STAKEHOLDER NEEDS AND INFORMATION USE IN CRYOSPHERIC HAZARD PLANNING AND RESPONSE: CASE STUDIES FROM ALASKA

By

Dina Abdel-Fattah, MSc.

A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy
in
Natural Resources and Sustainability

University of Alaska Fairbanks
May 2020

APPROVED:

Dr. Sarah Trainor, Committee Chair
Dr. Regine Hock, Committee Member
Dr. Eran Hood, Committee Member
Dr. Andrew Mahoney, Committee Member
Dr. David Valentine, Chair
Department of Natural Resources and Environment
Dr. Kinchel Doerner, Dean
College of Natural Science and Mathematics
Dr. Michael Castellini, *Dean of the Graduate School*

Abstract

The global cryosphere is experiencing rapid change, which potentially impacts the severity and magnitude of various cryospheric hazards. Alaska is home to a number of different communities that experience cryospheric hazards. These types of hazards can have potentially devastating impacts on surrounding biodiversity, communities, and infrastructure. However, there is a gap in understanding regarding what are stakeholder information needs for different cryospheric hazards, as well as what are the resources stakeholders use to meet these needs. This dissertation investigated stakeholder use of various information products and resources in three cryospheric hazard-prone communities in Alaska, which experience glacial lake outburst flood events (Juneau and the Kenai Peninsula) or anomalous high-speed sea ice motion events (Utqiaġvik). In addition, a clear need exists to understand how further cryosphere change affects cryospheric hazards. Therefore, I tested whether a structured decision-making methodology can be pertinent in a cryospheric hazard context, which has previously never been done before. Specifically, I tested whether structured decision-making can be employed by decision-makers to better understand the planning needs necessary to adequately prepare for future, but uncertain glacial surges from Bering Glacier, Alaska.

I found that identifying distinct stakeholder needs as well as stakeholder use of currently available information products and resources was particularly beneficial for information providers to understand how and why their products and resources are or are not used. This opened up opportunities for existing products to be enhanced or for new products to be developed. However, one of the main findings from the case study research is that there is no single information product that meets all stakeholder needs. Different stakeholders have different information needs, which need to be addressed in different ways. The structured decision-making approach tested in this dissertation was also found to be useful and applicable in a cryospheric hazard context. It can therefore be utilized as a methodological framework by decision-makers to integrate varying stakeholder needs in such a context. The findings from this research provide a unique contribution to the literature by displaying how social science and decision analysis research can support the development of information tools and resources that are both useful and relevant to those affected by cryospheric hazards.

Table of Contents

List of Figures

List of Tables

Dedication

To my parents, Dr. Tarek Abdel-Fattah and Dr. Gihan Mandour. You were my first examples of how rewarding a PhD can be; I caught the bug very early in life. Thank you for instilling in me your love for science and your commitment to serving others.

Acknowledgements

This dissertation would not have been possible without the help, support, and guidance of an incredibly wide spread of individuals and communities around the world. It takes a village to do many things but in the case of my dissertation, it truly took the whole state of Alaska.

I would like to thank my major advisor, Dr. Sarah Trainor, for her unwavering support and dedication to my work and my success. None of this would have been possible without you. You have not only opened many doors for me, but you have also allowed me the freedom to walk my own path, exploring my work and research in a way that I never thought would be possible. You helped me create a home to house the many dimensions of my social science, physical science, computer science, and practitioner self. Thank you for always pushing me to be more critical but also, for always doing it in a way that was kind and supportive of my own knowledge. I could not have asked for a better mentor.

I also am also greatly appreciative to the rest of my dissertation committee. Dr. Eran Hood, thank you for welcoming me to Juneau and for all the knowledge you shared with me, regarding both Suicide Basin and the city of Juneau itself. It was a great pleasure to work under your wing and to see firsthand your passion for and dedication to the community in Juneau. I have learned so much from you on how to do applied science well. Thank you for being a great role model. Dr. Regine Hock, where do I begin? Your Glaciers class is by far the best geophysics class, not only for the material you taught but also for how you taught it. I never thought I would be able to jump headfirst and succeed in a graduate-level geophysics class but you believed in me and made everything so easy to understand. This speaks to your own knowledge and your infectious love of your work. I wish I had met you earlier, I would not have diverted from science for so long if so. To Dr. Andy Mahoney, thank you for sharing all your insights about sea ice and Utqiaġvik with me. Our field school in Utqiaġvik was an incredible opportunity to see and learn from you firsthand about sea ice but more so, about community-based science. I am grateful for the countless hours in which you shared with me your own understanding of the physical-social nexus and for being an exemplary example of how to undertake community-based science in Alaska.

Another round of heartfelt thanks goes out to Dr. Love Ekenberg and Dr. Aron Larsson. Thank you for welcoming me to Sweden and for hosting a cryosphere scientist in your computer science department. My time at Stockholm University was very thought provoking; so many neurons fired. You pushed me to think outside of the box and to find ways to apply various decision and risk analysis methods into my research. Thank you for always being up for brainstorming how we can merge our two worlds together.

To the National Weather Service staff in Juneau and the Alaska-Pacific River Forecast Center, thank you for hosting me on numerous occasions, believing in the value-add of social science research to your work, and for supporting my research. I am incredibly grateful for the opportunity to operationalize my research within your organization. A big thanks goes out to Dr. Scott Lindsey, Dr. Jessie Cherry, Celine van Breukelen, Crane Johnson, and Aaron Jacobs for your honest and thoughtful feedback and for always carving out time despite your busy schedules. Dr. Christian Kienholz, thank you also for being my Suicide Basin colleague and friend. It was great to work with you both summers in Juneau, to discuss ideas together, and to see the novelty of your work in action.

As a scientist, scientific literature is an invaluable resource for us to further our understanding. However, if I only focus on the reading, citing, and writing scientific publications that were a part of my PhD process, I do not do justice to all the knowledge I gained from talking with countless individuals. Listening and conversing about my work was as important to my PhD as all the scientific knowledge that has been published on my topic. Importantly, to the communities of Juneau, the Kenai Peninsula, and Utqiaġvik, thank you for warmly welcoming me and for seeing the value of my work. I am so humbled to have been invited into so many homes and to have had sincere conversations with people about their decision-making but also their lives. I will always be happy to be a resource and advocate for you in the years to come.

To my funders, the Alaska Center for Climate Assessment and Policy (ACCAP) and the Arctic Domain Awareness Center (ADAC), as well as the UArctic north2north scholarship and many other scholarships and grants I received for travel assistance, thank you for your financial support. Without it, this research would not have happened.

Last, but not least, thank you to my family and friends for their constant support. Excluding my PhD, these were a difficult few years for me and you were there by my side the whole way. To my mom, dad, and sister, we have been through a lot and yet, we have overcome so much. Thank you for always believing in me. To all my family in Egypt, I love you all and miss you dearly. To Carolyn, Ben, and Cora, thank you for being my wonderful Fairbanks family and to Anna and Natalie, for being my equally wonderful Stockholm family. And to Lea, Federico, Jessie, Kaja, Lauren, Jamie, and Stacey, thank you for being my ever-burning sources of light and strength.

Preface

The cryosphere is rapidly changing due to climate change. Though the cryosphere has always been an important driver in global ecosystem dynamics, dramatic changes to the cryosphere, particularly in recent years, has caught the attention of the media and global public. Images, videos, graphs, and articles – scientific and populist alike – about glacial melt and sea ice retreat have been brought to the forefront of worldwide attention. Images pervade about melting ice and diminishing glaciers. The empathy that is activated in many individuals from seeing and hearing about cryosphere change is fascinating from a neurological but also behavioral perspective. *Melting ice-induced empathy* has triggered individuals around the world, myself included, to become more involved in climate change action.

However, media, and even scientific, coverage of cryosphere change largely describes it as an abstract concept, devoid of the immediate human experience. Images of pristine ice in remote areas predominant and often, the most calamitous impacts of cryosphere change are discussed and researched. Glacial melt currently is the largest contributor to sea level rise globally. The warming Arctic, due to diminished sea ice extent, is one of the largest contributors to rising mean global temperature. Glacial melt and sea ice loss have become anomalous with climate change and its effect on socioecological ecosystems. Glaciers and sea ice are often portrayed as the innocent bystanders to our human greed, victims of unencumbered human-driven growth. The rapid loss of our cryosphere has indeed resulted in these far-reaching, severe impacts on our global ecosystem. However, the localized impacts of glacial melt and sea ice loss are also fast and consequential. Loss of sea ice in particular affects marine mammals and Indigenous communities that rely on them for food, and on the ice for travel. Sea ice retreat is also greatly transforming many coastal Arctic communities in other ways; coastal erosion puts some communities at-risk for loss and relocation while a greater open water season has resulted in maritime and industrial booms for others.

Decision-making is incredibly complex. There will always be benefits and losers from any decision made. To make decisions, however, that are void of the holistic picture is a disservice to all those who are affected by a decision, decision-makers included. We need to discuss all aspects related to our changing cryosphere – including the ugly and hard parts –

in order to make informed, and hopefully good, decisions. The goal of this dissertation is to help illuminate that decision-making regarding cryosphere change is not only multi-faceted but that it also cannot only be science driven nor emotionally driven. Humans are ultimately irrational. Good decision-making is therefore less about making rational decisions but more about finding a way embrace our humanity while using our knowledge for positive social impact. Responding to our changing cryosphere, particularly to its hazards, calls for a change in our decision-making. Cryospheric change has negative *and* positive impacts as well as global *and* local impacts; all these factors need to be taken into account in our decision-making.

I hope you find my dissertation useful and thought provoking, more so the latter!

Introduction

Background

Cryospheric hazards can directly threaten and destroy life, property, and livelihoods as well as damage the economy and environment (Carey et al., 2015). Cryospheric hazards originate from glaciers, ice sheets, sea ice, permafrost, or snow (e.g. snow avalanches) and can have impacts on a local to global scale as well as cascading effects across different sectors and communities (Allen, Frey, & Huggel, 2017). Climate change has direct implication on the cryosphere, such that we are seeing increased melt and diminishing extent across the global cryosphere (IPCC, 2019). As the global cryosphere changes, so does the potential for increased risks and hazards generated from these changes. For example, increased ice instability as well as the creation of new glacial lakes, can potentially contribute to more glacial lake outburst floods (GLOF), which can have catastrophic impacts on downstream communities (Chen, Xu, Chen, Li, & Liu, 2010; Wang, Siegert, Zhou, & Franke, 2013).

There has been an increase in research in recent years to understand if, how, and to what extent climate-driven changes to glaciers, sea ice, permafrost, and snow will make them more susceptible to hazardous conditions from a socioecological perspective (Adler, Huggel, Orlove, & Nolin, 2019; Huss et al., 2017; Milner et al., 2017; Orlove et al., 2019). For example, we are seeing a rise in global mean seal level due to increased fresh water input from glacier melt, which impacts coastal communities around the world (IPCC, 2019). Sea ice retreat translates into a loss of hunting and ice travel platforms for Indigenous communities who rely on the sea ice, while catastrophic flooding from GLOFs negatively impacts downstream life, property, livelihoods, economies, and environments (Eicken & Mahoney, 2015; Emmer & Vilímek, 2013; Kattelmann, 2003). Though there is significant research being conducted on the scientific processes involved in these hazards as well as their global and local impacts, there is a large gap in the literature regarding the decision-making that needs to take place to plan for and respond to cryospheric hazards (Cuellar & McKinney, 2017; Lovecraft, Meek, & Eicken, 2013). This gap is particularly apparent for non-traditional decision-makers; those not involved in national, regional, and local planning, but are affected by these changes directly, such as homeowners, local businesses, and tourists. As the cryosphere diminishes, access to previously remote and inaccessible areas improves (Allen et al., 2017). This results in new tourism opportunities but also increased vulnerability to cryospheric hazards. The tourism industry is a particularly prominent emerging cryosphere hazard stakeholder as well as the emergency responders, both formal and volunteer, who are drawn upon to respond to an event.

