that can sample tens of kilometers of optical fiber at sub-meter sensor spacing.

The fiber-optic distributed sensing has unique and attractive characteristics that allow its deployment in the Arctic: it can transform tens of kilometers of telecommunication fiber-optic cables into a system that obtains distributed measurements without requiring additional components (Zhu and Stensrud, 2019); it is low-maintenance once embedded in the ground (Martin et al., 2017); fiber-optic cables are inexpensive (on the order of $1 per meter), flexible, and insensitive to electrical noise; and the distributed sensing interrogator unit only requires a standard AC power source.

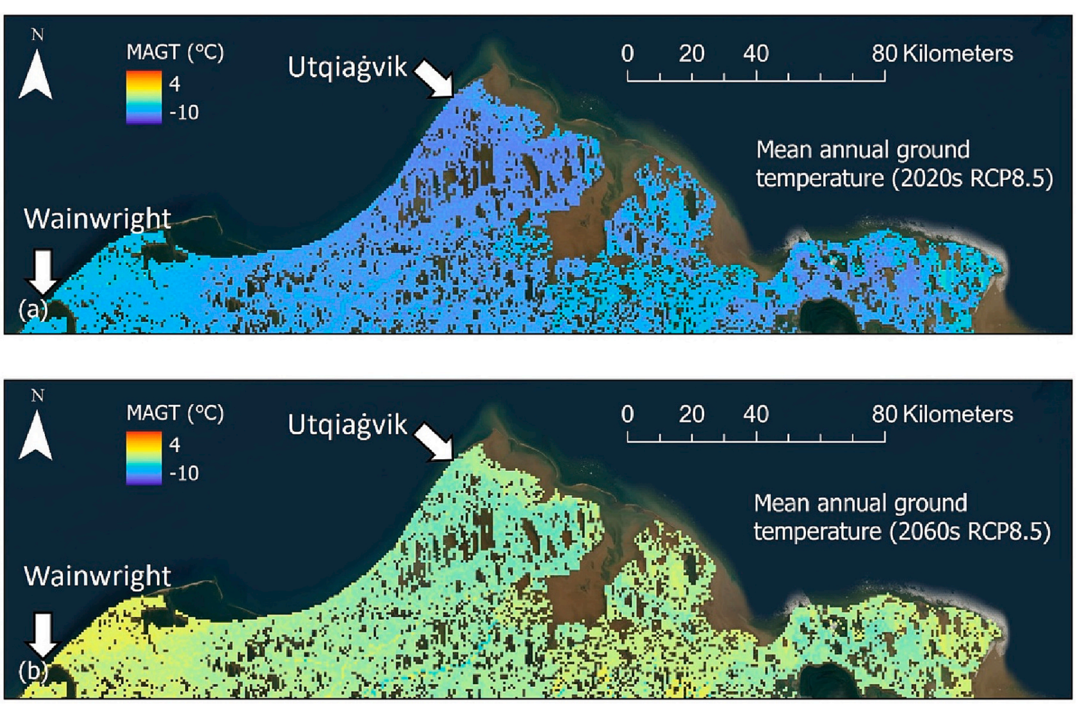

Fig. 5. Application of GIPL2.0 model for evaluating mean annual ground temperature of Alaska, NSB. (a) 2020s using RCP8.5; (b) 2060s using RCP8.5.

