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Risk governance of climate-related hazards in Longyearbyen, Svalbard: A review of risk governance approaches and knowledge gaps

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ABSTRACT

Climate-related risks pose challenges to communities globally as changing climatic conditions alter the patterns of natural hazards which threaten human lives and infrastructure. In Longyearbyen, Norway, in the High Arctic Svalbard archipelago, climatic changes presently occur at rates well in excess of global means, with corresponding changes to climate-related risks requiring new and improved risk governance strategies. Here, we present the results from a literature review investigating how recent advances in climate-related risk governance can help inform risk governance strategy development in Longyearbyen. The literature identified in our work indicates recent research into the governance of climate-related risks has focused to a large extent on flooding or landslides. Successful risk governance in the reviewed literature often included data collection of both environmental and social information and emphasized local, context-specific knowledge via bi-directional risk communication throughout the risk governance process. We identified knowledge gaps in the literature review. First, there is a missing societal safety perspective on climate changes and natural hazards: much of the identified literature views the climatic changes and natural hazards either through a physical process-based perspective rooted in the natural sciences, or focuses on physical mitigation measures, without considering the interaction of nature, technology, and society. Second, there is a lack of research on data collection and analysis strategies that combine the acquisition of local knowledge via a discourse-based approach with data and knowledge generated from sensors or physical models via a technical approach. Third, more research is required on uncertainty assessment and handling in the risk governance process. Fourth, there is missing consideration of short-term disaster handling approaches – especially in relation to relatively more frequent consideration of long-term climate adaptation strategies. Finally, as none of the reviewed works specifically addressed risk governance in an Arctic setting, we discuss how the results from this literature review and the proposed risk governance framework can help transfer knowledge to Longyearbyen's context. Our results help clarify current knowledge related to the governance of climate-related risks and provide a foundation for future work in Arctic locations.

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1. Introduction

Climate-related risks stem from natural hazards posed by changing climatic conditions. Changes to the hydrologic cycle (e.g. Gudmundsson et al., 2021; Yang et al., 2021), the cryosphere (e.g. Khan et al., 2014; Stroeve et al., 2012; Thackeray et al., 2019), and the increasing frequency and magnitude of extreme weather and climate events (Clarke et al., 2022; Walsh et al., 2020) all relate to the increasing air temperatures which broadly typify global climatic changes. As these geophysical systems and their associated natural hazards undergo sometimes dramatic changes, new, often unprecedented patterns of risk can emerge. Characterized as systemic risks due to the manner in which the physical hazards (e.g. extreme weather, flooding, and sea-level rise) related to climatic changes can propagate across interconnected geophysical and anthropogenic systems, these climate-related risks present a complex challenge for humanity. In addition to the broad, societal impacts of climate change, climate-related risks also pose direct human health impacts via, for example, affecting patterns of drowning (Sindall et al., 2022) or heat-related injuries (Ebi et al., 2021).

Risk governance provides a conceptual foundation on which to base efforts to manage complex, systemic risks such as those posed by climatic changes. Risk governance involves applying the principles of governance – the processes and institutions by which groups arrive at decisions – to situations with uncertain consequences, or risks (e.g. Renn et al., 2011). This involves integrating risk analysis and risk management procedures with a wide range of interconnected actors, viewpoints, activities, and goals (e.g. IRGC, 2017). Various frameworks, therefore, exist to help clarify and formalize the complex processes and concepts comprising risk governance. Well-recognized existing risk governance frameworks include the International Organization for Standards (ISO)'s Risk Management Guidelines (International Standards Organization, 2018), the International Risk Governance Council (IRGC)'s Risk Governance Framework (IRGC, 2017), and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015). While developed to handle complex, systemic risks, none of these frameworks explicitly address the combination of active climate adaptation and implementation of mitigation measures highlighted by the latest International Panel on Climate Change (IPCC) report (IPCC, 2022) as necessary to handle climate-related risks. Demonstrating how risk governance approaches can support risk handling at the intersection of climate change, natural hazards, and society's functions and infrastructures will generate valuable knowledge needed to understand and improve mitigation of climate-related risks.

The research project "Risk governance of climate-related systemic risk in the Arctic" focusing on climate-related risks in Longyearbyen, Norway, the administrative center of the High Arctic Svalbard archipelago (Fig. 1) serves as the basis for the present study. Located at 78°N on the eastern margins of the Barents Sea, Svalbard has experienced among the fastest warming globally, with average temperature increases on the order of 7 °C over land during the winter months over the last forty years (Hanssen-Bauer et al., 2019). This places Svalbard squarely at the forefront of realized recent climatic changes, even in the context of Arctic Amplification (e.g. Cohen et al., 2014; Rantanen et al., 2022) where the high-latitude North warms at four times the rate of lower latitudes. This warming has coincided with progressively wetter conditions across the Arctic, with net precipitation (snow and rain) and the fraction of precipitation falling as rain both increasing in recent decades (AMAP, 2021).

Longyearbyen's physical setting in close proximity to steep mountain slopes and along the banks of a glacially-fed river system exposes the settlement to a variety of natural hazards. In the last decade Longyearbyen has experienced:

- a slush avalanche – the first ever recorded in Longyearbyen during the winter season – that destroyed a pedestrian bridge near the city center (Serreze et al., 2015)
- large snow avalanches that struck infrastructure in 2015 – resulting in two fatalities – and again in 2017 (Hancock et al., 2018)
- heavy autumn rains contributed to multiple landslides in autumn affecting infrastructure in 2016
- an active coal mine flooded following extreme heat and a new all-time temperature record in July 2020.

These events, superimposed upon the dramatic climate changes underway throughout Svalbard, emphasize the need for continued

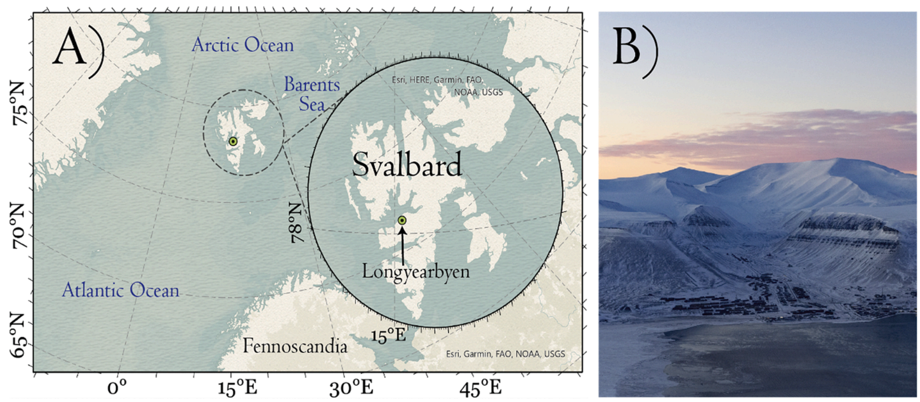

Fig. 1. Svalbard's physical setting in the High Arctic (panel A) and Longyearbyen's specific location with close proximity to steep mountain slopes and a glacially-fed river (panel B) result in exposure to a variety of natural hazards and climate-related risks.

improvements to the way societies – especially those in remote, Arctic settings such as Longyearbyen – handle climate-related risk.

Longyearbyen's societal context differentiates the settlement from many other Arctic locations facing dramatic climate changes and, in many ways, forms a unique case in the circumpolar regions. Perhaps most strikingly, the area does not have an indigenous population and the settlement's inhabitance has always centered around discontinuous periods of exploration and resource exploitation (Arlov, 2003; Sokolíčková, 2022). Transience and asynchronicity in both human population (Arlov, 2003; Kotašková, 2022; Sokolickova et al., 2022) and knowledge (Johannessen, 2022; Sokolickova et al., 2022) therefore characterize Longyearbyen and Svalbard's social context. The Longyearbyen society has been taking significant steps in climate adaptation to ensure a sustainable and resilient society for several years now. One of the reasons for this development is the Norwegian government's active interest in maintaining Svalbard's status as sovereignly Norwegian affords the municipality considerable financial resources for climate adaptation and mitigation measures not available to similarly remote locations (e.g. Kaltenborn et al., 2020; Meyer, 2022).