There is also a need for more extensive research not only on the changing landscape of the decision contexts regarding cryospheric hazards but also on the information that is needed and used to make these decisions. Scientific information resources and products as well as traditional and local knowledge are often used by stakeholders to understand the risks, potential, and magnitude of these hazards (Carey, Huggel, Bury, Portocarrero, & Haeberli, 2012; Eicken, Lovecraft, & Druckenmiller, 2009; Laidler et al., 2011). A substantial amount of research has been conducted in recent years, particularly in the Himalayas, Andes, and Alps, to develop remote sensing and other observational data to monitor GLOF-prone glaciers, as well as develop early warning systems for downstream GLOF-prone communities (Huggel, Kääb, Haeberli, Teysseire, & Paul, 2002; Kääb, Huggel, & Fischer, 2006). There has been an increase in research too regarding integrating traditional and local knowledge into scientific monitoring and observation systems of sea ice in the Arctic (Berkes, Berkes, & Fast, 2007; Druckenmiller, Eicken, Johnson, Pringle, & Williams, 2009; Laidler et al., 2011; Lovecraft, Meek, & Eicken, 2016). Though not without its challenges, co-production of knowledge between scientists and local communities has been on the rise as its merits and benefits have been acknowledged by scientists and communities alike (Armitage, Berkes, Dale, Kocho-Schellenberg, & Patton, 2011; Meadow et al., 2015; van der Hel, 2016). As we see an increase in new information products and resources that can be utilized in a cryospheric hazards context, there is a need to understand how these products are used, if at all, by stakeholders (Jeuring, Knol-Kauffman, & Sivle, 2019; Kettle et al., 2019). More so, though some scientific information products for cryospheric hazards are developed with the input of a set of stakeholders and users, for example via the process of co-production, many are not. Therefore, cryospheric hazard information developed by scientists with the intent to be used by a variety of users would benefit from structured and systematic user assessments.

Research objectives

This research sought to address the gap in the literature regarding what are the various decisions different stakeholders need to make in different cryosphere hazard contexts. Secondly, I sought to identify which information products and resources are used by different stakeholders in different cryosphere hazard contexts, specifically for sea ice hazards and GLOFs, which has, to my knowledge, previously never been done before. Thirdly, I intended to contribute to the research by testing whether a well-established decision analysis framework, structured decision-making, can be applied in a cryosphere hazard context, to help support decision-makers for future hazard planning. I used a case study of a glacial surge to test this methodology. This was another novel contribution to the literature, as structured decision-making has never been applied in a cryosphere hazard context previously.

The research questions this research sought to answer were three-fold, based on the different literature to which this research contributes: cryospheric hazard decision analysis, use-inspired science, and structured decision-making. The first set of research questions serve as the overarching research questions regarding cryospheric hazard decision-making.

1.1. What are the decisions that stakeholders need to make regarding cryospheric hazards?

1.2. Do these decisions differ by the type of stakeholder?

1.3. Do these decisions differ by the type of cryospheric hazard?

The second set of research questions, regarding cryospheric hazard information use, was investigated via the GLOF and sea ice hazards case studies.

2.1. To what extent does the manner in which information is presented affect the ability of a stakeholder to use a data product or data resource for decision-making?

2.2. What are specific decisions and conditions that serve as barriers for stakeholders to use a data product or data resource?

2.3. What conditions drive stakeholders to seek additional information to make a decision and where do stakeholders turn for information in this situation?

Lastly, the third set of research questions, regarding parameterizing cryospheric hazard uncertainty for decision-making, were addressed via the theoretical application of a structured decision-making methodology for a glacier surge case study.

3.1. Does parameterizing scientific uncertainty regarding a cryospheric hazard help a stakeholder in their decision-making?

3.2. Does structured decision-making relay cryospheric hazard uncertainty in a manner that is understandable and useable to stakeholders?

The operationalization of these three sets of research questions are discussed next in the methodology section.

Methodology

This dissertation consisted of three different case study applications. I analyzed three different types of cryospheric hazards, specifically GLOFs, sea ice hazards, and glacier surges. The reason behind analyzing different cryospheric hazards is to see whether the decision-making regarding cryospheric hazards is unique to a specific type of hazard, or if there are more generalizable decision-making needs and processes that exist across different cryosphere hazards. For my GLOF research, I conducted a comparative case study between two GLOF-affected communities in Alaska, Juneau and the Kenai Peninsula. Specifically, I investigated what are the information products GLOF-affected stakeholders use to inform their decision-making regarding GLOFs. I conducted a comparative case study in order to validate and compare my findings from one community against those from another. I also conducted a longitudinal study for my Juneau case study, in order to see how and if stakeholder use of the various available information products changed over time.

For the sea ice research, I conducted a deep dive case study analysis of a Search and Rescue (SAR) incident in Utqiaġvik, Alaska. Similarly, to the GLOF research, the SAR case study was conducted to see how information – particularly scientific and university-developed information products – is or is not used by stakeholders in an emergency sea ice hazards context. Stakeholders involved in the SAR incident were identified and interviewed for this case study, as well as the information providers who developed and maintain the relevant information products. This case study presented a unique research opportunity since, to our knowledge, this SAR incident was the first time the scientific community was actively drawn upon to support a SAR event in Arctic Alaska.

With regards to my glacial surge research, I tested whether a structured decision-making approach can be applied in a cryospheric hazard planning context by conducting a theoretical case study of how Bering Glacier decision-makers can consider potential Bering Glacier surges for management decisions. The structured decision-making approach utilized in this research was adapted from the existing literature and applied for the first time in a cryospheric hazards context.

I employed a mixed methods methodology across all my research. For the GLOF and sea ice hazards case studies, I conducted semi-structured interviews with stakeholders, coded my interviews, and conducted statistical analyses to summarize my findings. For the structured decision-making methodology application, I employed both qualitative and quantitative analyses to assess the different alternatives developed for how to manage the area surrounding Bering Glacier in light of its potential upcoming glacial surge.

Dissertation outline

This dissertation is a compilation of three publications. The first publication presented is the GLOF case study research, titled: *The use of glacial lake outburst flood information products by stakeholders in Juneau and the Kenai Peninsula, Alaska*.[1] The second publication presented is the sea ice hazards case study research, titled: *Sea ice hazard data needs for Search and Rescue (SAR) in Utqiaġvik, Alaska.*[2] The third publication presented is the methodology publication about applying structured decision-making in a glacial surge context, titled: *Application of structured decision-making in cryospheric hazard planning: theoretical case study of Bering Glacier surges on local state planning in Alaska*.[3] Lastly, a conclusions chapter is presented which synthesizes the findings from the three publications as well as contextualizes them in the broader cryospheric hazards literature. Limitations and challenges faced during this research are also presented. Finally, broader implications from this research are discussed as well as recommendations for future research.

[1] Target journal for publication: *Environmental Science & Policy.*
[2] Accepted for publication in: Decisionmaking for Sustainability Volume II: Building Common Interests in the Arctic Ocean with Global Inclusion. *Springer.*
[3] Target journal for publication: *Group Decision and Negotiation.*

References

Adler, C., Huggel, C., Orlove, B., & Nolin, A. (2019, June 1). Climate change in the mountain cryosphere: impacts and responses. *Regional Environmental Change*, Vol. 19, pp. 1225–1228. https://doi.org/10.1007/s10113-019-01507-6

Allen, S., Frey, H., & Huggel, C. (2017). Assessment of Glacier and Permafrost Hazards in Mountain Regions. *Technical Guidance Document*.

Armitage, D., Berkes, F., Dale, A., Kocho-Schellenberg, E., & Patton, E. (2011). Co-management and the co-production of knowledge: Learning to adapt in Canada's Arctic. *Global Environmental Change*, *21*(3), 995–1004. https://doi.org/10.1016/j.gloenvcha.2011.04.006

Berkes, F., Berkes, M. K., & Fast, H. (2007). Collaborative Integrated Management in Canada's North: The Role of Local and Traditional Knowledge and Community-Based Monitoring. *Coastal Management*, *35*(1), 143–162. https://doi.org/10.1080/08920750600970487

Carey, M., Huggel, C., Bury, J., Portocarrero, C., & Haeberli, W. (2012). An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change*, *112*(3–4), 733–767.

Carey, M., McDowell, G., Huggel, C., Jackson, J., Portocarrero, C., Reynolds, J. M., & Vicuña, L. (2015). Integrated Approaches to Adaptation and Disaster Risk Reduction in Dynamic Socio-cryospheric Systems. *Snow and Ice-Related Hazards, Risks and Disasters*, 219–261. https://doi.org/10.1016/B978-0-12-394849-6.00008-1

Chen, Y., Xu, C., Chen, Y., Li, W., & Liu, J. (2010). Response of glacial-lake outburst floods to climate change in the Yarkant River basin on northern slope of Karakoram Mountains, China. *Quaternary International*, *226*(1–2), 75–81. https://doi.org/10.1016/j.quaint.2010.01.003

Cuellar, A. D., & McKinney, D. C. (2017). Decision-Making Methodology for Risk Management Applied to Imja Lake in Nepal. *Water*, *9*(8), 591. https://doi.org/10.3390/w9080591

Druckenmiller, M. L., Eicken, H., Johnson, M. A., Pringle, D. J., & Williams, C. C. (2009). Toward an integrated coastal sea-ice observatory: System components and a case study at Barrow, Alaska. *Cold Regions Science and Technology*, *56*(2–3), 61–72. https://doi.org/10.1016/j.coldregions.2008.12.003

Eicken, H., Lovecraft, A. L., & Druckenmiller, M. L. (2009). Sea-ice system services: A framework to help identify and meet information needs relevant for Arctic observing networks. *Arctic*, 119–136.

Eicken, H., & Mahoney, A. R. (2015). Sea ice: Hazards, risks, and implications for disasters. In *Coastal and Marine Hazards, Risks, and Disasters* (pp. 381–401). Elsevier.

Emmer, A., & Vilímek, V. (2013). Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). *Natural Hazards and Earth System Sciences*, *13*(6), 1551.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., & Paul, F. (2002). Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotechnical Journal*, *39*(2), 316–330.

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., … Winder, M. (2017). Toward mountains without permanent snow and ice. *Earth's Future*, *5*(5), 418–435. https://doi.org/10.1002/2016EF000514

IPCC (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Jeuring, J., Knol-Kauffman, M., & Sivle, A. (2019). Toward valuable weather and sea-ice services for the marine Arctic: exploring user–producer interfaces of the Norwegian Meteorological Institute. *Polar Geography*, 1–21. https://doi.org/10.1080/1088937X.2019.1679270

Kääb, A., Huggel, C., & Fischer, L. (2006). Remote Sensing Technologies for Monitoring Climate Change Impacts on Glacier- and Permafrost-Related Hazards. *Geohazards*. Retrieved from https://dc.engconfintl.org/geohazards/2

Kattelmann, R. (2003). Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard? *Natural Hazards*, *28*(1), 145–154.

Kettle, N. P., Abdel-Fattah, D., Mahoney, A. R., Eicken, H., Brigham, L. W., & Jones, J. (2019). Linking Arctic system science research to decision maker needs: co-producing sea ice decision support tools in Utqiaġvik, Alaska. *Polar Geography*, 1–17. https://doi.org/10.1080/1088937X.2019.1707318

Laidler, G. J., Hirose, T., Kapfer, M., Ikummaq, T., Joamie, E., & Elee, P. (2011). Evaluating the Floe Edge Service: how well can SAR imagery address Inuit community concerns around sea ice change and travel safety? *The Canadian Geographer/Le Géographe Canadien*, *55*(1), 91–107.

Lovecraft, Amy L, Meek, C., & Eicken, H. (2016). Data portals as institutional bridges: Connecting scientific observations to stakeholder needs in sea ice social-environmental systems. *Arctic Observing Summit*, 15–18.

Lovecraft, Amy Lauren, Meek, C., & Eicken, H. (2013). Connecting scientific observations to stakeholder needs in sea ice social–environmental systems: the institutional geography of northern Alaska. *Polar Geography*, *36*(1–2), 105–125. https://doi.org/10.1080/1088937X.2012.733893

Meadow, A. M., Ferguson, D. B., Guido, Z., Horangic, A., Owen, G., & Wall, T. (2015). Moving toward the deliberate coproduction of climate science knowledge. *Weather, Climate, and Society*, *7*(2), 179–191. https://doi.org/10.1175/WCAS-D-14-00050.1

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., … Brown, L. E. (2017, September 12). Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 114, pp. 9770–9778. https://doi.org/10.1073/pnas.1619807114

Orlove, B., Milch, K., Zaval, L., Ungemach, C., Brugger, J., Dunbar, K., & Jurt, C. (2019). Framing climate change in frontline communities: anthropological insights on how mountain dwellers in the USA, Peru, and Italy adapt to glacier retreat. *Regional Environmental Change*, *19*(5), 1295–1309. https://doi.org/10.1007/s10113-019-01482-y

van der Hel, S. (2016). New science for global sustainability? The institutionalisation of knowledge co-production in Future Earth. Environmental Science and Policy, 61, 165–175. https://doi.org/10.1016/j.envsci.2016.03.012

Wang, X., Siegert, F., Zhou, A. guo, & Franke, J. (2013). Glacier and glacial lake changes and their relationship in the context of climate change, Central Tibetan Plateau 1972-2010. *Global and Planetary Change*, *111*, 246–257. https://doi.org/10.1016/j.gloplacha.2013.09.011

Chapter 1. The use of glacial lake outburst flood information products by stakeholders in Juneau and the Kenai Peninsula, Alaska[4]

1.1. Abstract

Glacial lake outburst floods (GLOFs) significantly affect some downstream communities in Alaska. Notably, GLOFs originating from Suicide Basin, adjacent to Mendenhall Glacier, have impacted populated areas downstream along Mendenhall Lake and River in Juneau since 2011. On the Kenai Peninsula, records of GLOFs from Snow Glacier date as far back as 1949, affecting downstream communities and infrastructure along the Kenai and Snow river systems. Several informational products produced by the US National Weather Service, the US Geological Survey, as well as the University of Alaska Southeast with regard to Suicide Basin are available to aid the public in monitoring both these glacial dammed lakes as well as the ensuing GLOFs. This two-year study (2018 – 2019) analyzed how stakeholders affected by the aforementioned GLOFs utilize these various products. The participants in this project included stakeholders from a variety of different sectors and backgrounds to help capture a diverse set of perspectives and insights, such as homeowners, emergency responders, tour operators, and staff at federal and state agencies. In addition, feedback and suggestions were collected from stakeholders to facilitate improvements or modifications by the relevant entities to make the informational products more usable. Findings from this study were used to inform changes to the US National Weather Service monitoring websites for both Suicide Basin and Snow Glacier. This paper also discusses the relevancy of these findings for other GLOF-affected communities, from both a stakeholder and information developer perspective.