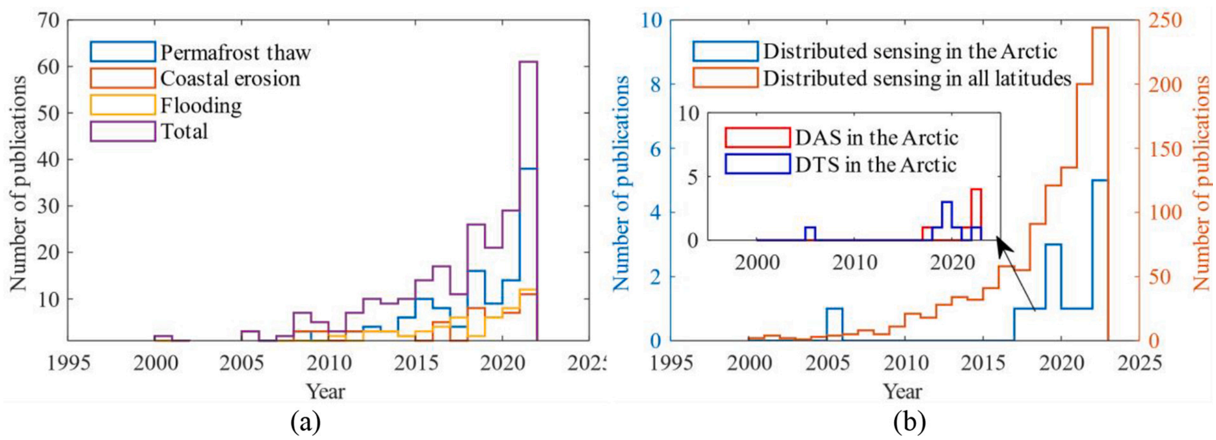

Fig. 6. Data characteristics from a literature survey of peer-reviewed publications on the applications of remote and in-situ sensing techniques to the Arctic region. (a) Remote sensing based on 227 peer-reviewed publications; (b) distributed fiber-optic sensing based on 13 peer-reviewed publications (in the Arctic). Data source: Web of Science; period 2000–2022; survey criteria and collected data can be found in Tables S3 and S4.

3. The role of co-production of knowledge in developing a robust tool for mapping geohazard

Arctic geohazard evaluation using mapping tools that are reviewed in previous sections provides an estimation of the occurrence probability of spatially-distributed geohazard. The continued engagement with the communities to enable genuine co-production of knowledge is vital to apply these tools in evaluating geohazards at the local community level. For example, a community survey can be conducted in Arctic villages on civil infrastructure affected by various types of Arctic geohazards. Community-scale geohazard evaluation is then conducted based on a statistical analysis of the survey data. Such high-resolution geohazard evaluation can be incorporated into the large-scale geohazard map created by tools that are reviewed in Section 2. An example of such survey-based geohazard maps using knowledge co-production with Arctic communities can be found in Liew et al. (2022).

Residents of Indigenous communities are keen observers of the local environment, including changes in hydrology, coastal and riverine erosion, ground subsidence, vegetation changes, etc. Fig. 7 shows an example of local observations of civil infrastructure damage due to permafrost thaw (Fig. 7a) and coastal erosion (Fig. 7b). Such observations are generally highly detailed and at a finer scale than many of the remote and in-situ sensors or existing mapping can provide (Eicken et al., 2022). They also extend over much longer periods than most scientific or engineering studies can and may provide information on extended sequences of changes. Residents have often experienced failure of older infrastructure and may be able to give detailed sequential descriptions of what happened.

In general, the co-production of knowledge requires a problem-oriented approach with a focus on specific outcomes (Roué and Nakashima, 2022). Development of an evaluation tool would be one of the outcomes of collaboration, most likely one that would be an early focus of the work since determining all the relevant dimensions for the evaluation could serve to guide the actual engineering and design work. It should also be useful in building and sustaining a collaborative effort that can result in the true co-production of knowledge.

To this point, the co-production of knowledge has been most prominent in areas such as healthcare (Filipe et al., 2017), wildlife biology (Gadamus et al., 2015; Huntington et al., 2002; Johannes, 1978; Kofinas and Braund, 1998,) and sea ice research, where it quickly became clear to researchers that Indigenous residents had a far more fine-grained understanding of the phenomena of interest than was possible with the tools available to non-resident sciences (Eicken et al., 2022). More recently, it has been applied to other aspects of science relating to global environmental change. However, while there is a growing literature addressing the evaluation of efforts on the co-production of knowledge in various settings (Brix et al., 2020; Norström et al., 2020), the literature regarding the use of co-production in the development of evaluation tools outside of health care and public governance is extremely sparse.