In this work, we seek to improve the understanding of climate-related risk and identify strategies for improving the risk governance process both locally and in other locations where climate change threatens human activities. This includes identification of knowledge gaps in the current research literature on risk governance of climate changes' effects on natural hazards and its impact on society. These knowledge gaps will serve as an important foundation for future research on risk governance of climate-related risks in societies, in particular for the relevant case of research on climate change and climate adaptation in Longyearbyen and other places that experience a huge impact of climate changes on society. We structure the literature review around the following specific research questions:

1) *How does the reviewed literature consider climate change in the elements of risk governance? and*
2) *To what extent can we transfer knowledge on climate-related risk governance into Longyearbyen's Arctic setting?*

Finally, we discuss the results from the literature review in the context of identified knowledge gaps, our proposed risk governance framework, and the climate-related risks currently experienced in Longyearbyen. This work emphasizes the importance of risk governance approaches which can frame climate-related risk from a societal safety perspective, incorporate context-specific, local knowledge, and comprehensively handle uncertainty.

Although we acknowledge a body of work related to risk governance and risk management in the Arctic focused on maritime (Fu et al., 2021; Shapovalova-Krout, 2019) and industrial activity (Ayele et al., 2016; Johannsdottir and Cook, 2019; Taarup-Esbensen, 2021), in this work we more specifically investigate the impact of natural hazards on societal safety– particularly those, such as landslides and avalanches, which have more recently impacted Longyearbyen and have received attention as case-studies for previous risk management research (e.g. Terrado et al., 2023). Thus, we intend our literature review results to capture recent studies related to the risk governance of natural hazards and their associated risks in Svalbard's Arctic setting, recognizing we may omit hazards such as wildfires which threaten other Arctic environments (e.g. Canosa et al., 2023) but have not previously occurred on Svalbard due to lack of forests.

2. A framework for governance of climate-related risk

In this work, we introduce a conceptual governance framework to better understand the handling of systemic climate risk over both short- and long-term time perspectives. The aim of introducing this conceptual framework is to use it to categorize the contents of the identified literature according to different risk governance steps. Existing methods for conceptually structuring the risk management or

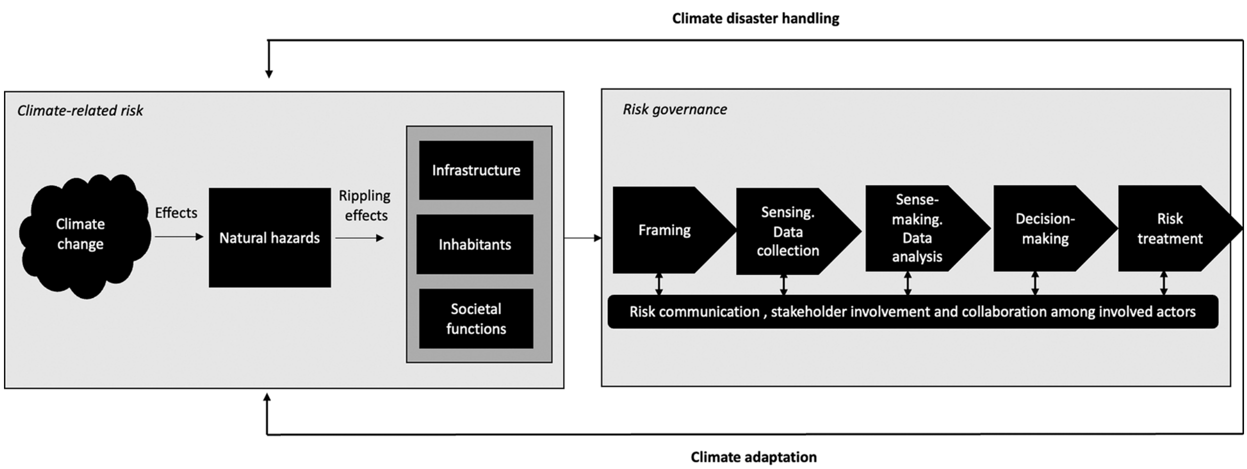

Fig. 2. The framework for understanding climate-related risk governance employed in this work. The left panel represents the factors comprising climate-related risk. The right panel shows the phases of risk governance. Note the feedback arrows indicating the iterative nature of risk governance.

risk governance process which have helped inform our proposed framework include the ISO31000 risk management standards (International Standards Organization 2018), the IRGC's Risk Governance Framework (IRGC, 2017), the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR, 2015), and the IPCC's framework for disaster risk management and climate change adaptation (e.g. IPCC, 2018). Additionally, we have considered aspects from the Canadian Avalanche Association's *Technical Aspects of Snow avalanche risk management* (Canadian Avalanche Association 2016) and work by (Bründl and Margreth, 2021) and (Statham et al., 2018) into our framework.

Although the terms risk management and risk governance are often used somewhat interchangeably in previous literature, we use risk governance in this work to highlight the process as collective effort to deal with risk. According to the IRGC (2017), governance:

> *"refers to the actions, processes, traditions and institutions by which authority is exercised and decisions are taken and implemented. Risk governance applies the principles of good governance to the identification, assessment, management and communication of risks."*

Risk governance, in this definition, thus refers to the methods by which multiple stakeholders collaborate to somehow assess, manage, and communicate risk. Understanding how risk assessment, decision-making, and communication of climate-related risk entails recognizing that several organizations with differing competencies and agendas interact to govern risk in this setting.

The conceptual framework (Fig. 2) used in our study adapts the IRGC's generic, flexible risk governance framework to model handling of climate-related risk in both a short-term perspective (e.g. residential evacuations due to snow avalanche risk) and in the long-term (e.g. building physical barriers to protect infrastructure from snow avalanches, slush avalanches, and flooding). In our framework, climate-related risk (the left panel of Fig. 2) results as climatic changes influence the character, frequency, and intensity of natural hazards. These hazards, in turn, produce rippling, complex, and interconnected effects in the human world by impacting socio-technical systems as systemic risks. Risk governance (the right panel in Fig. 2) consists of a multi-step or phase process underscored by consistent communication, involvement, and collaboration to develop strategies in response to climate-related risk. The resulting strategies – climate disaster handling in the short-term or climate adaptation in the long-term – ultimately modify the climate-related risk, such that the process requires regular re-assessment and iteration. A limitation of this framework is that it assumes that risk governance allows climate-related risks to be controlled. However, due to the changing characteristics of climate-driven hazards, it might be that in particular, long-term adaptation measures turn into what IPCC (2022) section 17.5 denotes maladaptation, i.e., "current or potential negative consequences of adaptation-related responses that lead to an increase in the climate vulnerability of a system, sector or group by exacerbating or shifting vulnerability or exposure now or in the future and eroding sustainable development". The mechanisms for maladaptation as well as successful adaptation are influenced by several factors, including changes in climate hazards and the effects of iterative risk governance (IPCC, 2022).

Fig. 2 also demonstrates a key delimitation of scope in the presented study. The study addresses how society copes with the consequences of climate change on societal safety, through climate change adaptation and disaster risk management. Climate change risk management commonly concerns both climate change mitigation and sustainable development (e.g., reduction of CO2 emissions) as well as climate change adaptation and disaster handling (IPCC, 2020). The scope of the paper has not addressed reduced emissions and land-use change.

The 2022 IPCC report "Climate Change 2022: Impacts, Adaptation and Vulnerability" provides an extensive review of literature on risk governance, or risk management as it is referred to in the report (IPCC, 2022). The report emphasizes the importance of understanding how climate change causes impacts and risks, and how these changes affect human society and ecosystems, as a foundation for climate adaptation processes. The report also recognizes the value of diverse forms of knowledge, such as scientific and local knowledge, in understanding and evaluating risks from human-induced climate change. This knowledge is used, among other sources, for adaptation and mitigation actions that the IPCC (2022) denotes as climate resilient development. These actions are enabled by governance, finance, knowledge, technology, and catalyzing conditions.