[4] Abdel-Fattah, D., S. Trainor, E. Hood, R. Hock, C. Kienholz. Socioeconomic impacts of glacial lake outburst floods in Juneau and the Kenai Peninsula. *Environmental Science &Policy.* . **In preparation (2020).**

1.2. Introduction

Climate change is directly and immediately impacting the state of the cryosphere in Alaska (USGCRP, 2018). Understanding the impacts of climate change on the cryosphere in Alaska, particularly from a hazards perspective, is of great scientific and socioeconomic interest (Harrison et al., 2018). Glacial lake outburst floods (GLOFs) are one of the most dangerous cryospheric hazards present in Alaska. A GLOF is characterized by the rapid release of water from within or under a glacier or from an ice-dammed lake due to unstable glacial dynamics (Hambrey & Alean, 2004). They can drastically and severely impact downstream ecosystems, human systems, and infrastructure; for example, a GLOF in combination with heavy rainfall in Kedarnath, India in 2013 resulted in more 6,000 fatalities as well as significant road and infrastructure (e.g. power plants) damage (Allen, Rastner, Arora, Huggel, & Stoffel, 2016). The impact of GLOFs on human systems and infrastructure is generally acute, sudden, and potentially catastrophic. A GLOF can also affect human systems in less direct ways. Although GLOFs are not frequent events, they can have damaging and long-lasting social and environmental impacts (IPCC, 2012). GLOFs can impact downstream water sources, tourism economies, energy production (particularly in glacierized basins with hydropower infrastructure), as well as livestock, agriculture and other food supplies.

GLOFs in Alaska, though not as destructive in terms of life and property as in other parts of the world due to low population density, can result in damage to downstream homes, infrastructure, riverbank erosion, and the local economy. This article discusses case studies of the socioecological implications of GLOFs in two locations in Alaska: Suicide Basin, in Juneau and Snow Glacier, on the Kenai Peninsula. The main objective of this research was to elucidate the most effective ways to relay GLOF-related information to different stakeholder groups. This study investigated how presenting information, in different formats and to different stakeholders, changed 1) their perception of, if at all, the utility of GLOF predictive modeling and 2) their use, if at all, of GLOF predictive modeling. Importantly, this study sought to understand the decisions different stakeholders need to make regarding GLOFs and how current informational products meet or do not meet those needs.

1.2.1. Decision support tools

Decision support tools are resources that help support a variety of decision tasks including information gathering and analysis, model building, sensitivity analysis, collaboration, and decision implementation (Bhargava et al., 2007). Decision support tools do not necessarily have to be computer-based, or web-based. However, most literature defines them as being at least computer-based (Welp, 2001). The information technology literature, where the concept of decision support tools first emerged in the late 1960s, argues the two most widely utilized approaches to implement a decision support tool are via data-driven and model-driven approaches. Data-driven approaches support managers in utilizing a large amount of pertinent information while model-driven approaches help managers in using analytical and/or predictive models (Bhargava et al., 2007).

Decision support tools hold a different meaning in the natural resource management literature, where their use is focused less on analytical simulation and instead on communication, training, forecasting, and/or experimentation (Van de Ven et al., 1998). Natural resource management decision support tools also differ from traditional information technology tools in that they can also integrate ordinary knowledge, e.g. qualitative information into modeling efforts. Though such information can provide richer and more robust meaning to a model's outputs, it can also complicate modeling efforts. Welp (2001) thus stresses the importance of developing decision support tools in a participatory manner, as early as possible, with applicable stakeholders and decision-makers so that these nuisances can be accounted for, tested, and iterated upon in a meaningful manner. For this research, we utilized a combined definition of decision support tool, based off a) the definition of the model-driven system definition from the information technology literature and b) the natural resources management definition of decision support systems, which emphasizes stakeholder engagement in a decision support system.

1.2.2. Usability of decision support tools in flood management

The existing literature on evaluating the use and usability of decision-support tools in natural hazard planning and response encompasses a variety of hazard scenarios. Flood management lends itself well to use of decision support tools given that completely predicting and controlling the impact of a flood is seldom, if ever, possible. Ahmad and Simonovic (2006) describe the flood management process as a three-phase process that consists of: 1) pre-flood planning, 2) flood emergency management, and 3) post-flood recovery. The key features of a decision support tool in the context of flood management should therefore address the different decisions that need to be made at each of the aforementioned phases.

Ahmad and Simonovic (2006) assessed the applicability of the Decision Support for Management of Floods (DESMOF) tool via a case study application in the Red River basin in Manitoba, Canada. Their research involved assessing the tool's features with flood managers. Though their research focused on engaging stakeholders and decision-makers and eliciting their feedback, they did not revise or change their tool based on this collected feedback. Rather, their research focused on assessing whether such a tool could be helpful to decision-makers. Todini (1999) conducted a similar review of a flood decision support system (FLOODSS) in Italy, to see how it can better meet the needs of its users. In the context of flood management, these users are generally meteorologists, operational managers, and civil response managers. Todini (1999) describes how decision support tools consist of two components: the technological and social. He stresses that it is important to take into consideration *both* components in order to achieve an effective decision support tool. Despite Todini's (1999) focus on the importance of addressing the social subsystem in a decision support system, his research did not include specific components of stakeholder engagement nor iterative development based off stakeholder feedback.

Levy (2005) addressed how multiple criteria decision-making can support the transfer of knowledge about flood processes as well as the facilitation of coordination between flood decision-makers and affected citizens. Levy (2005) also did not include any stakeholder engagement or feedback incorporation in his research design. However, he stresses in particular the analysis of the human-computer interface to better facilitate knowledge transfer, increase decision-making transparency, improve communication, as well as make linkages and assumptions more explicit and understandable to flood information users (Levy 2005).

Though there is less explicit literature on the use of decision support tools in the GLOF context, there is increasingly more literature being published on the use of hazards assessments for GLOF monitoring (Allen, Zhang, Wang, Yao, & Bolch, 2019; Huggel, Kääb, Haeberli, Teysseire, & Paul, 2002; Klimeš, Benešová, Vilímek, Bouška, & Rapre, 2014;

McKillop & Clague, 2007; Rounce, McKinney, Lala, Byers, & Watson, 2016; Shrestha et al., 2010; Thompson, Shrestha, Chhetri, & Agusdinata, 2020; Wang, Yao, Gao, Yang, & Kattel, 2011). Therefore, what this research seeks to contribute to the existing literature is addressing the gap in knowledge on the use of decision support tools in a GLOF context but also to providing the broader flood management literature with an analysis of stakeholder engagement and feedback incorporation by flood information providers in GLOF decision support tools.

1.3. Research goals

This research contributes to the literature and current understanding on decision-making under uncertainty, risk analysis, and co-producing use-inspired science in a cryosphere context (Becker, 2018; Bremer & Meisch, 2017; Bremer et al., 2019; Huggel et al., 2020; Luke et al., 2018; Nel et al., 2016; Vincent, Daly, Scannell, & Leathes, 2018). The research questions addressed by this work are tri-fold and grounded in the fields of decision-making, risk analysis, and communicating uncertainty.

The purpose of this research was to determine the most effective ways to relay GLOF hazard information to different stakeholder groups in Juneau and on the Kenai Peninsula, given the breadth and variety of actors affected by a GLOF event. This research investigated 1) how current GLOF informational products are used by different stakeholders, 2) what challenges and/or barriers exist for stakeholders regarding their use of current informational products, 3) whether different stakeholder have different informational needs, and 4) what are the best formats and communication mechanisms to meet identified stakeholder needs. Lastly, this research aimed to be an example of successful knowledge co-production. By involving both information developers and stakeholders, this work sought to support stakeholder engagement from an institutional and user perspective.

1.4. Background and study sites

GLOFs differ in how they form, depending on the local geological and glacial conditions. Over the course of the melt season, glacier dammed lakes fill up with water until there is enough water to lift up the glacier from its bed, which allows for the water to suddenly release from the lake (Hambrey & Alean, 2004). The Icelandic term *jökulhlaup* is commonly used to refer to these types of events, in which a glacier-dammed lake or water impounded within a glacier suddenly or rapidly drains (Cuffey & Paterson, 2010). An ice-dammed lake usually develops when a glacier acts as a dam for a stream draining a side valley or an adjacent lake, formed from melt from an up-valley ice cap or glacier (Cuffey & Paterson, 2010). Ice-dammed lakes typically form in three locations:

1. Where ice-free side valleys are blocked by a glacier in the trunk valley

2. Where trunk valleys are blocked by glaciers spilling out from side valleys, or

3. At the junction between two valley glaciers (Benn & Evans, 2014).

GLOFs differ from precipitation-induced floods in that they are characterized by a non-linear increase in discharge. GLOFs tend to start very slowly, as the drainage water connects to the sub-glacial drainage system. However, once this connection is established, friction from the flowing water expands the glacial drainage conduits, leading to a rapid, exponential rise in discharge. After peak flow is achieved, the drainage system is wide open, and the descending limb of the hydrograph is extremely steep such that the GLOFs "tapers off" much more rapidly, within minutes or hours, than floods generated by precipitation events (Hambrey & Alean, 2004).

GLOFs typically occur in summertime or early autumn, when the water supply to a glacial lake is at its peak and there is increasing summer ablation (Xu, Bogen, Wang, Bønsnes, & Gytri, 2015). Precipitation-induced floods, on the other hand, do not necessarily have as much seasonal dependence. Glacierized basins in general tend to have distinct annual variation in discharge, due to snow formation in winter and snow melt in summer as well as distinct daily variation due to the daily diurnal cycle of meteorological and temperature conditions (Klok, Jasper, Roelofsma, Gurtz, & Badoux, 2001).

The impacts of GLOFs often exceed those of other flood events, particularly in the context of the Andes and the Himalayas (Clague & Evans, 2000). This is predominantly due to the sudden release of water that is associated with these types of floods, particularly from moraine dam failures, which typically result in flood discharges that are substantially larger than those from rain, snow or glacier melt (Cenderelli & Wohl, 2003). A recent study by (Cook, Andermann, Gimbert, Adhikari, & Hovius, 2018) – which involved analyzing seismic records of a July 2016 glacial outburst flood in the Bhotekoshi / Sunkoshi Rover of Nepal – has provided new knowledge on how GLOFs mobilize large boulders, that would normally prevent channel erosion, allowing the impacts of GLOFs to be much larger than the impacts of the annual summer monsoon. Research like this holds implications for human systems and infrastructure in GLOF-prone areas. Though GLOFs are rare in comparison to storm events, they can have much larger and more damaging impacts. There is thus a clear need to think of and communicate GLOFs as unlikely but extreme events.

1.4.1. Suicide Basin, Juneau, Alaska

The GLOFs originating in Suicide Basin, the glacier dammed lake, presents a unique opportunity to analyze and understand more direct societal and economic impacts of GLOF events on a downstream community, given the close proximity of Suicide Basin to the city of Juneau, the state capital of Alaska. Numerous homes are in the floodplain of Mendenhall River and have been affected in previous GLOF events as well as US Forest Service campsites along Mendenhall Lake, which are closed during large GLOFs. In addition, tour operators operating in Mendenhall Lake have cancelled tours during GLOFs due to unsafe conditions.