(a) (b)

Fig. 7. Local observations of civil infrastructure damage due to permafrost thaw and coastal erosion in the Arctic (photo credit: Benjamin M. Jones): (a) Exposed pilings under a residential structure in Alaska; (b) Residential structure damage due to coastal erosion in Alaska.

4. An integrated framework for Arctic high spatial-resolution muti-geohazards mapping

4.1. Framework of an integrated tool

Geohazard evaluation tools, sensing techniques, and knowledge co-production are growing rapidly in the Arctic research but mostly work separately. Across the Arctic, the lack of high spatial resolution data and convergent approach limits the ability of current tools to create high-resolution multi-geohazards assessment for civil infrastructure planning. There is an urgent need to develop robust evaluation tools to aid civil infrastructure planning and adaptation. The definition of risks demonstrates that the built environment in the Arctic does not exist in isolation but should be evaluated entirely. Recently, efforts have been made to create coupled predictive tools for Arctic coastal erosion in several studies (Frederick et al., 2016; Afzal and Lubbad, 2019). These integrated tools couple three physical processes in modeling Arctic coastal erosion. These physical processes include changing oceanographic condition, the thermal state of permafrost, and the stress state of the coastal permafrost. The integrated tools for the Arctic coast consist of four different types of models: the Earth system model to provide boundary conditions; the hydrodynamic module to calculate flow, sediment transport, and wave propagation in ice; the thermal permafrost model to provide permafrost temperature field, ice content, bulk density to the Arctic coastal erosion model (Afzal and Lubbad, 2019). Such integrated predictive tools allow us to couple various types of modeling approaches. They provide an example for developing an integrated tool to evaluate the geohazard and potential of future infrastructure failure in the warming Arctic. But these predictive tools were only designed specifically for Arctic coastal erosion modeling.

This paper presents an integrated framework (Fig. 8) for evaluating and mapping the Arctic multi-geohazards with high spatial-resolution; it considers thawing permafrost, and Arctic coastal vulnerability. The integrated framework includes three tasks: (1) high spatial-resolution data collection, (2) permafrost degradation modeling, and (3) Arctic multi-geohazards mapping. In the first task, the obtained environmental or physical data will be utilized in task 2 (degrading permafrost modeling) (process #1) and task 3 (geohazards mapping) (process #3). Remote and distributed fiber-optic sensing can assess surface deformation that is used to determine geophysical and geomechanical properties of soil in a high spatial and temporal resolution. The framework integrates Indigenous knowledge in the data collection process, as shown in the example in task 1 of Fig. 8. The large-scale geohazard maps can also directly integrate the Indigenous knowledge. For instance, community-scale geohazard maps can be created based on local observations and statistical analysis of geohazards (Liew et al., 2022).

In the second task, we present the potential of linking the coarse-scale land surface and fine-scale geotechnical models to the process-based tiling model for predicting the extent of permafrost degradation in the Arctic (after Schneider von Deimling et al., 2021). The process-based tiling model can support both the geotechnical model in fine-scale modeling and the land surface model in coarse-scale modeling. We show an application of the GIPL2.0 process-based tiling model in NSB, Alaska (in task 2 of Fig. 8). The results depict the spatially distributed MAGT of NSB, Alaska in the 2020s and 2060s. The high-latitude lowland of NSB has low annual temperature compared with low-latitude upland. To provide a high-resolution ground temperature map, the numerical model utilizes the high spatial-resolution physical data from task 1. The output of task 2, including MAGT, ALT, TT in spatial distribution can be used for multi-geohazards evaluation in task 3 (process #2).