The following subsections detail the individual phases of risk governance using illustrative examples from applied snow avalanche risk management in Longyearbyen to provide tangible context to these concepts.

2.1. *Framing of risk and planning*

The IRGC (2017) names the first phase of risk governance 'pre-assessment' which includes identification and framing of risk in addition to preparations for the assessment and eventual handling of the risk. Similarly, ISO31000 refers to this phase as 'establishing the context", which involves defining the analysis object, determining its limits, and planning of the risk assessment.

Here, we refer to this initial phase of risk governance as framing. Defined as the process where some phenomena are selected and interpreted as risks (Aven and Renn, 2010), framing reflects 'defining the scope' in ISO31000. In the framing phase we seek to gather available knowledge to imagine what events could happen without closing our minds to possible unimagined events.

Climate change underscores framing's importance since we must assume climatic changes can alter the unwanted events stemming from natural hazards. For example, climatic changes in Svalbard may lead to snow covers with differing physical characteristics in the future than we currently experience today, which can change the temporal and spatial patterns of avalanche activity (e.g. Thackeray et al., 2019). As a result, planning of manual snow observations may need to emphasize new, potentially novel, snow characteristics, and data from automated snow sensors may need to be interpreted differently. Projections of considerably reduced snow cover in Svalbard 20–40 years in the future (Hanssen-Bauer et al., 2019) also impact framing; future hazard assessments may need to consider new or different types of snow avalanches, such as slush avalanches, or even non-snow hydrological hazards such as flooding.

The IRGC (2017) emphasizes how different actors or stakeholders may frame risk differently. As a result, identifying relevant actors and stakeholder groups – and how their viewpoints and agendas may shape their risk perceptions – also forms a key part of the framing phase of risk governance.

2.2. Sensing/data collection

Sensing, as the second phase of the framework, encompasses the acquisition of available and relevant knowledge about the system of risks framed in the previous risk governance phase. Also described as *data collection*, our naming of this risk governance element alludes to the way humans 'sense' the world around us and reflects how this phase will also require gathering information from diverse sources using multiple techniques. In ISO31000, 'sensing' falls within the 'establishing the context' phase of risk management, i.e. collecting data and information about the risk object.

Examples of sensing activities for snow avalanche risk management in Longyearbyen include:

1) Sensor technology to measure parameters related to natural hazards and the physical environment such as air temperature, wind speed, snow depth, or drifting snow;
2) Manual observations of natural hazards and the physical environment including visual inspections as well as measurements (measuring the size of different layers in a dig out snow profile with a yard stick) which require the physical presence of an observer;
3) Collection of meteorological or climate data from the past and present; and
4) Identification of experience carriers and databases, including tacit knowledge of inhabitants.

The last sensing activity has particular relevance for climate risk governance as one must assess whether past experiential knowledge adequately represents new environmental conditions. Kjellén and Albrechtsen (2017) provide an overview of how experience carriers (e.g. drawings, procedures, and regulations) and experience databases (e.g. overviews of previous incidents, experienced weather conditions) serve as input to the risk governance process. This foundation, in turn, informs the handling of experience data in the risk governance framework.

2.3. Sense-making/data analysis

In the context of this framework, sense-making involves *synthesizing and analyzing knowledge generated in the sensing phase to express a risk picture.* Weick (1995) describes sense-making as "the processes by which sometimes ambiguous cues from sensing systems are extracted, interpreted, and translated into meaningful alternatives for action." Weick et al. (2009) explain that sense-making involves incorporating knowledge about the past, indications about the present, and imaginations of the future as a foundation for action. Sense-making is analogous to the risk assessment process (hazard identification, risk analysis, and risk evaluation) from the terminology employed by ISO31000.

In practice, this risk governance phase entails systemizing available knowledge to 1) express what can go wrong, 2) establish a risk picture, and 3) compare the risk picture with risk acceptance criteria to determine whether the risk is acceptable. Applying and systemizing available knowledge to identify scenarios on what can go wrong and the impacts of these defined scenarios are similar to a scenario approach to climate risk assessment suggested by, e.g., the Task Force on Climate-related Financial Disclosures (TCFD, 2017). Risk evaluation includes determining whether the results of the risk analysis are acceptable, unacceptable, or tolerable. The societal risk tolerance level will vary over time depending on the nature, magnitude, and distribution of the benefits and costs of the risk, as well as the values, preferences, and perceptions of the society. This implies that what risks are mitigated also will vary according to the variability of tolerance level. The tolerable risk region occurs when risks fall between the risk acceptance criterion and the goal. In this region, implementation of risk reducing measures should strive to lessen the remaining risk to as low as reasonably practicable (ALARP). Applying the so-called ALARP principle typically includes a cost-benefit analysis and/or demonstrating that intrinsic safety is designed and recognized standards are followed (e.g. Vinnem and Røed, 2014). The ALARP principle is valid both for short-term and long-term perspectives, although the time to decide if risks are ALARP is shorter in disaster handling than in planning for adaptations. LQI (Life Quality Index) is an alternative to ALARP, which estimates societal willingness to pay for safety programs (Nathwani et al., 2020). The ALARP principle differs from the LQI principle as it does not only pay attention to cost-benefit analysis. Sense-making also involves expressing uncertainty either directly in the risk picture or as additional information, depending on the specific definition of risk being used.

Risk assessment as outlined by the IRGC (2017) largely reflects the procedures from ISO31000, but also includes a so-called 'concern assessment' as part of the risk assessment phase, which comprises assessments of different stakeholders' opinions and concerns about the risk. This approach specifically considers the sense-making process of how people give meaning to their experience.

2.4. Decision-making

In risk governance, decision-making is a complex process that involves weighing the potential risks and benefits of different courses of action. A key part of this process is to make informed decisions using the information obtained through risk assessment and other sensing and sense-making processes. Decisions about how to handle a risk are thus made on the knowledge generated and synthesized in the previous phases of the risk governance process. In most cases, this process involves risk-informed decision-making where decisions are made based on inputs from the risk assessment in addition to other operational and technical considerations (Rausand and Haugen, 2020). The decision-making process in risk governance is often influenced by a variety of factors, including scientific evidence, social values, political considerations, and economic factors (Renn, 2020). Stakeholder involvement is also an important aspect of the decision-making process, as it helps to ensure that the perspectives of all relevant parties are taken into account. This implies that conflicting alternatives may need to be considered with inconsistent goals and values and then matched to formal requirements and expectations (e.g. March 1994).

The decision-making process in risk governance is closely linked to risk treatment. Once risks and other relevant information have been identified, assessed, and evaluated, the next step is to determine the most appropriate course of action for managing them. The decision-making process involves evaluating the available options for managing the risks and selecting the most appropriate one based on the risk picture and other concerns and benefits of each option. The process of risk treatment involves implementing the selected course of action for managing the risks.

A clear distinction exists between short-term (e.g. evacuation of inhabitants exposed to avalanche risk) and long-term (e.g. establishing snow fences or other physical measures) risk governance in this phase. Time constraints and potentially impending disaster will have great influence on decisions made with a short-term perspective. By contrast, more time can be spent on decision-making for long-term climate adaptations.

Decision-making related to the consequences of climate change involves deep uncertainty, i.e. situations where decision-makers and stakeholders do not know or cannot agree on the outcomes of the system, the external context of the system and/or how the systems work (Marchau et al., 2019). Deep uncertainty is relevant to climate change because it makes it difficult to 1) predict the future impacts of climate change due to limited knowledge of future developments and due to inadequate supporting models(Aven, 2013) and 2) to develop effective strategies for mitigating and adapting to impacts of climate change, among other things due to the unknown long-term effects of short-term risk mitigation measures.