Suicide Basin is an approximately 0.7 km^2 ice-covered basin that sits roughly ~3 km upglacier from the terminus of Mendenhall Glacier and is located approximately 22 km from downtown Juneau (Kienholz et al., 2020). The first reported GLOF from Suicide Basin was in 2011. Since then Suicide Basin has regularly (e.g. at least once annually) released an outburst flood into Mendenhall Lake via Mendenhall Glacier, raising water levels in both Mendenhall Lake and Mendenhall River to varying degrees (Morgan, Walter, Peng, Amundson, & Meng, 2013). Though the largest GLOF recorded thus far was in 2016, this research comes at an opportune time, given that 2018 was the third largest GLOF on record ("National Weather Service Advanced Hydrologic Prediction Service," n.d.). A GLOF occurred in 2019 as well though it was not of record magnitude ("National Weather Service Advanced Hydrologic Prediction Service," n.d.). Overall, four of the seven largest floods in the Mendenhall River streamflow record (1966-present) have occurred in the last 8 years as a result of GLOFs (USGS, n.d.).

1.4.2. Snow Glacier, Kenai Peninsula, Alaska

GLOFs from the Snow Glacier dammed lake, approximately 0.8 km long and ~140 m deep and located about 40 km northeast from Seward, have occurred approximately every two to three years raising water levels in the Snow River on the Kenai Peninsula (Wilcox, Wade, & Evans, 2014). The earliest reported GLOF from Snow Glacier was in 1949 ("Glacial Dammed Lake Data," n.d.). Though flooding from these GLOF events has not historically caused widespread damage to life or property, stakeholders have experienced, particularly in recent events, nuisance flooding, damage to various transportation-related infrastructure, as well as negative impact on the local economy, due to the cancellation of tour operations because of heightened river and lake levels. Typical GLOF events from Snow Glacier can raise river water levels several meters in communities like Cooper Landing and Kenai Keys on the Kenai Peninsula. Elevated river levels from the Snow Glacier GLOFs increase debris and sediment in the Kenai River and can impact fish, particularly salmon runs, with implications for the sport fishing, rafting, and tourism sectors on the Kenai Peninsula, both of which play a significant role in the local economy. An additional consideration is that the occurrence of a GLOF coincident with high water levels, caused by heavy mountain snowpack or a deluge from an Atmospheric River, could result in unprecedented flooding along the Kenai River.

1.4.3. Challenges with forecasting GLOFs

Forecasting a GLOF as well as predicting its potential impact is challenging given the limited amount of quantitative or observational data regarding this type of hazard (Worni, Huggel, Clague, Schaub, & Stoffel, 2014). The magnitude of a GLOF is dependent on both climate-driven changes in glacier dynamics as well as year-to-year weather variability, impacting the ability to consistently forecast the timing and magnitude of a GLOF accurately (Li & Sheng, 2012).

Given the uncertainties associated with forecasting GLOFs, and potential compound effects from other climate change-induced events (such as Atmospheric Rivers, increased snowmelt, and increased precipitation) with GLOFs, information developers fundamentally want to accurately communicate hazard levels to stakeholders in the surrounding areas. Specifically, information developers are interested in learning how to better communicate the uncertainties associated with their hazard forecasts and thus provide products that are understandable to stakeholders. For example, the National Weather Service's (NWS) Alaska-Pacific River Forecast Center (APRFC) is responsible for issuing all flood-related forecasts in Alaska, which in turn are used by the NWS Weather Forecast Offices (WFO) to issue local forecasts and outlooks to the emergency managers, the media, and the public in their jurisdiction.

Beyond the need to create understandable products, creating useable products is another fundamental goal for information developers, particularly in a hazard context. The hydrographs, time series plots of discharge or streamflow, maintained and issued by the APRFC regarding the downstream GLOF-affected lakes and rivers, and which are utilized by the WFOs, are one of the main resources stakeholders use to understand and prepare for a GLOF. Therefore, feedback on how and if stakeholders utilize these hydrographs is critical in understanding the information needs and use of stakeholders in GLOF-affected communities in Alaska.

1.5. Materials and methods

1.5.1. Methods

A case study comparison was selected for this research in order to assess the transferability and applicability of the methodologies and theories developed as part of this research across different communities. The Suicide Basin case study was a longitudinal case study that was conducted over the course of two years (2018 - 2019), so that we could assess whether stakeholders who participated in this research experienced any changes in 1) their perception of the utility of GLOF predictive modeling and 2) their use of GLOF predictive modeling. The Suicide Basin case study underwent Phase I, Phase II, and Phase III outlined below. The Snow Glacier case study was conducted over the course of one year (2019), to assess the transferability of the methodology (specifically, Phase I) in a different site location. A longitudinal assessment of the Snow Glacier case study (e.g. Phases II and III) was not possible for this research due to the fact the Snow Glacier GLOF occurs at a different time scale than the Suicide Basin GLOF (every two or three years versus every year, respectively).

1.5.1.1. Research participants

An analysis of downstream communities from Suicide Basin and Snow Glacier identified the following groups as the most integral stakeholders in each community, from the perspective of decision-making regarding GLOFs as well as potential to be affected by GLOFs (Table 1.1).

A total of 37 unique individuals were interviewed for the Suicide Basin case study over the course of 2018 and 2019, 33 unique individuals in 2018 and an additional four unique individuals in 2019. Regarding the difference in interviewees between the Suicide Basin 2018 and 2019 GLOF events, of the 33 people interviewed in Juneau for the 2018 GLOF event, only 16 were re-interviewed in 2019. Of the 17 individuals not interviewed again in 2019, five individuals were no longer in the same position in 2019, six did not respond to the re-interview request, and five we were not able to get in contact with again. In addition, there were four new interviewees for the Suicide Basin 2019 GLOF event; however, two of the new interviewees did not provide meaningful responses to all of the interview questions.

A total of 13 unique individuals were interviewed for the Snow Glacier case study. It is important to note that some individuals did not respond to each interview question, due to lack of familiarity with the information product and/or context. We list the sample size (n) in each table and figure, where appropriate, in order to portray participant totals accurately (Table 1.2).

1.5.1.2. Type of organization

Interviewees were then grouped into six different types of organizations: Homeowner, Interested Citizen, Federal Agency, Local Agency, Local Business, and State Agency (Table 1.2). The same organization groups were identified for both the Suicide Basin and Snow Glacier case studies, however there was only one interested citizen interviewed in the Suicide Basin case study, and none in the Snow Glacier case study. For the Suicide Basin 2018 interviews, the largest interviewee pool representation was from local agencies (30% of 33 interviewees). However, for the Suicide Basin 2019 interviews, the largest interviewee pool presentation was from homeowners, (35% of 20 interviewees). For the Snow Glacier case study, the largest interviewee pool representation was from federal agencies (54% of 13 interviewees).

1.5.1.3. Information developer or affected party

We also distinguished between whether a stakeholder was an information developer or an affected party regarding the GLOF events. Five information developer organizations were identified for this research, as indicated in Table 1.1. However, the University of Alaska Southeast is only an information developer for the Suicide Basin case study.

Of the 33 Suicide Basin 2018 interviewees, 10 (30% of the total) were identified as information developers (Figure 1.1). All of the information developers were associated with either a federal agency or a state agency. The remaining interviewees, 23 out of the 33 Suicide Basin 2018 (70% of the total) were identified as affected parties. Although the overall number of interviewees was different for Suicide Basin in 2019, the ratio of information developer to affected party remained the same. Of the Suicide Basin 2019 interviewees, 30% were identified as information developers while 70% were identified as an affected party. Similarly, federal agency and state agency representatives comprised the information developer group.

For the Snow Glacier 2019 interviewees (see Figure 1.2), six interviewees (46% of 13 total) were information developers, leaving the remaining seven interviewees (54% of 13 total) as an affected party. The main difference between the Suicide Basin and Snow Glacier case study, apart from the different information developer – affected party ratio, was that the information developer group for Snow Glacier was comprised of only federal agency representatives. This is predominantly because no university researchers, who are classified as state agency researchers, are actively involved in the Snow Glacier GLOF monitoring. In Juneau, several University of Alaska researchers are involved in the Suicide Basin monitoring effort.

1.5.1.4. Interviewee sampling

We identified interviewees based on a number of different avenues. Information providers were identified via informational meetings with the NWS APRFC, NWS WFOs in Juneau and Anchorage, USGS in Juneau and Anchorage, and the University of Alaska Southeast. Via these meetings, all relevant information providers were identified for both studies. Affected party interviewees were identified via these meetings as well, particularly for all the local agencies involved in emergency management as well as community members in high-risk areas. Businesses were identified via discussion with the US Forest Service in Juneau, who maintains a list of all active businesses operating on Mendenhall Lake, as well as with the local visitor centers in the Kenai Peninsula, who have records of all active business operations on the Snow and Kenai River. Public notices for further community input were sent out via the NWS Twitter accounts in Juneau and Anchorage in addition to the local newspapers. Lastly, we also utilized a snowball sampling method to identify further interviews (Handcock & Gile, 2011). A complete list of the stakeholder groups interviewed for this research can be found in Table 1.1.

1.5.1.5. Interviewee coding

For Phase I of the research, described further below, a structured interview protocol (see Appendices I and II for the interview questions for the Suicide Basin and Snow Glacier case studies, respectively) was used to ask the interviewees about: 1) their experiences and familiarity with GLOF events, 2) their familiarity and use of GLOF informational products, 3) their preferred method of information provision, and 4) their preferred mediums to receive information. For Phase II of the research, also described below, a structured interview protocol was used (see Appendix I) for the 2019 Suicide Basin information providers, to share the stakeholder feedback from Phase I with them. A new GLOF information product was developed by the Suicide Basin information providers in response to Phase II. Lastly, for Phase III of the research, see below, a structured interview protocol (see Appendix II) was also utilized to collect feedback from Suicide Basin interviewees on their experiences utilizing the new product that was developed.

All interviews were transcribed with the consent of the interviewees. Given that the interview protocol was structured, interview analysis consisted of coding the transcriptions so that the information could be synthesized into a spreadsheet, based off each interview questions, in order to be analyzed systematically. Interviews were coded twice by one coder to ensure the information was accurately reported and relayed. Interviews were also analyzed using qualitative content analysis for themes related to challenges of using GLOF informational products, the use of GLOF informational products in decision-making, challenges to data use in general, and lessons learned and recommendations for future GLOF events (Mayring, 2004).

1.5.2. Materials

1.5.2.1. Data

Five information products were analyzed for the Suicide Basin case study: 1) NWS APRFC Mendenhall Lake hydrograph, 2) NWS flood advisory and flood watch statements, 3)

NWS inundation map of Juneau, 4) US Geological Survey (USGS) timelapse camera images of Suicide Basin, and 5) USGS stream gage at Suicide Basin. In addition, a newly developed product (June 2019), a webpage hosted by the NWS Juneau Forecast Office that has all the aforementioned materials for Suicide Basin compiled on one page, was analyzed as part of phase II and III for the Suicide Basin case study.

For the Snow Glacier case study, four comparable information products were analyzed: 1) NWS APRFC Snow and Kenai river systems hydrographs, 2) NWS flood advisory and flood watch statements, 3) USGS stream gages along the Snow and Kenai Rivers, and 4) Civil Air Patrol photos. At the time of this research, USGS timelapse camera imagery was not available to be analyzed nor was there a comparable inundation map for the Snow Glacier watershed to be used in this study.

1.5.2.2. Research phases

1.5.2.2.1. Phase I: Baseline assessment of GLOF familiarity and information product usage

Stakeholders were interviewed during the 2018 GLOF from Suicide Basin and the 2019 GLOF from Snow Glacier. The purpose of Phase I was to gather a baseline assessment of each stakeholder's familiarity with: a) GLOFs, b) the current information products available on Suicide Basin and Snow Glacier, and c) their use, if at all, of these products. In addition, Phase I assessed stakeholders preferred formats (written, oral, visual) and media (email, radio, social media) for receiving and using information. The information collected during Phase I provided insight into stakeholder decision-making needs regarding GLOFs and any feedback they provided on information gaps or for improvements in the current information landscape. Information developers, a subset of the overall stakeholders that participated in this research, were also asked to answer a few additional questions to help assess their willingness and ability to engage in feedback iterations for this research.

1.5.2.2.2. Phase II: Sharing stakeholder feedback with information developers & new product development

We only conducted Phase II for the Suicide Basin case study, since Snow Glacier only had one GLOF during our research period. The findings from Phase I were shared with the identified information developers. During these feedback-relaying sessions, information developers were asked to relay their uptake and understanding of the stakeholder feedback as well as how they plan to adapt their products and tools to better meet stakeholder needs. The results from these feedback-relaying sessions helped to inform changes in the public-facing GLOF information products. Findings from Phase I helped to inform the development of public-facing graphs, created by University of Alaska Southeast researchers, as well as the new Suicide Basin monitoring website, hosted by the NWS Juneau WFO.