In the third task, the holistic framework integrates settlement, bearing capacity, and coastal vulnerability index for multi-geohazards evaluation. For example, the settlement and bearing capacity indexes can serve as input variables for the Arctic coastal vulnerability index. These three analytical and statistical indices are coupled with the multi-scale simulation results from the modeling approaches (task 2) and high-resolution environmental data (task 1) to provide an Arctic multi-geohazards map with high spatial-resolution evaluation. This integrated index can be plotted in current infrastructure map with Geographic Information System (GIS) to create an infrastructure hazard map. We show an example of applying a simple settlement index proposed by Nelson et al. (2001) to the pan-Arctic region by Hjort et al. (2018) (in task 3 of Fig. 8). The result shows the pan-Arctic thaw settlement hazard potential in the period 2041–2060. With the proposed integrated framework, the Arctic high-resolution multi-geohazards maps are created. The maps can be utilized as decision-making tools by policymakers, and the public to increase the resilience of communities

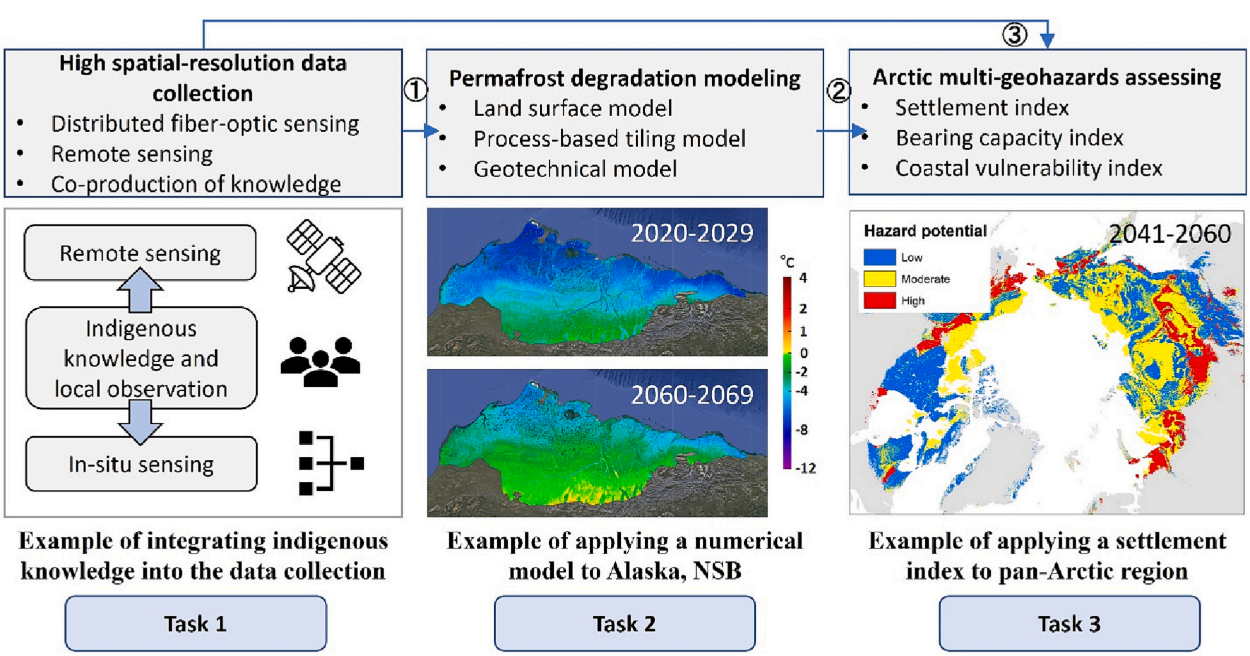

Fig. 8. An integrated framework for Arctic geohazard mapping. MAGT of NSB are derived from a numerical model provided by the GIPL2.0 of UAF (Map (alaska.edu)). Pan-Arctic thaw subsidence hazard map is adopted from Hjort et al. (2018).

and to adapt to the changing environment.