Decision making under deep uncertainty is thus relevant for climate risk governance, which is a process that involves making decisions in situations where there is a high degree of uncertainty about the future. This approach is often used in the context of climate change, where the complexity and unpredictability of the Earth's climate system make it difficult to predict the future impacts of climate change. Decision making under deep uncertainty requires a different approach than traditional decision-making, as it involves considering a wide range of possible future scenarios and developing strategies that are robust across multiple scenarios, see e.g. Marchau et al. (2019) for an overview of approaches.

Deep uncertainty affects the governance of climate-related risk in both decision-making and risk assessment. Statistical methods and tools for risk assessment are not suitable when there is deep uncertainty, because the supporting models may be invalid and the required data may be unavailable(Aven, 2013; Cox, 2012). Climate risk poses an additional challenge, as the changing risk picture and the changing societal perception of risk make it difficult to apply conventional risk assessment and risk management approaches. Shortridge et al. (2017) propose three different approaches to assess risk under deep uncertainty: qualitative uncertainty factors, probability bounds, and robust decision making. The first two are different ways to identify and quantify uncertainty factors (i.e. gaps in knowledge) in the short and long term. Robust decision making is an approach that simulates several scenarios to evaluate system performance in an iterative process that aims at robust strategies. These approaches enable a consideration of both short-term and long-term effects of risk mitigation measures, and thus account for how short-term decisions can influence long-term outcomes. This is highly relevant for climate adaptation, as also described in the (International Standards Organization, 2021) principles for assessing climate change impacts and for monitoring and evaluation.

2.5. Risk treatment

Risk treatment entails the implementation of *measures to eliminate or reduce risk* where required (ISO31000). In our framework, we differentiate risk treatment between 1) disaster handling in acute situations with a short-term perspective (e.g. evacuation due to high snow avalanche risk) and 2) climate adaptation with a long-term perspective (e.g. permanent measures to control avalanche hazards such as fences and dams). This differentiation follows IPCC recommendations to separate between 1) disaster risk management and 2) climate change adaptation as the two main approaches to deal with climate-related risk. In general, the contents of the steps in risk governance leading up to risk treatment are the same for both disaster handling and climate adaptation.

2.6. Communication, stakeholder involvement, and collaboration

Communication, stakeholder involvement, and collaboration between actors are integrated throughout all phases of risk governance and have relevance in both short- and long-term perspectives, where multiple actors are involved during the governance process from data collection to decision-making. In Longyearbyen, climate risk governance involves collaboration between various stakeholders. The local government, The Norwegian Water Resources and Energy Directorate, and the Governor of Svalbard serve as the police authority. For short-term avalanche warning systems, a consultancy company provides forecasts, and an observation group conducts visual controls of the snow pack. Other key stakeholders include inhabitants, businesses, and industry. Additionally, consideration of wildlife and cultural heritage is crucial in Longyearbyen.

According to IRGC (2017, p. 27) risk communication is "the process of exchanging or sharing risk-related data, information and knowledge among different groups such as scientists, regulators, industry, consumers or the general public. It is of utmost importance for effective risk governance…effective and early communication is key to creating long term trust in risk management, in particular when risks are perceived complex, uncertain or ambiguous." Stakeholders who could be impacted by the risk and risk treatments should therefore be involved in the risk governance process since they possess valuable insights to contribute to different parts of the risk governance process.

The double-arrowed lines between the box ‘communication, stakeholder involvement and collaboration’ and the other boxes in the risk governance framework illustrate feedback channels and loops in the risk governance framework. Although the model seems linear, risk governance in practice is a more iterative approach. The model is conceptual and will be used to categorize the contents of the identified literature according to different risk governance steps. Such feedback for example acknowledges the systemic nature of risk with feedback loops, non-linear effects and ripple effects that impact both assessment and management of risk (Renn et al., 2022); responses by stakeholders and affected citizens for both ongoing and planned assessment and management (Renn and Klinke, 2013); or resilient approaches that avoid and reduce systemic risk in a dynamic way by reacting to early warning signals that appear continuously (Trump et al., 2019).

3. Methods

We conducted a qualitative literature review to synthesize knowledge related to the governance of climate-related risks and assess the transferability of this knowledge to Longyearbyen’s Arctic setting. Although we follow an abductive iterative methodology (after Blaikie and Priest, 2019; Timmermans and Tavory, 2012), we have structured our literature sampling around the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for conducting review studies to promote transparency and repeatability in our methodology. Furthermore, PRISMA methods have become increasingly common for reviews in the social sciences and for more specifically investigating climate-related and systemic risks (e.g. Berrang-Ford et al., 2015; Raikes et al., 2019).

3.1. Limitations

Studies investigating risk governance, the effects of climate change, or natural hazards’ impacts on societies span a wide range of topics and perspectives, meaning we cannot address all aspects of these concepts in our study. We have thus made some necessary delimitations. The conceptual framework applied in this work (Fig. 2) illustrates these delimitations by showing that we focus on the effects of climatic changes on natural hazards which impact societal safety, defined as “society’s ability to maintain critical social functions, to protect the life and health of the citizens and to meet the citizens’ basic needs in a variety of stress situations (Olsen et al., 2007). This delimitation implies that we limit our literature review to risk governance approaches that address climate change impact on certain types of natural hazards and their effect on societal safety. This would exclude publications on risk governance and risk management related to maritime and industrial activities and tourism which are relevant for Arctic areas (Ayele et al., 2016; Fu et al., 2021; Johannsdottir and Cook, 2019; Shapovalova-Krout, 2019; Taarup-Esbensen, 2021).. Similarly, we limited the natural hazards we investigated to those contributing to high-impact events with considerable societal and governmental response in Longyearbyen in the latest years: flooding, snow avalanches, and landslides. Thus we do not include potential risks related to, for example, increased permafrost thaw, erosion, or increased sediment transport identified as concerns for Svalbard (e.g. Hanssen-Bauer et al., 2019). Finally, we defined a temporal range from 2017 to 2021 to ensure the articles represented the current state of the art and to best capture climatic spatial–temporal changes that have most recently occurred alongside societal changes in Longyearbyen.

3.2. Sampling

In this work, we initiated our literature selection by searching the Web of Science data base with the following search string (Fig. 3):

With this search string, we sought to include abstracts of recent (2017–2021) studies broadly focused on risk governance via the risk management, risk governance, multi-hazard management, relevant natural hazards, climate adaptation, disaster risk reduction, and disaster risk management search terms. To better ensure our results specifically contributed to the understanding of climate-related risk, we added the search terms climate change, climate risk, and climate-related via the AND modifier. We similarly included the flood, snow avalanche, landslide, and arctic search terms via an AND modifier to focus on the selected hazards which pertain to the Arctic environment in Longyearbyen’s administrative area. The search initially produced 271 paper abstracts (Fig. 5-1).

To refine results to our specific topics, we enclosed terms like risk management, risk governance, disaster risk reduction, climate change, extreme weather, and systemic risk in quotation marks. This adjustment ensured that only abstracts directly mentioning these phrases were included. Next, we excluded early access and proceedings papers due to their preliminary nature and in some instances lack of peer-review to ensure that we only considered fully published and reviewed works in our analysis. This new search string (Fig. 4) excluded a total of 102 article abstracts from our sample (Fig. 5-2).

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(((AB=(risk management) OR AB=(risk governance)OR AB=(multi-hazard management) OR
AB=(climate adaptation) OR AB=("disaster risk reduction") OR AB=(disaster management))) AND
(AB=(climate change) OR AB=("climate risk") OR AB=(climate-related) OR AB= (extreme
weather)) AND (AB=(systemic risk) OR AB=(natural hazards) OR AB=(societal safety) OR
AB=(critical infrastructure)) AND (AB=(flood) OR AB=(snow avalanche) OR AB=(landslide) OR
AB=(arctic))) AND (PY==("2021" OR "2020" OR "2019" OR "2018" OR "2017"))
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Fig. 3. Initial search string used on Web of Science.