1.5.2.2.3. Phase III: Stakeholder feedback on new products

For the Suicide Basin case study, a second round of interviews was set up with previously interviewed stakeholders during the following year's Suicide Basin GLOF event (2019). Stakeholders engaged in user testing regarding the new informational products developed during Phase II. In addition, a third informational product was assessed with stakeholders: a new educational website, developed by the Alaska Climate Adaptation Science Center, on Suicide Basin. The interview questions for Phase III were developed and grounded in the literature on user testing and tool development. Stakeholders were asked a series of interview questions after the user testing, to assess whether the modified / new tools met their identified needs. Stakeholders were also asked for any suggestions for further improvements to the Suicide Basin informational landscape.

1.6. Results

1.6.1. Phase I results: Baseline assessment of GLOF familiarity and information product usage

<u>1.6.1.1. Previous experience with GLOF event</u>

For both case studies, the majority of interviewees had previously experienced a GLOF prior to the interview (Figure 1.3). For the Suicide Basin case study, there were only four out of 35 interviewees who had not previously experienced a GLOF. For the Snow Glacier case study, there were five out of the 13 interviewees who had not previously experienced a GLOF.

It is worth noting the difference in the interviewees' self-expressed understanding of the concept of a GLOF (Figure 1.4) between the two different case studies. Interviewees were asked to quantify their understanding of the concept of a GLOF on a scale of 1 to 5, which 1 being the least familiar and 5 being the most familiar. For the Suicide Basin case study, there was a high self-reported understanding of the concept in comparison to the

Snow Glacier case study. This difference can possibly be due to fewer Snow Glacier interviewees having experienced a GLOF compared to the Suicide Basin interviewees.

1.6.1.2. Interviewee use and understanding of GLOF information products

Tables 1.3 and 1.4 below summarize the findings from the interviews from both case studies regarding how interviewees use and understand the relevant GLOF information products. The NWS hydrograph was the most understood and used information product for the Suicide Basin case study: 98% of interviewees reported having seen and used the NWS hydrograph (Table 1.3). The NWS hydrograph and the USGS stream gage were the only two information products that did not have any difference between whether a user had seen and used the product. Homeowners did not report a difference in seeing and using an information product except for the NWS inundation map. All homeowners reported they had seen the NWS inundation map but only 86% of them had actually used it.

Regarding the Snow Glacier case study (Table 1.4), there was no reported difference between seeing and using any of the information products. Compared to the Suicide Basin case study, the NWS flood statement was the most understood and used information product for the Snow Glacier case study: 100% of interviewees reported having seen and used the NWS flood statement. There was generally a lower incidence of using of the various information products in the Snow Glacier case study compared to the Suicide Basin case study. This is seen both across the various different information products but also across each organization group.

1.6.1.3. How often information products are used

Interviewees were asked how often they used any given GLOF information product. The majority of interviewees in both case studies reported using these products (apart from the NWS inundation map for the Suicide Basin case study and the NWS hydrograph for the Snow Glacier case study) on a daily basis before, during, or after an event (Table 1.5). Is it important to note however that very few interviewees from either case study reported using the GLOF information products outside of an expected GLOF season.

1.6.1.4. Preferred media and formats to receive information

Lastly, we analyzed the preferred information media and formats interviewees identified in both case studies. For the Suicide Basin case study (Figure 1.5), the top three media interviewees preferred to receive information in were: e-mail (77% of 35 interviewees), text message (71% of 35 respondents), and social media (46% of respondents). E-mail was the top preferred medium among federal agencies, while homeowners preferred text messages. Local agencies, local businesses, and state agencies were tied between email and text message as their preferred method to receive information. It is interesting to note that no organization group had social media as their top preferred method.

For the Snow Glacier case study (Figure 1.6), phone calls were the preferred medium to receive information (62% of 13 respondents), followed by e-mail (54% of 13 respondents) and text messages (23%of 13 respondents). State agencies and local businesses reported e-mail as their preferred medium while federal agencies reported phone calls. Homeowners were tied between phone calls and text messages and local agencies between phone calls and emails as their preferred medium. Finally, local businesses reported email as their preferred. The main difference between the preferred media for Suicide Basin and Snow Glacier case studies was the difference in phone calls and social media, where phone calls play a larger role in the Snow Glacier case study and social media for the Suicide Basin case study.

Regarding the preferred formats identified in the Suicide Basin case study (Figure 1.7), graphs and charts were mentioned as the overall preferred format by interviewees, followed by written narratives and face-to-face communication. Graphs and charts were the preferred format for all organization groups apart from homeowners, where written narratives were identified as the preferred format.

In comparison, graphs and charts were also identified as the overall preferred format by interviewees in the Snow Glacier case study (Figure 1.8). However, there was a three-way tie between face-to-face communication, pictures, and written narratives for the second preferred format. Federal agencies and local business representatives indicated graphs and charts were their preferred format and homeowners indicated written narratives, which is similar to the Suicide Basin case study. However, local agencies were tied between face-to-face communication and graphs and charts as their preferred format meanwhile state agencies preferred written narratives. Compared to the Suicide Basin case study, there was more variance for preferred formats in the Snow Glacier case study.

1.6.2. Phase II results: Sharing stakeholder feedback with information developers & new product development

This research identified preferred informational needs for different stakeholder groups regarding GLOF events and whether current informational products are meeting those needs. Collecting this stakeholder information helped inform modifications to existing informational products, as well as the development of new ones, so that they could better meet stakeholder needs in the Kenai Peninsula and Juneau respectively. Two new GLOF monitoring websites, hosted by the NWS and compiled with information collected by the NWS, USGS, and the University of Alaska, were developed over the course of this project, based off the stakeholder feedback that was collected for the Suicide Basin case study. Given the success of the new Suicide Basin monitoring website over the 2019 GLOF season, a similar site was set-up by the NWS, compiled with information collected from the NWS and USGS, in time for the Snow Glacier GLOF later that summer. Though the 2019 Snow Glacier interviews were conducted prior to the new website going live, informal feedback collected thereafter showed that it was used and useful to stakeholders.

1.6.3. Phase III results: Stakeholder feedback on new product

Stakeholders had different preferences for how they want to see information and how they want to receive information as seen in sections 1.6.1.3 and 1.6.1.4; however, it was clear across all interviewees for Phase III of this research, that they appreciated the new one-stop-shop Suicide Basin monitoring page, as it helped them to easily and readily access information on the GLOF events. Importantly, all stakeholders indicated they were very pleased that the information providers worked to meet their needs. Many interviewees indicated they have a need to feel "connected" to someone knowledgeable about GLOF events. Thus, seeing the new product go online and that their feedback was utilized, was assuring to stakeholders.

Nonetheless, nearly all interviewees expressed a desire to have face-to-face meetings, texts, or community meetings to talk about and learn more about the GLOFs. The hazardous potential of GLOFs along with the fascination that people have living alongside these active glaciers increases interviewees' desire to learn more about the process of GLOFs as well as their future outlook and impact on their communities. As one interviewee (homeowner) mentioned,

> *"I have questions about the long-term outlook of the glacier. It kind of connects us to it in a way that might not be there for everyone. GLOFs impact decisions about our home that we make. Until I know for certain that the GLOFs are not going to get past a certain level into our house, I don't want to put new hardwoods in, only to have them get ruined."*

Stakeholders in the Suicide Basin case study expressed an interest in having more engagement with scientists studying these glacial hazards, to learn more about both the processes at play behind GLOFs as well as their projected impacts and changes. Several stakeholders expressed an interest in having community forums where they can discuss and document the impacts they have experienced from GLOFs, so that there is not only a formalized record of what is happening on a local level, but to also serve as a liaison for scientists and agencies wanting to know more how these events impact communities in Alaska.

1.7. Discussion

1.7.1. Novel approach to assessing stakeholder use of GLOF information products

This research served as a prototype for GLOF information developers on how to integrate social science- and stakeholder-driven feedback into their product offerings and communication strategies; to our knowledge, social science-based research like this has not been previously done for GLOF communities (Sherpa, Shrestha, Eakin, & Boone, 2019; Shreevastav, 2019; Welling, Ólafsdóttir, Árnason, & Guðmundsson, 2019). Specifically, this research created a methodology and blueprint for how to elicit stakeholder input for GLOF-related information development and communication and how to integrate this input back into existing information products. This research built off the existing decision support tool literature to help provide a reproducible, transparent, and relevant process for future stakeholder elicitation and integration endeavors. In particular, it is important for information and service providers, such as the NWS, to know what are stakeholder concerns, in order to have tools and communication products better target actual, versus perceived, stakeholder needs. This research also helped support information developers, such as the NWS, in fulfilling their strategic mandates to create more tailored products for specific end users.

Three main findings emerged from our analysis. Firstly, there is difference in information product understanding and use by stakeholder group. The stakeholders' use of information products varied with their familiarity with GLOFs (Figure 1.4) as well as their previous experiences (Figure 1.3). As one interviewee (homeowner) mentioned, "I'm not concerned anymore since I've seen this happen for a long time so unless it's expected to be higher than what I've already seen, I'm not too worried." This suggests that some stakeholders, particularly those that have had previous, direct experiences with a GLOF, do not use the information products since they feel comfortable with their acquired knowledge of GLOFs and their impacts. Though this speaks highly to the amount of local knowledge that exists regarding these events, there is potential concern that some of these stakeholders could be at-risk for serious impacts if they are not monitoring early warning information and an unprecedentedly large GLOF event occurs (Sellnow & Seeger, 2001).

Secondly, there are differences in the understanding of GLOF-related information by stakeholders in the two different case studies. In comparison, the Snow Glacier interviewees were less familiar than the Suicide Basin interviewees with the concept of GLOFs. This can be due to a number of reasons. Snow Glacier is further away from populated areas when compared to Suicide Basin. That being the case, there is more reported monetary damage to infrastructure and property in the Snow Glacier watershed due to GLOFs compared to Suicide Basin. This initially seemed like a surprising finding – many interviewees were not familiar with the Snow Glacier GLOFs but they were aware of their impacts. One interviewee (local agency) illuminated this point during our discussion, "we get a lot of high water events here, whether it's coming from rain, snowmelt, or a glacier, it doesn't really matter to us." Similarly, though there is a wealth of local knowledge and familiarity regarding high water events on the Kenai Peninsula, GLOFs can have catastrophically large impacts, particularly if they are compounded with a high rainfall event or snowmelt season. The Kenai Peninsula in particular is more at-risk for such a compounded GLOF event, given the area's predisposition for high water events and increased reliance on past, local knowledge. This is a similar finding to other flood literature, where assessments of severe floods (1998, 2000) in the United Kingdom found that groups that were at-risk during these events was not due to their lack of awareness; instead, they underestimated the magnitude of these unprecedented events due to their reliance on local knowledge acquired from previous flood events (Burningham, Fielding, & Thrush, 2008). Therefore, there is clear benefit and a need to communicate the potential risk from an unprecedented GLOF on the surrounding communities, and to ensure that equally robust monitoring efforts take place in the Snow Glacier drainage system, as is currently taking place via the University of Alaska Southeast for Suicide Basin and Mendenhall Glacier (Sellnow & Seeger, 2001).

Lastly, despite the differences in how stakeholders want to see information and ultimately use it, the feedback from the Suicide Basin case study Phase I results indicated a very strong message: that all stakeholders wanted information in a central, one-stop-shop place. Many stakeholders indicated in a hazards context, they want to be able to access GLOF information in one place, so that they can make quick and informed decisions. This piece of feedback was well-received by information providers in Phase II and via the NWS, USGS, and the University of Alaska Southeast, a one-stop-shop webpage to monitor information on Suicide Basin was developed prior to the 2019 flood season. Findings from the Phase III interviews, in which this new informational product was assessed, showed that unanimously, all interviewed stakeholders approved of and appreciated the new informational product. Over the course of two years, interviewed stakeholders indicated they appreciated seeing information providers taking their feedback seriously and that they appreciated also being a part of a research project that provided actionable and meaningful results to their community. This type of finding, though community-specific, nonetheless speaks to the success and importance of both co-producing knowledge as well as boundary spanning. Information providers also expressed that engaging in this research, where they were able to engage with stakeholders indirectly via a sustained social science and community-based project, was a very useful experience for them, as they were able to better understand stakeholder needs and in the Suicide Basin case study, actually meet them. Though this is only one case study, this research helped to highlight the importance, as well as the utility of, boundary spanning via providing a bridge between the information provider and information user worlds in a cryospheric hazard context.

1.7.2. Limitations

The methodology created and utilized in this research was used to identify best practices for how to elicit and integrate stakeholder feedback into science tool development, particularly tools that are created to help inform and support decision-making regarding GLOF hazards. Lessons learned from the Suicide Basin case study were used to assess the transferability of the developed methodology regarding stakeholder needs in GLOF forecasting to another case study in Alaska, regarding the Snow Glacier GLOFs. However, there were differences in interviewee pool composition and overall interviewee pool size that should be considered when looking at the case study comparison. Furthermore, due to limitations in predicting GLOFs and the different timescales of the GLOF events for both case studies (annually for the Suicide Basin case study, and every 2 to 3 years for the Snow Glacier case study), a temporal study was not possible for the Snow Glacier case study. However, the way this research was structured, in which the second year interviews for the Suicide Basin case study looked at the stakeholder feedback for the newly developed GLOF monitoring product, comparing the Suicide Basin and Snow Glacier case studies on the basis of Phase I of this research was nonetheless possible.