4.2. The challenges and limitation of the integrated framework for Arctic geohazard mapping

The limitation of the integrated framework is spatial scaling. For fine-scale analysis with high spatial-resolution data, the precision of assessment results may be limited by the finite variables that are constituted in the statistical or analytical equations. The assessment oversimplifies the dynamic interactions of the complex geohazard processes.

Arctic communities face challenges when applying the integrated tool to aid the future adaptation of social systems and the built environment to the unprecedented changes in the natural environment of the Arctic. The application of the integrated tool requires complex and convergent efforts, which will be conducted by transdisciplinary teams (scientists and engineers), Indigenous Peoples, and the government. These challenges arise from three aspects: policy and decision-making, social system, and research system. The limited decision-making power at local levels can result in negligible progress overall (Albert et al., 2018). For example, relocating high-risk villages in Alaska has been postponed even though researchers have recognized the high risks of the community civil infrastructures (Ford et al., 2021). From the social system perspective, the ties between research teams and Indigenous people are still weak when applying the integrated tool. Developing workshops may be an effective strategy to promote producing and communicating knowledge among Arctic communities. For the research system, the challenges of applying the integrated tool can be the collaborations among natural, social scientists and engineers. Hence, true convergent collaborations between engineering and scientific communities are necessary.

5. Summary and conclusions

The aim of this study is to synthesize existing tools for mapping the geohazard-induced risks of civil infrastructure in the Arctic and to provide an integrated framework, which will ultimately lead to a new understanding of the ongoing climate change and its impact on the Arctic community. A systematic review is conducted on the current geohazard mapping tools that are used for Arctic civil infrastructure. Tools selected in this study fall into three categories: analytical and statistical equations for assessing geohazards, modeling approaches for evaluating permafrost degradation, and remote or in-situ sensing techniques for monitoring and collecting environmental and physical data.

A description of analytical and statistical equations used to evaluate permafrost thaw and coastal vulnerability, along with their limitations, applicability, and recommended improvement, is provided. Then, we conduct an analysis of modeling approaches, including the descriptions of their applicable spatial scales, advantages, limitations, and examples of the specific models. Through a literature review, we find there has been rapid growth in the number of remote and distributed fiber-optic sensing studies. The most applied remote sensing techniques relevant to Arctic civil infrastructure geohazards are for permafrost thaw monitoring. The fiber-optic distributed sensing has unique and attractive characteristics that allow their potential deployment in the Arctic.

Residents of Indigenous communities are keen observers of the local environment, including changes in hydrology, erosion, subsidence, and vegetation changes. There is growing literature addressing the evaluation of efforts of the co-production of knowledge in various settings. We discuss the role of the co-production of knowledge in developing a robust geohazard assessment tool. Based on the scientific and gray literature publications, we find that the literature regarding the use of co-production in the development of evaluation tools outside of health care and public governance is highly sparse.

We present an integrated framework for developing a holistic Arctic high spatial-resolution multi-geohazards assessment tool. This comprehensive framework integrates high spatial-resolution data collection, permafrost degradation modeling, and multi-geohazards evaluating process. Finally, we discuss the challenges and limitations of the proposed integrated framework.

Author contributions

Z.W. led the original draft preparation and visualization. M.X. led the initiation and conceptualization of this paper. All co-authors provided input on the manuscript text, figures, discussion of scientific content, and editing. In addition, A.J. drafted the section on knowledge co-production. B.M.J. contributed to the section on remote sensing. M.L., D.N., L.F., V.R., C.M. contributed to the conceptualization and organization of the paper outline and content. X.Z. and L.A. contributed to the conceptualization of the paper.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

Source data for Fig. 3, Fig. 4, Fig. 5, and Fig. 6 are available in Supplementary Dataset. All other data supporting the findings of this work are available from the corresponding author upon reasonable request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.coldregions.2023.103969.

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