(((AB=("risk management") OR AB=("risk governance")OR AB=(multi-hazard management) OR AB=(climate adaptation) OR AB=("disaster risk reduction") OR AB=(disaster management))) AND (AB=("climate change") OR AB=("climate risk") OR AB=(climate-related) OR AB= ("extreme weather")) AND (AB=(systemic risk) OR AB=(natural hazards) OR AB=(societal safety) OR AB=(critical infrastructure)) AND (AB=(flood) OR AB=(snow avalanche) OR AB=(landslide) OR AB=(arctic))) AND (PY==("2021" OR "2020" OR "2019" OR "2018" OR "2017")) and Early Access or Proceedings paper (Exclude – Document Types).

Fig. 4. Adjusted search string per Fig. 5-2 used on Web of Science.

This yielded a total sample of 169 article abstracts from Web of Science. We then split the 169 sample of abstracts into samples of 42, 42, 42, and 43 and read them independently to determine relevance within our scope. Following these independent readings, we held two qualitative inter-rating meetings to ensure the reliability and consistency in the application of our filtering criteria. We, based on a qualitative assessment of the paper's relevance to our scope, eliminated 99 article abstracts from our sample in the first meeting and then further eliminated another 10 paper full-text articles with an additional inter-rater meeting, totaling an elimination of 109

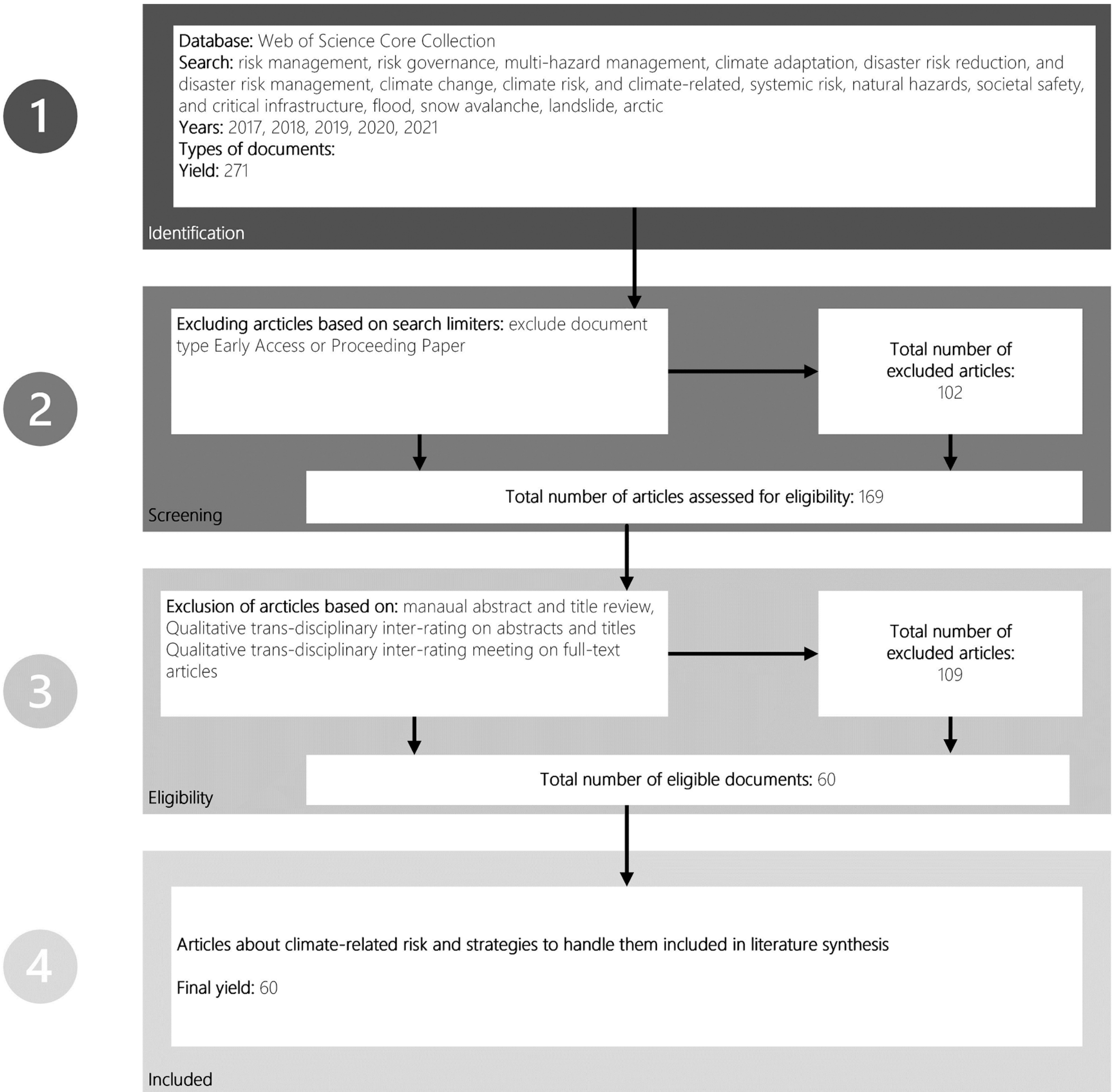

Fig. 5. Schematic outlining our literature review methodology.

paper abstracts (Fig. 5-3). This left us with a sample of 60 full papers to read and analyze, which we split between each other in groupings of 12, 13, 17, 18 (Fig. 5-4).

3.3. Analysis and reliability

We employed an abductive iterative analysis technique (Blaikie and Priest, 2019; Timmermans and Tavory, 2012) when identifying themes in our literature analysis. This technique revolved around iterative cycles of reading and analyzing to develop a progressively clearer overview of the content in our literature sample.

We began by constructing a provisional coding scheme (Miles and Huberman, 1984) based on the phases of our framework for risk governance, and factors pertinent to climate risk governance in the Arctic. This resulted in the following provisional coding categories, all under the umbrella of 'relevance to': climate-related risk, framing, sensing, sensemaking, decision-making, risk treatment, risk communication, as well as categories addressing short or long-term climate risk handling, consideration of weather and/or climate in governance, uncertainty handling, involvement of local stakeholders, use of digital solutions, and the Arctic context. We thereafter grouped in-vivo (Corbin and Strauss, 1990) citations or summarizing descriptions of paper content as first order codes (Van Maanen, 1979) in the provisional coding scheme. In our coding process, we avoided mutually exclusive coding of papers into one or another category. In our bid to understand risk governance of climate-related risk in Longyearbyen and elsewhere in its perpetuity we avoided mutually exclusive coding of papers into one or another category. We did so as risk governance consist of highly interconnected parts with non-directionally determined feedback and feedforward processes, meant to deal with simple to non-linear and risk problems. Risk governance is thus, as much about the subsumed emergent effects of interactions between its constituent parts as it is about the subsumed and emergent effects of its whole. In the same way we avoided quantitative tallies and representations of which paper belongs in which categories, as the papers reflect this interconnected and subsuming nature and would belong in multiple categories. Higher-order themes, i.e. themes that emerge through natural inquiry from data analysis, rather than themes that is explicitly mentioned in the data (Gioia et al., 2013)aven, emerged through further iterative cycles of reading and analyzing, with this refinement process continuing until we had analyzed all 60 articles and developed an understanding of the articles' content and data relationships. Each subsection of Section 4 represents these higher-order themes (e.g. 4.2.3 Risk communication deals with the higher order themes uni- and bi- directional risk communication).