However, there were statistical limitations, due to the small and different, sample sizes between the two case studies. Particularly due to the small sample size for the Snow Glacier case study (n = 13), statistical analyses were not possible and therefore no tests of significance were conducted for either case study. Therefore, the information presented in this paper is relayed in a qualitative manner since the results are limited in their ability to provide broader generalizations and implications.

1.7.3. Future research and recommendations

It would be ideal to collect stakeholder feedback on the newly developed GLOF monitoring product for the Snow Glacier case study during the next GLOF (~2021 or 2022) so that the findings can be compared with the feedback collected during the Suicide Basin 2019 interviewees. In addition, it would be worthwhile to compare the findings from this research with other case studies from GLOF communities in other parts of the world, to see if the findings are specific to the Alaska context or transferrable to other areas.

Although this research was focused on decision-making under uncertainty regarding cryospheric hazards - an under-researched hazard in current stakeholder engagement literature - it sought to also create generalizable principles and lessons learned that could be applied in other hazard scenarios. Namely, this research shows there is benefit from conducting a formalized stakeholder assessment to understand stakeholder needs as well as stakeholder comprehension of scientific information and products, particularly those that are utilized in a hazard context. The feedback gathered from stakeholders also helped informed the development of new GLOF-related information websites as well as provided information developers an opportunity to understand how their products are being used and what are areas for further expansion and enhancement.

Lessons learned from this research can benefit those working in the GLOF sector but also other entities working to streamline and integrate community and stakeholder feedback into their products and resources, particularly those focused on community-based hazards. Taking the time to talk to stakeholders to understand their needs and concerns is important for information and service providers (Lemos & Morehouse, 2005). It helps to build trust within the community, but also opens the avenue to understand what people are thinking about, such that information products can be better tailored to real needs. Furthermore, stakeholders in a hazard context also have their own supply of local knowledge, given their past experiences with hazard events and successful adaptation strategies (McEwen, Krause, Jones, & Garde Hansen, 2012; McEwen & Jones, 2012). It is in the interest of the community as a whole, but for information providers in particular, to find ways to utilize this knowledge, particularly in remote areas where observational data may be scarce. Community members in both case studies in this research expressed a desire to be able to contribute to the dialogue and information provision on GLOF events. Concepts like co-production, boundary spanning, and community-based knowledge development can potentially help empower and strengthen the relationship between communities and information providers and offer new avenues for engaging in meaningful two-way dialogue and collaboration (Bednarek et al., 2018; Meadow et al., 2015; Nel et al., 2016; Posner & Cvitanovic, 2019; Shaw, Danese, & Stocker, 2013). Though this research was case study-based, it helps show the benefit of engaging information providers and affected community members together, to better understand and prepare for hazardous events.

1.8. References

Ahmad, S., & Simonovic, S. P. (2006). An intelligent decision support system for management of floods. Water Resources Management, 20(3), 391–410.

Allen, S. K., Rastner, P., Arora, M., Huggel, C., & Stoffel, M. (2016). Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. Landslides, 13(6), 1479–1491. https://doi.org/10.1007/s10346-015-0584-3

Allen, Simon Keith, Zhang, G., Wang, W., Yao, T., & Bolch, T. (2019). Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. Science Bulletin, 64(7), 435–445.

Becker, M. (2018). The Role of Intermediaries in flood risk management. In Oxford Research Encyclopedia of Natural Hazard Science.

Bednarek, A. T., Wyborn, C., Cvitanovic, C., Meyer, R., Colvin, R. M., Addison, P. F. E., … Goldman, E. (2018). Boundary spanning at the science–policy interface: the practitioners' perspectives. Sustainability Science, 13(4), 1175–1183.

Benn, D., & Evans, D. J. A. (2014). Glaciers and glaciation. Routledge.

Bhargava, H. K., Power, D. J., & Sun, D. (2007). Progress in Web-based decision support technologies. Decision Support Systems, 43(4), 1083–1095.

Bremer, S., & Meisch, S. (2017). Co‐production in climate change research: reviewing different perspectives. Wiley Interdisciplinary Reviews: Climate Change, 8(6), e482.

Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R., & van der Sluijs, J. (2019). Toward a multi-faceted conception of co-production of climate services. Climate Services, 13, 42–50.

Burningham, K., Fielding, J., & Thrush, D. (2008). "It'll never happen to me": Understanding public awareness of local flood risk. Disasters, 32(2), 216–238. https://doi.org/10.1111/j.1467-7717.2007.01036.x

Cenderelli, D. A., & Wohl, E. E. (2003). Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest region, Nepal. Earth Surface Processes and Landforms, 28(4), 385–407. https://doi.org/10.1002/esp.448

Clague, J. J., & Evans, S. G. (2000). A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary Science Reviews, 19(17–18), 1763–1783. https://doi.org/10.1016/S0277-3791(00)00090-1

Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R., & Hovius, N. (2018). Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. Science (New York, N.Y.), 362(6410), 53–57. https://doi.org/10.1126/science.aat4981

Cuffey, K. M., & Paterson, W. S. B. (2010). The physics of glaciers. Academic Press.

Glacial Dammed Lake Data. (n.d.). Retrieved January 14, 2020, from https://www.weather.gov/aprfc/gdlData?10

Hambrey, M. J., & Alean, J. (2004). Glaciers (Vol. 10). Cambridge University Press Cambridge.

Handcock, M. S., & Gile, K. J. (2011). Comment: On the concept of snowball sampling. Sociological Methodology, 41(1), 367–371.

Harrison, S., Kargel, J. S., Huggel, C., Reynolds, J., Shugar, D. H., Betts, R. A., … Reinhardt, L. (2018). Climate change and the global pattern of moraine-dammed glacial lake outburst floods. The Cryosphere, 12.

Huggel, C., Allen, S., von Dach, S. W., Dimri, A. P., Mal, S., Linbauer, A., … Bolch, T. (2020). An Integrative and Joint Approach to Climate Impacts, Hydrological Risks and Adaptation in the Indian Himalayan Region. In Himalayan Weather and Climate and their Impact on the Environment (pp. 553–573). Springer.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., & Paul, F. (2002). Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Canadian Geotechnical Journal, 39(2), 316–330.

IPCC. (2012). Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.) Available from Cambridge University Press, The Edinburgh Building, Shaftesbury Road, Cambridge CB2 8RU ENGLAND, 582 pp.

Kienholz, C., Pierce, J., Hood, E., Amundson, J. M., Wolken, G., Jacobs, A., Hart, S., Wikstrom Jones, K., Abdel-Fattah, D., Johnson, C., & Conaway, J. (2020) Evolution of an ice-covered marginal basin and implications for outburst floods, Mendenhall Glacier, Alaska. Frontiers in Earth Science: Cryospheric Sciences. *Accepted.*

Klimeš, J., Benešová, M., Vilímek, V., Bouška, P., & Rapre, A. C. (2014). The reconstruction of a glacial lake outburst flood using HEC-RAS and its significance for future hazard assessments: an example from Lake 513 in the Cordillera Blanca, Peru. Natural Hazards, 71(3), 1617–1638.

Klok, E. J., Jasper, K., Roelofsma, K. P., Gurtz, J., & Badoux, A. (2001). Distributed hydrological modelling of a heavily glaciated Alpine river basin. Hydrological Sciences Journal, 46(4), 553–570.

Lemos, M. C., & Morehouse, B. J. (2005). The co-production of science and policy in integrated climate assessments. Global Environmental Change, 15(1), 57–68. https://doi.org/10.1016/j.gloenvcha.2004.09.004

Levy, J. K. (2005). Multiple criteria decision making and decision support systems for flood risk management. Stochastic Environmental Research and Risk Assessment, 19(6), 438–447.

Li, J., & Sheng, Y. (2012). An automated scheme for glacial lake dynamics mapping using Landsat imagery and digital elevation models: a case study in the Himalayas. International Journal of Remote Sensing, 33(16), 5194–5213. https://doi.org/10.1080/01431161.2012.657370

Luke, A., Sanders, B. F., Goodrich, K. A., Feldman, D. L., Boudreau, D., Eguiarte, A., … Kouchak, A. (2018). Going beyond the flood insurance rate map: insights from flood hazard map co-production.

Mayring, P. (2004). Qualitative content analysis. A Companion to Qualitative Research, 1, 159–176.

McEwen, L. J., Krause, F., Jones, O., & Garde Hansen, J. (2012). Sustainable flood memories, informal knowledge and the development of community resilience to future flood risk. WIT Transactions on Ecology and the Environment, 159, 253–264. https://doi.org/10.2495/FRIAR120211

McEwen, L., & Jones, O. (2012). Building local/lay flood knowledges into community flood resilience planning after the July 2007 floods, Gloucestershire, UK. Hydrology Research, 43(5), 675–688. https://doi.org/10.2166/nh.2012.022

McKillop, R. J., & Clague, J. J. (2007). A procedure for making objective preliminary assessments of outburst flood hazard from moraine-dammed lakes in southwestern British Columbia. Natural Hazards, 41(1), 131–157.

Meadow, A. M., Ferguson, D. B., Guido, Z., Horangic, A., Owen, G., & Wall, T. (2015). Moving toward the deliberate coproduction of climate science knowledge. Weather, Climate, and Society, 7(2), 179–191. https://doi.org/10.1175/WCAS-D-14-00050.1

Morgan, P. M., Walter, J. I., Peng, Z., Amundson, J. M., & Meng, X. (2013). Mendenhall Glacier (Juneau, Alaska) icequake seismicity and its relationship to the 2012 outburst flood and other environmental forcing. In AGU Fall Meeting Abstracts.

National Weather Service Advanced Hydrologic Prediction Service. (n.d.). Retrieved January 13, 2020, from https://water.weather.gov/ahps2/hydrograph.php?wfo=PAJK&gage=mnda2

Nel, J. L., Roux, D. J., Driver, A., Hill, L., Maherry, A. C., Snaddon, K., ⋯ Reyers, B. (2016). Knowledge co‐production and boundary work to promote implementation of conservation plans. Conservation Biology, 30(1), 176‐188.

Posner, S. M., & Cvitanovic, C. (2019). Evaluating the impacts of boundary-spanning activities at the interface of environmental science and policy: A review of progress and future research needs. Environmental Science & Policy, 92, 141–151.

Rounce, D. R., McKinney, D. C., Lala, J. M., Byers, A. C., & Watson, C. S. (2016). A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. Hydrology and Earth System Sciences, 20(9), 3455.

Sellnow, T. L., & Seeger, M. (2001). Exploring the boundaries of crisis communication: The case of the 1997 red river valley flood. Communication Studies, 52(2), 153–167. https://doi.org/10.1080/10510970109388549

Shaw, J., Danese, C., & Stocker, L. (2013). Spanning the boundary between climate science and coastal communities: opportunities and challenges. Ocean & Coastal Management, 86, 80–87.

Sherpa, S. F., Shrestha, M., Eakin, H., & Boone, C. G. (2019). Cryospheric hazards and risk perceptions in the Sagarmatha (Mt. Everest) National Park and Buffer Zone, Nepal. Natural Hazards, 96(2), 607–626. https://doi.org/10.1007/s11069-018-3560-0

Shreevastav, B. B. (2019). Flood Scenario and its Risk Management, Policy, Practices in Nepal. International Journal of Scientific & Engineering Research, 10(4), 571–581. https://doi.org/10.14299/ijser.2019.04.07

Shrestha, A. B., Eriksson, M., Mool, P., Ghimire, P., Mishra, B., & Khanal, N. R. (2010). Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. Geomatics, Natural Hazards and Risk, 1(2), 157–169.

Thompson, I., Shrestha, M., Chhetri, N., & Agusdinata, D. B. (2020). An institutional analysis of glacial floods and disaster risk management in the Nepal Himalaya. International Journal of Disaster Risk Reduction, 101567.

Todini, E. (1999). An operational decision support system for flood risk mapping, forecasting and management. Urban Water, 1(2), 131–143.

USGCRP. (2018). Fourth National Climate Assessment.

USGS. (n.d.). Retrieved March 17, 2020, from https://waterdata.usgs.gov/nwis/inventory/?site_no=15052500

Van de Ven, F. H. M., Van Haperen, H., & Ubbels, A. (1998). New ways for decision making in water management and their effects on decision support systems. In International Symposium on Lowland Technology. Saga, Japan.