We undertook several steps following Lincoln and Guba (1985) to ensure we conducted a reliable data analysis that elevated a coherent representation of climate-related risk and associated governance strategies in the selected literature. The initial step in the analysis was conducted through the identification and screening process within the search engine of Web of Science Core Collection (as detailed in 5–1 and Fig. 5-1/5–2). Thereafter, we organized the data using EndNote and MS Excel. To ensure we gave the articles a valid assessment of eligibility (Fig. 5-3), we followed a structured workflow which sought to best utilize our research groups trans-disciplinary expertise from meteorology, geology, snow science, civil engineering, and safety and risk related science. The papers then received individual review by a group member with the competencies most closely aligned with the article's subject matter. As a part of this step, we held qualitative inter-rating meetings (McDonald et al., 2019; Armstrong et al., 1997; Elliott et al., 1999) where the transdisciplinary group determine whether the paper abstracts or paper full-texts consistently fit within our scope of creating an understanding of risk governance of climate-related risks in Longyearbyen and in other areas where climate change impact human activities. In the final literature synthesis (Fig. 5-4). In these meetings we filtered out abstracts and full-paper texts that exclusively dealt with quantitative modelling, or the development of quantitative models, which did not deal with nor fit into the scope of governance. Subsequent project meetings were held to allow to transdisciplinary group to iteratively review individual findings, and served as a final venue for when doubt arose about the categorization and coding of the contents of the full-text articles.

4. Results of literature review

4.1. Relevance to climate risk and framing

All but two of the reviewed studies indicate climate-related risk has relevance to societal safety via the impacts of either current climatic conditions or future conditions anticipated by climate projections. The reviewed literature covers a large part of our globe but has a concentrated focus in the coastal regions of Southeast Asia and in the Himalaya. Flooding serves as the most studied natural hazard in the reviewed literature. Only a few studies specifically address slope hazards, only one study deals specifically with snow avalanches, and no studies investigate Arctic regions.

The reviewed studies frame climate risk primarily through two lenses; either by reviewing existing climate risk pictures and applied mitigation measures (e.g. Chan et al., 2018; McElwee et al., 2017; Tadgell et al., 2018; Tellman et al., 2018) or by incorporating projected climatic changes into the future risk picture (Feinberg, 2021; Jamshed et al., 2019; Ravankhah et al., 2019; Stevens et al., 2020). Several studies include elements from each of these perspectives as they address climate risk by, for example, focusing on both the current and anticipated future impacts of a given natural hazard's occurrence (e.g. Dikshit et al., 2020; Thaler et al., 2019).

The studies addressing existing climate risk pictures largely focus on characterizing and mapping the effects of ongoing climate changes or providing case studies of current mitigation and adaptation strategies. Commonly, these studies approach climate risk by examining how the current natural hazard environment relates to climate and climate changes in the studied region (e.g. Forzieri et al., 2018; Reynard et al., 2017). Furthermore, such studies demonstrate a strong regional and local characterization of the climate-related risks. This regional to local focus, in our view, stems from two main factors. First, the nature and magnitude of the physical climatic changes vary considerably in both space and time (Dikshit et al., 2020; Gallina and Sidle, 2018; Reynard et al., 2017; Sekhri et al., 2020). Secondly, regional and sub-regional variations in socioeconomics influence infrastructure robustness and the availability of resources to mitigate or adapt to climate risks (Diana et al., 2021; Lwasa, 2018; McElwee et al., 2017; Mohanty et al., 2019; Sekhri et al., 2020). Regions with relatively low socioeconomic status experiencing rapidly changing extreme weather occurrences and hydrologic risks are thus overrepresented in the data.

Studies focusing on future climate-related risks take largely two approaches. The first approach attempts to establish or update a future risk picture by anticipating changes in the frequency, distribution, and intensity of existing natural hazards based on climate projections (Chan et al., 2018; Forzieri et al., 2018; Reynard et al., 2017). The second approach attempts to characterize a risk picture by considering dynamic human responses and potentially novel natural hazards related to future climate forcings (Stevens et al., 2020; Tellman et al., 2018).

Although studies employ frameworks such as the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) and strategies such as vulnerability index models (Mukherjee and Siddique, 2020) to address climate risk, a demand for new guidelines and frameworks for climate risk governance emerges as a common theme in this literature (Christoplos et al., 2017; Fekete, 2019; Mohanty et al., 2019).

4.2. Relevance to addressing climate risk

4.2.1. Sensing/data collection

Knowledge generation – or 'sensing' – in the investigated works incorporates methodologies ranging from direct physical measurements (e.g. Ali et al., 2017; Dikshit et al., 2020) and models of physical processes (Dikshit et al., 2020; Hattermann et al., 2018; Russo et al., 2020) to qualitative sensing methods including questionnaires/surveys (e.g. Barua et al., 2017; Mukherjee and Siddique, 2020; Nguyen et al., 2017) and interviews (e.g. Haeffner and Hellman, 2020; Penalba et al., 2021; Roy et al., 2021; Thaler et al., 2019).

Physical measurements and modeling efforts serve to generate knowledge primarily related to the spatial and temporal components of climate risks. Many studies employ geographic information systems (GIS) and other modeling approaches to identify, analyze, visualize, and understand how climate-related risks manifest spatially. For example, Russo et al. (2020) use regional climate projections to spatially model urban flooding in Barcelona, while Gallina and Sidle (2018) use IPCC emissions scenarios as a basis to assess changing spatial patterns of coastal hazards along Australia's eastern shoreline.

A review of rainfall-induced landslide studies in the Indian Himalayan region by Dikshit et al. (2020) represents the conceptual basis underlying many of these works – namely, better understanding the physical processes involved in a climate-related natural hazard will aid in better risk management. In the framework of Dikshit et al. (2020), environmental sensing (e.g. rainfall measurements, geological mapping, observations of landslide activity) help force physical models which can then aid in predicting future hazard occurrence. Uncertainty in the generated knowledge in these works commonly relates to unresolved spatial and temporal variations in modelled climatic changes (Dikshit et al., 2020; Reynard et al., 2017), with uncertainty typically expressed quantitatively as a range on a physical parameter (e.g. Fuchs et al., 2019; Mills et al., 2021; Minano et al., 2018).

Qualitative sensing techniques, contrastingly, attempt to better incorporate the human perceptions of risk which physical measurements or models may not capture. Two studies in our database (Penalba et al., 2021; Yoshioka et al., 2021) employ qualitative methods such as interviews, focus group discussions, and participatory mapping exercises to incorporate local knowledge in efforts to better map flood hazard and risk in the Philippines. According to Penalba et al. (2021),

"reliance on not only expert knowledge but also on local knowledge has become a critical component of developing maps because local knowledge reflects how community residents utilize strategies to cope with changing climate conditions.".

Although physical and qualitative knowledge generation methods both provide valuable and disparate data to better manage climate risk, relatively few studies in the database explicitly work to merge these strategies. One particularly compelling example from the Alsatian region of north-eastern France developed an online participative platform to collect and synthesize information related to flooding in the Rhine River watershed (Giacona et al., 2019). The online platform provides information derived from physical measurements, geohistorical investigations, and crowd-sourced data to develop a long-term flood hazard database for this region. Similarly, work to develop an early warning system for outdoor tourist attractions in Greece seeks to aggregate hazard and risk information for managers and the general populous (Psaroudakis et al., 2021). This platform allows users to interactively explore the hazard and risk picture for a given location, as well as allowing managers to input or update hazard information as a situation warrants. These two examples highlight how digital solutions which allow users to interactively explore the physical data and models can form the basis for understanding a hazard. By also asking users to contribute local knowledge to the overall risk picture, these digital solutions can help combine physical and qualitative knowledge generation strategies.

4.2.2. Sense-making, decision-making, and risk treatment

Sense-making, decision-making, and risk treatment collectively represent how knowledge generated through sensing ultimately results in the implementation of risk reduction measures. Sense-making – the analytical processes by which sensed knowledge develops into a risk picture – follows sensing in the risk governance process and, in the investigated literature, often overlaps the sensing process. For example, physical models which generate knowledge about climate-related risks can also serve as a sensemaking tool to better understand these risks (Gallina and Sidle, 2018; Hattermann et al., 2018; Mills et al., 2021; Russo et al., 2020). Similarly, participatory mapping exercises discussed by, as two examples, Penalba et al. (2021) and Yen et al. (2019) as a sensing method can also be seen as a sense-making strategy. Sensemaking via multi-hazard approaches (e.g. Forzieri et al., 2018; Sekhri et al., 2020) or consideration of cascading effects (e.g. Fekete, 2019; Russo et al., 2020) combine various forms of data and knowledge generation strategies to consider the risk picture more broadly. Finally, we found a clear emphasis on vulnerability in the reviewed sensemaking strategies (e.g. Diana et al., 2021; Fuchs et al., 2019; Jamshed et al., 2019; Mukherjee and Siddique, 2020), where sense is made of risk via an understanding of vulnerability, i.e. propensity of exposed elements such as human beings, their livelihoods, and assets to suffer adverse effects when impacted by hazard events (IPCC, 2022).

Discussions of decision-making, as the subsequent phase in risk governance after sensemaking, in the literature often emphasize having sufficient knowledge – via data collection and sensemaking – on which to base decisions (Hattermann et al., 2018; Lamaury et al., 2021; Russo et al., 2020). As discussed by, for example, Reynard et al. (2017), effective decision-making in situations where climate changes lead to new hazard situations, where insufficient data exists or sensemaking does not succeed in developing a risk picture, additional knowledge to reduce uncertainty must be obtained for effective decision-making. Here, various studies point to cooperation among diverse stakeholder groups (Muir, 2021; Weber et al., 2019; Yumagulova and Vertinsky, 2017), IT systems which support decision-makers (Goniewicz and Burkle, 2019; Psaroudakis et al., 2021), and a focus on locally-based decisions (McElwee et al., 2017; Penalba et al., 2021; Pilone et al., 2021; Roy et al., 2021; Thaler et al., 2019) as key components of decision-making for climate-related risks.

Decision-making in the risk governance process often involves community or society-level choices about risk treatments. Risk treatment in the reviewed works typically involves attempts to mitigate risks via physical barriers and improved infrastructure to control natural hazards (e.g. Tellman et al., 2018; Thaler et al., 2019), planning to limit human exposure to hazards (e.g. Kim and Kang, 2018; Yumagulova and Vertinsky, 2017), and, ultimately, adaptation to an altered risk picture (e.g. Barua et al., 2017; Nguyen et al., 2017). Much of the literature focuses primarily on hydrological and landslide risks, with specific risk treatments including the development of more resilient infrastructure (Henrique and Tschakert, 2019; Jocson and Magallon, 2018; Jung et al., 2021; Twinomuhangi et al., 2021), planning for resettlement, relocation, or retreat (Craig, 2019; Hofstede, 2019; Smith et al., 2021; Tadgell et al., 2018), and advocating for a more holistic flood governance approach (e.g. Chan et al., 2018). These treatments are often linked to knowledge generated by monitoring (Dikshit et al., 2020; Tirivangasi, 2018), sensemaking via model outputs (Hattermann et al., 2018; Lamaury et al., 2021; Mills et al., 2021; Russo et al., 2020), and early warning systems to aid in decision-making (Mohanty et al., 2019; Psaroudakis et al., 2021). We observed a dichotomy between risk treatments enacted at household level by individual residents based on local knowledge versus centralized treatments at a governmental level (McElwee et al., 2017; Penalba et al., 2021; Roy et al., 2021), with Ali et al. (2017) even relating increasing risks from slope processes in Pakistan, in part, to the loss of local knowledge through an overly-centralized risk governance process.

While various studies acknowledge uncertainty may impact the sensemaking, decision-making, and risk treatment phases of risk governance (e.g. Reynard et al., 2017; Sekhri et al., 2020) or mention expanding risk management frameworks to better incorporate assessment uncertainty (e.g. Fekete, 2019; Tirivangasi, 2018; Weber et al., 2019), few of the reviewed works presented a clear framework to handle uncertainty throughout the risk governance process. As an exception, Mills et al. (2021) evaluated uncertainty in coastal risks by quantifying the variance in outcome metrics (e.g. building impacted by coastal flooding) produced by a modeling approach which couples modeled climatic changes with scenario-based modeling of human adaptation strategies.

4.2.3. Risk communication

Risk communication serves as a phase of the risk governance process which aims to reduce uncertainty and ambiguity by exchanging risk-related information both within and outside of formal governance structures. We found risk communication to be especially important in societies experiencing the effects of climate change, where some studies showed local knowledge became as important as expert knowledge to make sense of local variations in climate- and weather-related risks (Christoplos et al., 2017; Dilling et al., 2017; McElwee et al., 2017). In these situations, various studies advocated for risk communication which crosses barriers between decision-makers, experts, and locals to improve the understanding of changes in the local area (Giacona et al., 2019; Sekhri et al., 2020; Tadgell et al., 2018; Thaler et al., 2019; Weber et al., 2019).

The reviewed literature, however, contained a range of risk communication strategies with differing methods for involving local stakeholders. Broadly, we can categorize these strategies as uni-directional and bi-directional risk communication. Uni-directional risk communication involves a top-down approach to sharing risk information. As evidenced by Reynard et al. (2017) and Orr (2020), the uni-directional approach typically involves experts or governmental authorities providing risk information or decisions with little involvement from local stakeholders. Other reviewed works discuss how either policies or communication strategies may exclude various stakeholders from the risk governance process (e.g. Yumagulova and Vertinsky, 2017) or highlight instances where a single stakeholder group dictates the risk governance narrative (Henrique and Tschakert, 2019; Tellman et al., 2018).

Bi-directional communication strategies in the reviewed works intend to promote active participation from local stakeholders to address how uni-directional communication limits the exchange of risk information both to and from local stakeholders. We found a clear emphasis on a bottom-up approach to risk communication in studies which employed bi-directional strategies. For example, Minano et al. (2018) and Kmoch et al. (2021) used workshops and public hearings with local stakeholders to improve communication between actors, better develop a risk picture, and make sense of the risks. Other works developed and tested digital solutions in which local stakeholders can both contribute knowledge to and receive risk information from experts and decision-makers (Giacona et al., 2019; Psaroudakis et al., 2021). Of particular relevance to Longyearbyen's risk picture, Thaler et al. (2019) identify local involvement via bottom-up communication as a key component to successful risk management strategy implementation following destructive snow avalanches in Galtür, Austria.

5. Discussion

5.1. Knowledge gaps

This section highlights the knowledge gaps that emerge in the reviewed literature related to guidelines and frameworks for climate-related risk governance. The knowledge gaps we identify here will serve as a foundation for more empirical studies of short- and long-term climate-related risk handling in Arctic societies. Specifically, we found the reviewed literature generally lacks:

- A societal safety perspective on climate changes and natural hazards. Much of the identified literature views the climatic changes and associated natural hazards either through a physical process-based perspective rooted in the natural sciences, or focuses on physical mitigation measures, without considering the interaction of nature, technology, and society.
- Data collection and analysis strategies which combine the acquisition of local knowledge via a discourse-based approach with data and knowledge generated from sensors or physical models via a technical approach.
- Explicit uncertainty assessment and handling in the risk governance process.
- Consideration of short-term disaster handling approaches – especially in relation to relatively more frequent consideration of long-term climate adaptation strategies.

The reviewed literature mainly frames climate change and risk governance in two ways: 1) by reviewing existing climate changes and implemented mitigation measures, and 2) by incorporating projected climatic changes into the future risk picture. Here, we note the existence of a knowledge gap in terms of framing climate-related risk from a societal safety perspective. In the context of climate-related risks, the term "envirotechnical disaster" (Pritchard, 2012) describes the inseparable relationship between nature, technology, and society. Sociotechnical systems, in this argument, cannot be considered as independent or isolated from nature. Framing climate-related risks and climate change adaptation from this perspective has relevance for more holistic risk governance approaches, both in the Arctic and elsewhere globally. Climate change research in general has also been dominated by the natural and technical sciences and less by social science research (Glavovic et al., 2022). The need for a intensified focus on the interaction between nature, technology and society in societal safety research is also found in other research on climate change. (Haasnoot et al., 2020) calls for solutions to climate change adaptation that are shaped by biophysical, cultural, socio-economic, and political-institutional dimensions. Taebi et al. (2020) add the inclusion of ethical considerations to natural, technical and societal considerations in governing risks. In a study by Lawrence et al. (2020) cascading was highlighted showing that climate change impacts several sub-systems in society. Furthermore, they concluded that paying attention to cascading effects on society provides a better assessment of risk compared to conventional methodologies for risk assessment practiced in New Zealand and elsewhere.