Vincent, K., Daly, M., Scannell, C., & Leathes, B. (2018). What can climate services learn from theory and practice of co-production? Climate Services, 12, 48–58.

Wang, W., Yao, T., Gao, Y., Yang, X., & Kattel, D. B. (2011). A first-order method to identify potentially dangerous glacial lakes in a region of the southeastern Tibetan Plateau. Mountain Research and Development, 31(2), 122–130.

Welling, J., Ólafsdóttir, R., Árnason, Þ., & Guðmundsson, S. (2019). Participatory Planning Under Scenarios of Glacier Retreat and Tourism Growth in Southeast Iceland. Mountain Research and Development, 39(2). https://doi.org/10.1659/mrd-journal-d-18-00090.1

Welp, M. (2001). The use of decision support tools in participatory river basin management. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 26(7–8), 535–539.

Wilcox, A. C., Wade, A. A., & Evans, E. G. (2014). Drainage events from a glacier-dammed lake, Bear Glacier, Alaska: Remote sensing and field observations. Geomorphology, 220, 41–49. https://doi.org/10.1016/j.geomorph.2014.05.025

Worni, R., Huggel, C., Clague, J. J., Schaub, Y., & Stoffel, M. (2014). Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective. Geomorphology, 224, 161–176.

Xu, M., Bogen, J., Wang, Z., Bønsnes, T. E., & Gytri, S. (2015). Pro‐glacial lake sedimentation from jökulhlaups (GLOF), Blåmannsisen, northern Norway. Earth Surface Processes and Landforms, 40(5), 654‐665.

1.9. Figures and tables

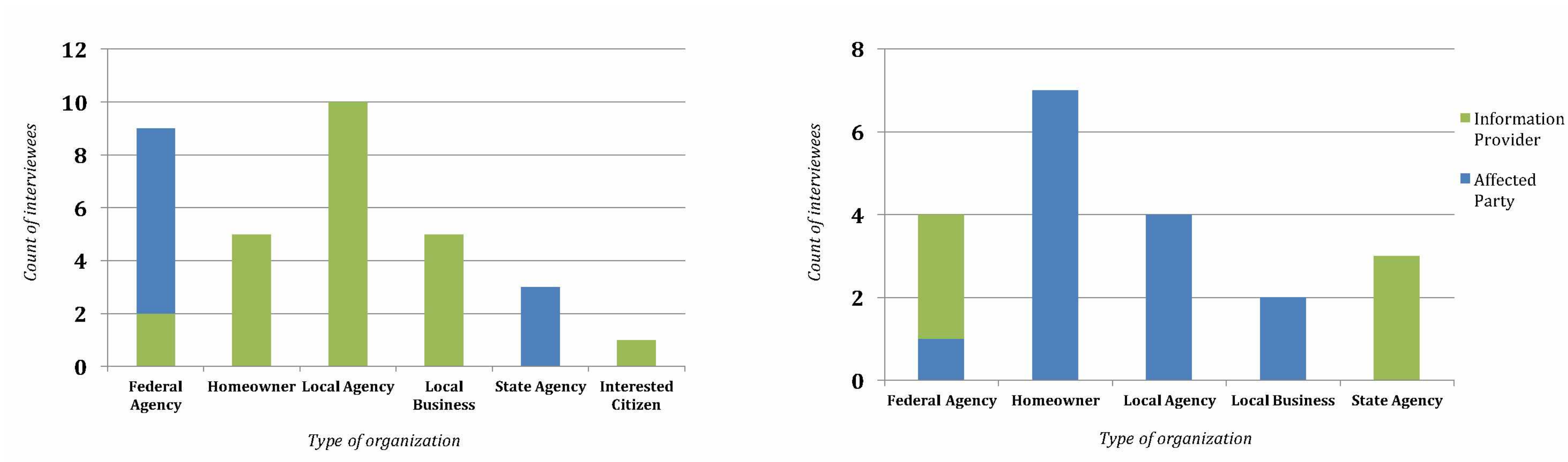

Figure 1.1. Number of interviewees Suicide Basin 2018 (n = 33, left) and Suicide Basin 2019 (n = 20, right).

Total number of interviewees for the Suicide Basin case studies, in 2018 (n = 33, left) and 2019 (n =20, right), by each type of organization represented in this study: federal agency, homeowner, local agency, local business, state agency, and interested citizen (Suicide Basin 2018 case study only). For each type of organization, the total number of interviewees was broken down by whether they were an information provider (green) or an affected party (blue). The difference in total n between each year is described in the text (Section 1.5.2.2) but in sum, is largely due to not being able to re-interview everyone from 2018 in 2019.

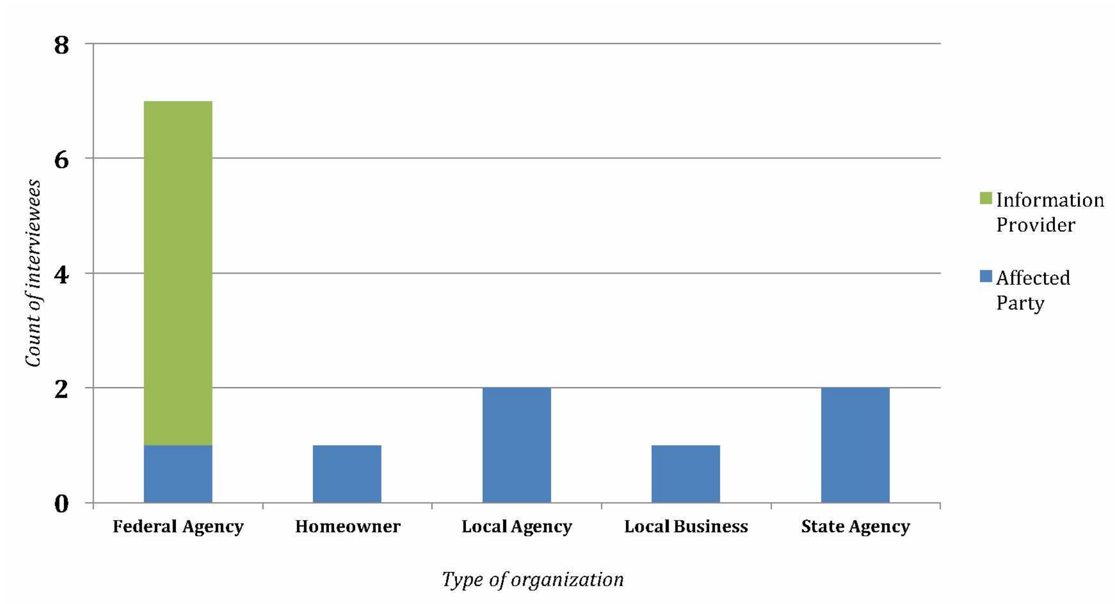

Figure 1.2. Number of interviewees Snow Glacier 2019 (n = 13).

Total number of interviewees for the Snow Glacier case study in 2019 (n = 13), by each type of organization represented in this study: federal agency, homeowner, local agency, local business, and state agency. For each type of organization, the total number of interviewees was broken down by whether they were an information provider (green) or an affected party (blue).

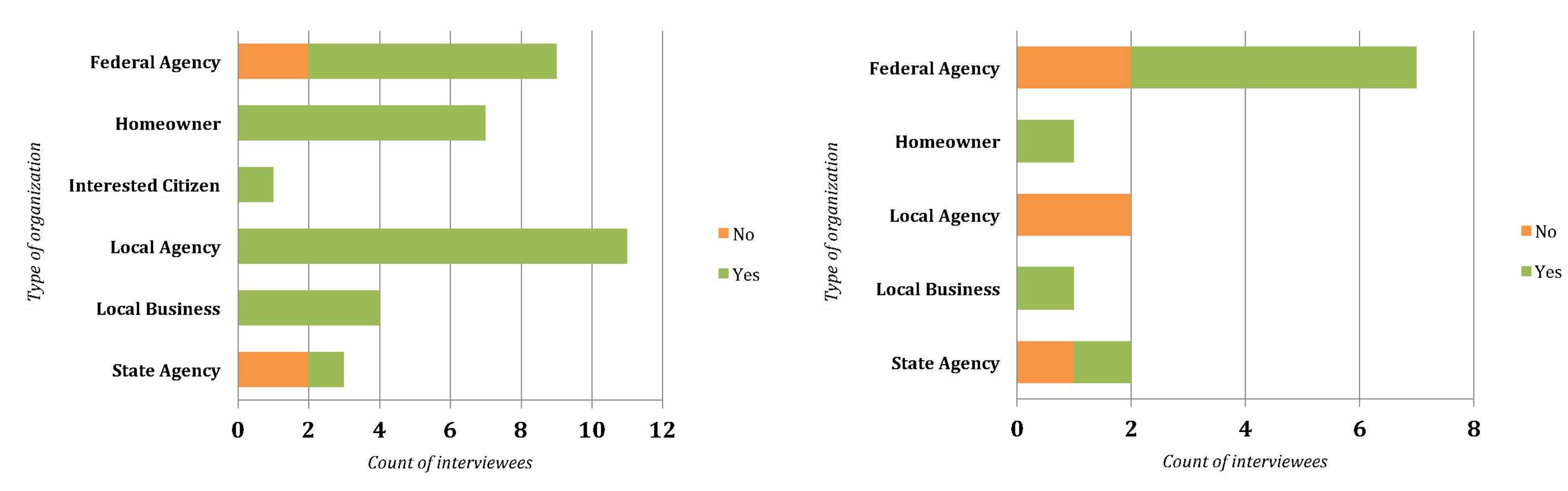

Figure 1.3. Suicide Basin (left, n = 35) and Snow Glacier (right, n = 13) interviewee experience with a GLOF event.

Interviewees in the cumulative Suicide Basin case study (left, n = 35) and the Snow Glacier case study (right, n = 13) who personally experienced a GLOF event. Of the 35 interviewees in the Suicide Basin case study, 31 interviewees (86% of total) had experienced a GLOF event. Of the 13 interviewees in the Snow Glacier case study, 8 interviewees (62% of total) had experienced a GLOF event.

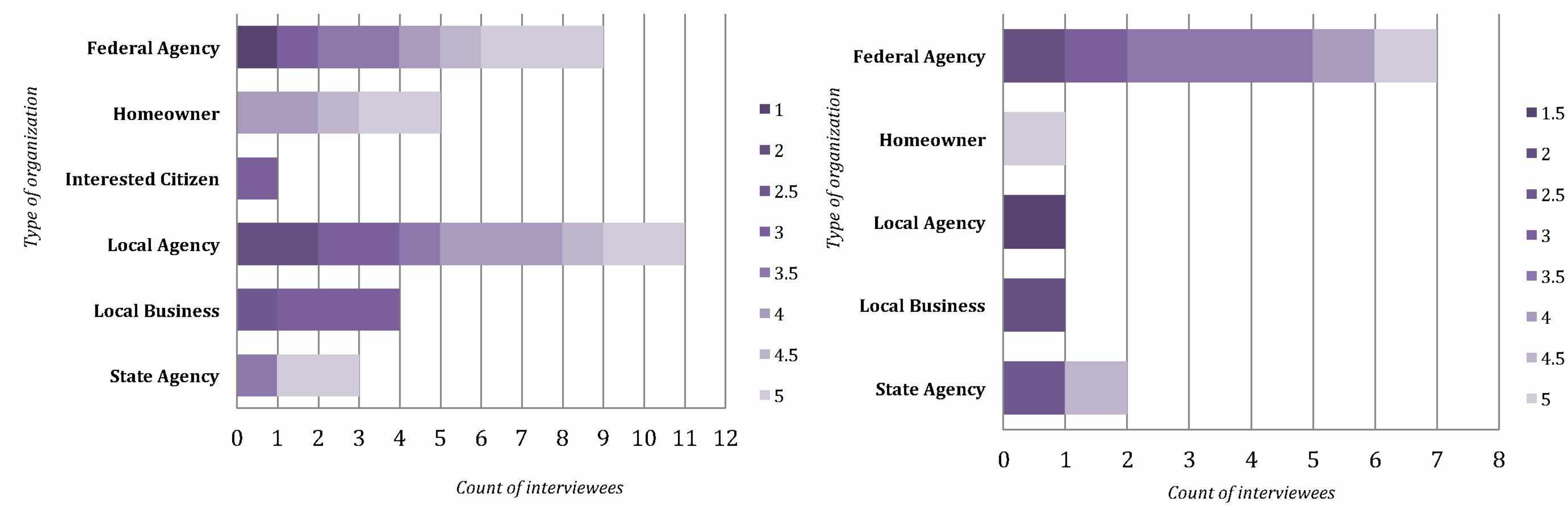

Figure 1.4. Suicide Basin (left, n=35) and Snow Glacier (right, n=13) interviewee understanding of the concept of GLOFs.