Sensing and data collection strategies described in the literature typically incorporate either physical measurements and models or local knowledge derived from qualitative techniques. The literature shows targeted work to develop data collection strategies to best sense climate changes often involves incorporating physical climate measurements and projections with existing methods or by developing novel methods to specifically consider climate-related risks. The literature includes a variety of data collection techniques for differing data types (ranging from physical measurements to interviews), which reflects the broad risk assessment and concern assessment objectives incorporated in risk governance. However, relatively few studies in the reviewed works explicitly strive to merge risk-based and discourse-based approaches, although other works not captured in our search have explicitly worked to do so (e.g. Kettle et al., 2014).

When climatic changes lead to new or novel hazard situations, where insufficient data exist, or where sensemaking fails to develop a risk picture, additional knowledge that contribute to the reduction of uncertainty must be obtained for to support decision-making processes or decision-making processes that deal with uncertainty must be applied. Including uncertainty analysis and handling as part of risk governance is receiving increasing attention in risk science work (e.g. Aven and Thekdi, 2021), but was not thoroughly addressed in the reviewed literature. Since future climatic changes include, almost by definition, considerable uncertainty due to inherent process variability and lack of knowledge, this represents an important knowledge gap in climate-related risk governance literature. One part of the knowledge gap in climate risk governance is the identification and assessment of uncertainty, i.e., the strength of knowledge (ISO31000:2018). (Aven, 2020) describes a conceptual approach to assess uncertainty in relation to climate risk by describing the strength of knowledge judgement and establishing scientific processes to scrutinize the underlying knowledge basis with respect to potential surprises. Such an approach is also shown in chapter 1 of the IPCC (2022) report, where it is described how uncertainty is assessed by evaluation of the evidence and evaluation of the scientific agreement. Similarly, Albrechtsen and Holen (2023) argue that uncertainty related to climate risk must be described in a user-friendly way to decision-makers.. A second part of the knowledge gap from the literature review is related to decision-making under deep uncertainty, i.e., processes that involve making decisions in situations where there is a high degree of uncertainty about the future (Marchau et al, 2019). Although not identified in our literature review, there already exists some research on climate change and decision making under deep uncertainty. For example, Brown et al. (2019) describe Decision Scaling as a decision-making process to deal with uncertainty for climate adaptation planning that emphasizes how to use available climate information to inform decision processes. Klima (2019) and Stanton and Roelich (2021) discuss a variety of decision-making approaches related to deep uncertainty and climate change. Using insights from such studies of decision-making under deep uncertainty will be a fruitful contribution to advances in research on climate risk governance.

The reviewed literature has a strong emphasis on long-term risk treatment of climate-related risks via climate adaptation. Although numerous studies focus on identifying, sensing, or assessing short-term, event-based risks, we discovered relatively few strategies for deciding on or implementing short-term treatments via disaster risk handling. Accordingly, continuing to develop risk governance frameworks and approaches which can aid decision-making and risk treatments across both short- and long-term timeframes can help address this knowledge gap.

The literature indicates that effective risk communication requires a transgressive/multi-directional approach with the involvement of many stakeholders. A multi-directional approach is especially important in situations with high uncertainty and high-outcome stakes. However, the facilitation of communication and the form of communication will differ depending on methods of communication, cultural differences, resources, and problems faced.

5.2. Risk governance in an Arctic setting

Our results also clearly highlight a dearth of previous climate-related risk governance work in the high-latitude North, with our literature search returning zero studies focused on the Arctic. Much of the reviewed work investigates, for example, coastal communities in Southeast Asia or mountain communities in the Himalaya. While unsurprising given the human population concentrations in these lower-latitude regions, this focus does not specifically address the geographical, environmental, and cultural factors characterizing Arctic areas. We therefore identify a need for continued research into how to best mitigate and govern climate-related risks in an Arctic context, where climate changes presently occur at higher rates than elsewhere on the planet and communities may need to develop risk management and climate adaptation strategies for unique or novel hazards in relative isolation.

The risk governance framework presented in Section 2 offers an avenue to better address climate-related risks in the Arctic and to apply knowledge gained in this review to Longyearbyen's Arctic context. As an example, the reviewed literature infrequently focused on snow avalanches – the natural hazard with the highest societal impact on Longyearbyen in recent years – as a climate-related risk. In a notable exception, Thaler et al. (2019) investigate the community responses and adaptations to an avalanche disaster in Galtür, Austria, providing a foundation for transferring similar governance processes to an Arctic setting. Although our search string does not capture a body of work related to snow avalanche risk management in the North American (Germain, 2016; Jamieson and Stethem, 2002), the European Alps (e.g. Poratelli et al., 2020), and the Himalaya (Ballesteros-Cánovas et al., 2018) in part due to publication dates, we also argue avalanches have traditionally received minimal attention as a climate-related risk or from a risk governance perspective. Eckert and Giacona (2022)'s recent review of long-term snow avalanche risk resulted in similar findings, with the authors arguing explicitly for more transdisciplinary, holistic approaches to long-term snow avalanche risk management. In our proposed framework, avalanches such as the fatal December 2015 event in Longyearbyen can be framed as climate-related risks with rippling effects in Longyearbyen. The phases of risk governance in the framework, informed by well-recognized standards and existing frameworks, all incorporate the communication, collaboration, and stakeholder involvement shown by Thaler et al. (2019) to promote effective governance of these avalanche risks. A focus on local stakeholder involvement opens the door to better incorporate both risk-based and discourse-based approaches as part of the sensing phase in the future. Furthermore, our framework highlights the need to consider both the long-term perspective addressed by Eckert and Giacona (2022) as well as the shorter-term perspectives related to avalanche forecasting and evacuations in more acute situations.

While we have used avalanche risk as an illustrative example of Arctic climate-related risks in this work due to recent high-impact avalanche events in Longyearbyen, risk governance frameworks must be flexible enough to handle a range – or combination – of climate-related risks in a variety of locations. The diversity of natural hazards and geographic locations covered in the literature highlights the context-dependent nature of climate-related risks, where differing specific climatic changes are superimposed on a variety of societal and physiographic settings. Successful risk governance in Longyearbyen – or any specific context threatened by climate-related risks –will therefore entail augmenting generic background information with more nuanced local knowledge and effective communication between stakeholders to best manage climate-related risks for a specific context.

6. Conclusions

In this work, we have conducted a literature review to identify knowledge gaps and understand how recent, relevant work can help inform risk governance in Longyearbyen's Arctic setting. We found a diversity of strategies to consider the elements of risk governance in the reviewed literature. Although none of the reviewed works specifically explored risk governance in the Arctic, the general findings related to framing climate-related risk from a societal safety perspective and reliance on local knowledge can also be applied to Longyearbyen. We contend the most effective strategies strive to merge risk and discoursed-based sensing approaches during data collection, and emphasize the incorporation of local, context-specific knowledge via bi-directional risk communication strategies during the sense-making, decision-making, and risk treatment phases of risk governance. Meaningful knowledge gaps emerge related to the framing of climate-related risk from a societal safety perspective and comprehensively managing uncertainty throughout each phase of the risk governance process. These knowledge gaps represent novelty for the societal safety science community and the risk science community which conventionally has addressed climate-related risk in a technical and natural scientific approach. The identified knowledge gaps are as excellent points of departure for advancing societal safety research.

CRediT authorship contribution statement

Stig Johannessen: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Holt Hancock:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Siiri Wickström:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Eirik Albrechtsen:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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