Individual interviewee understanding of the concept of GLOFs in both case studies, the cumulative Suicide Basin case study (n = 35) and the Snow Glacier case study (n = 13), based on a self-reported scale from 1 to 5, where 5 signifies the most understanding.

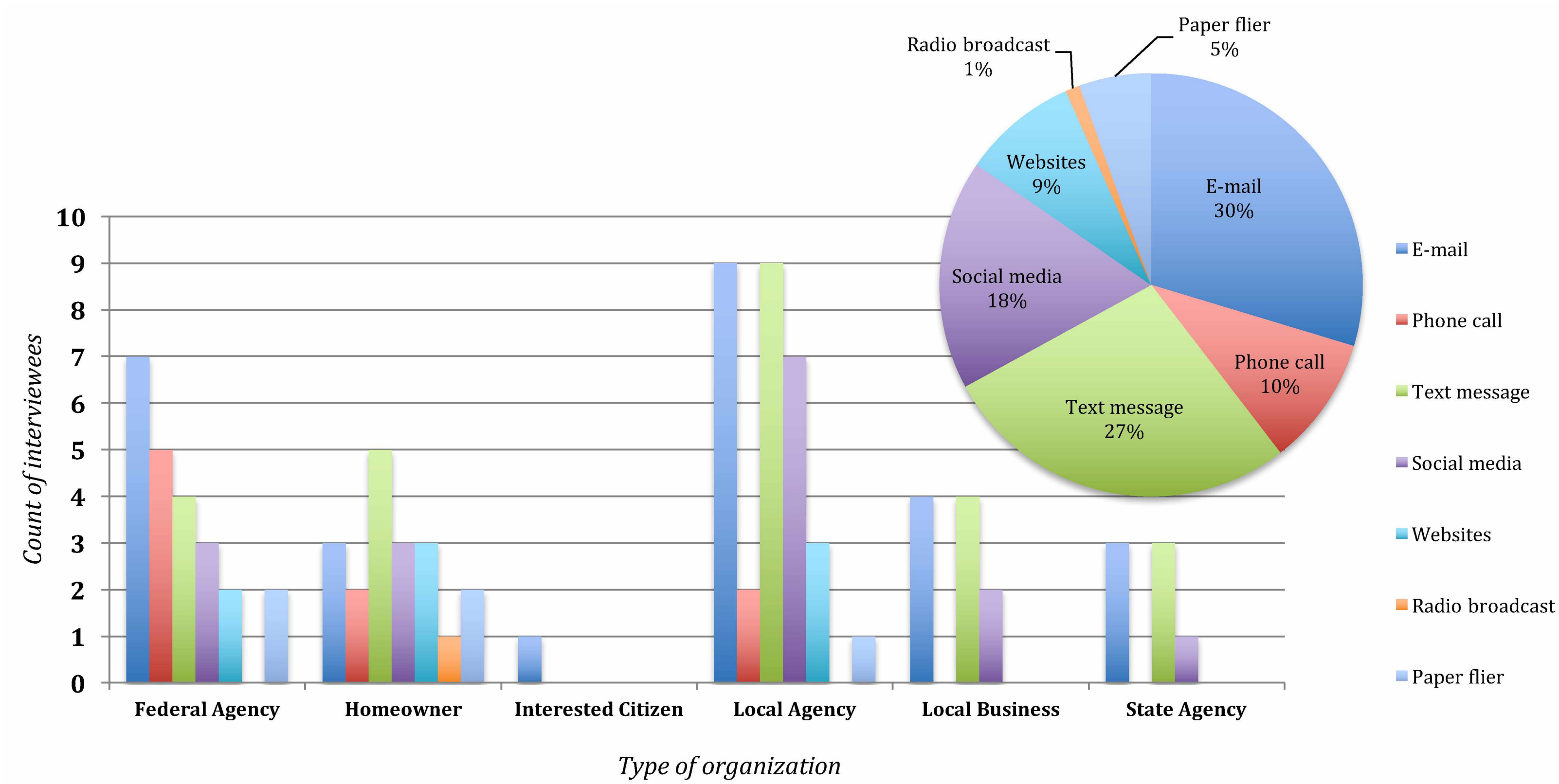

Figure 1.5. Suicide Basin interviewee (n = 35) preferred media to receive information.

Results from the Suicide Basin cumulative case study (n = 35) regarding interviewees preferred media to receive information, by type of organization (bar chart). Interviewees could list multiple preferred media, thus the results are not limited to the number of interviewees. The pie chart is an aggregated representation of all interviewee responses. In aggregate, email was the most preferred medium (30%) across all types of organizations, followed by text message (27%), and social media (18%).

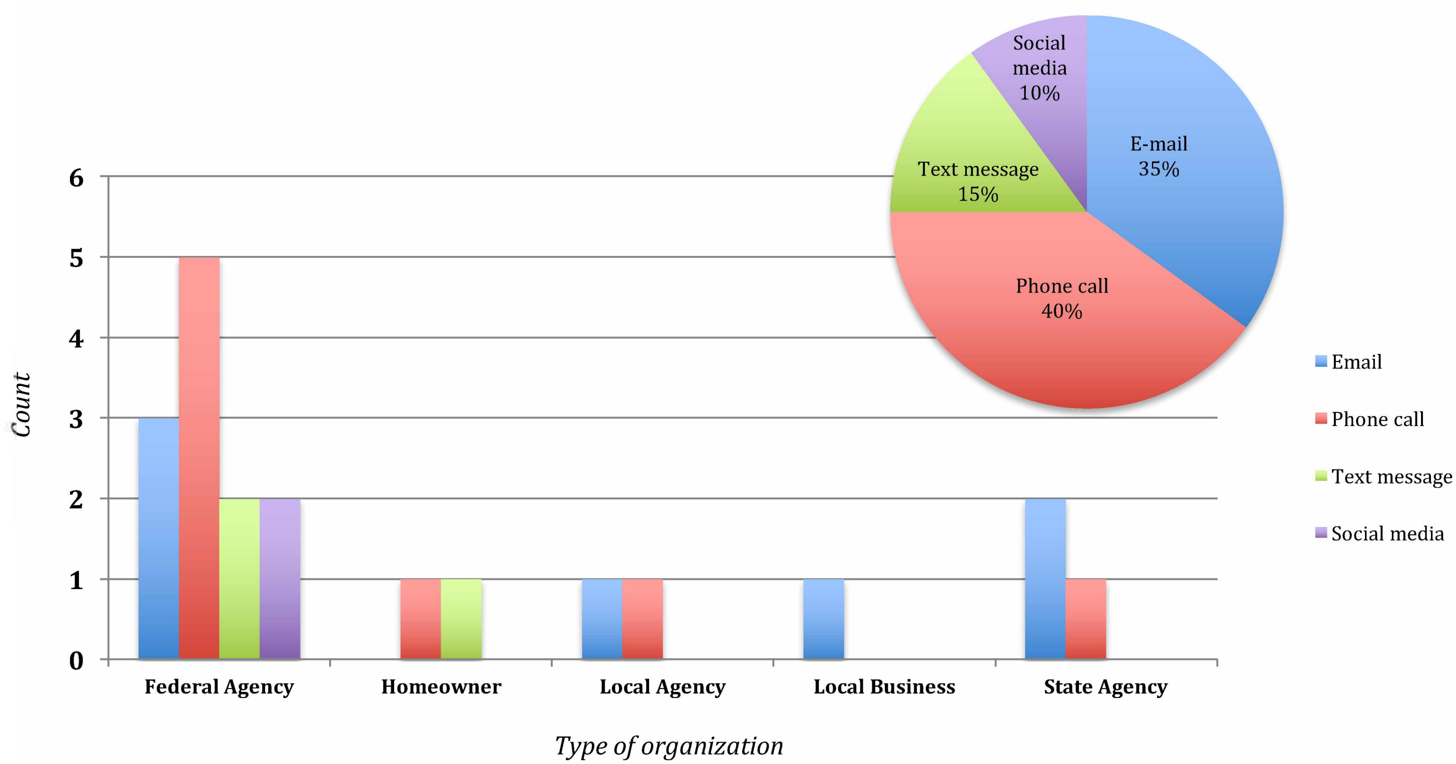

Figure 1.6. Snow Glacier interviewee (n=13) preferred media to receive GLOF information.

Results from the Snow Glacier case study (n = 13) regarding interviewees preferred media to receive information, by type of organization (bar chart). Interviewees could list multiple preferred media, thus the results are not limited to the number of interviewees. The pie chart is an aggregated representation of all interviewee responses. In aggregate, phone call was the most preferred medium (40%) across all types of organizations, followed by email (35%), and text message (15%).

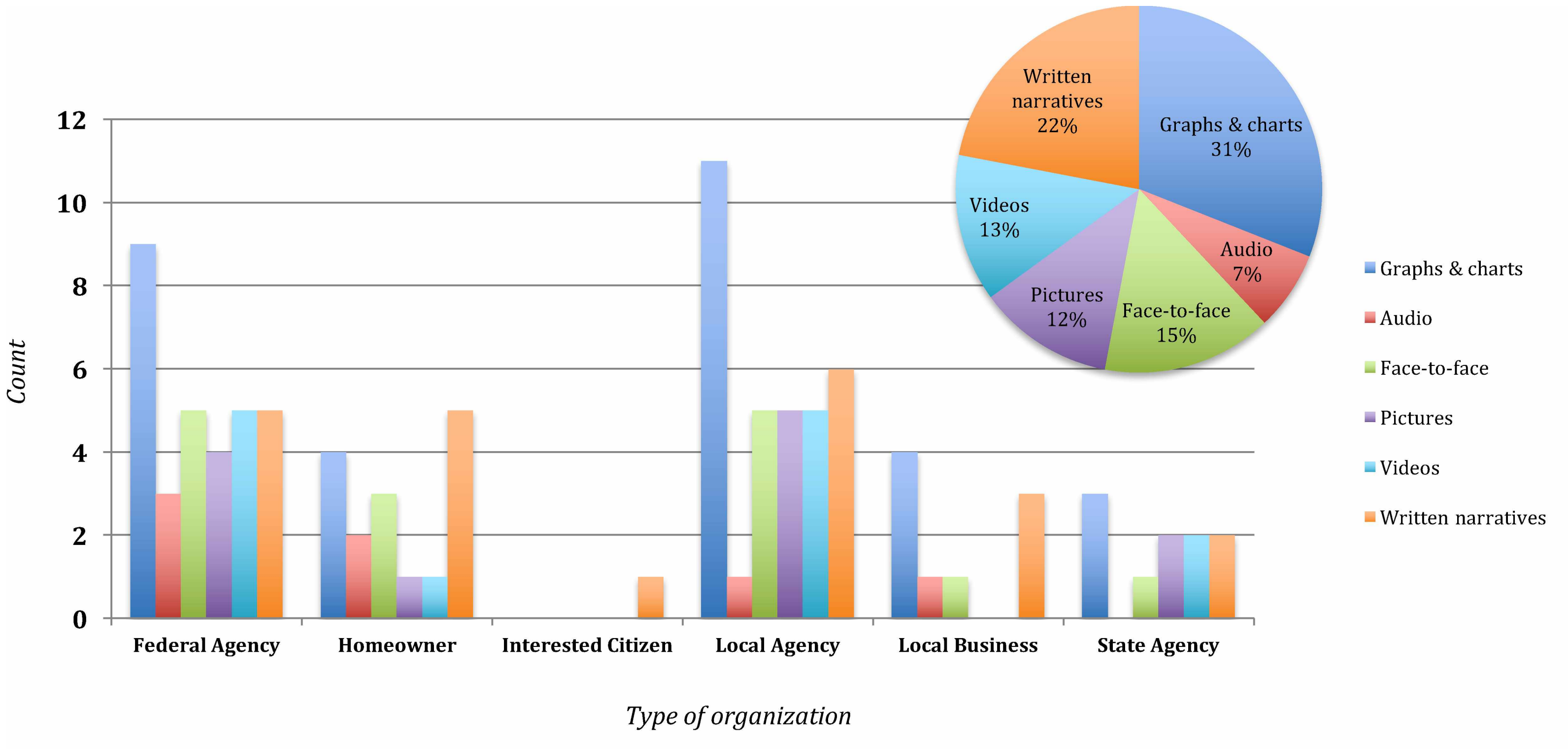

Figure 1.7. Suicide Basin interviewee (n=35) preferred formats to receive GLOF information.

Results from the Suicide Basin cumulative case study (n = 35) regarding interviewees preferred formats to receive GLOF information, by type of organization (bar chart). Interviewees could list multiple preferred formats, thus the results are not limited to the number of interviewees. The pie chart is an aggregated representation of all interviewee responses. In aggregate, graphs and charts were the most preferred format (31%) across all types of organizations, followed by written narratives (22%), and face-to-face communication (15%).

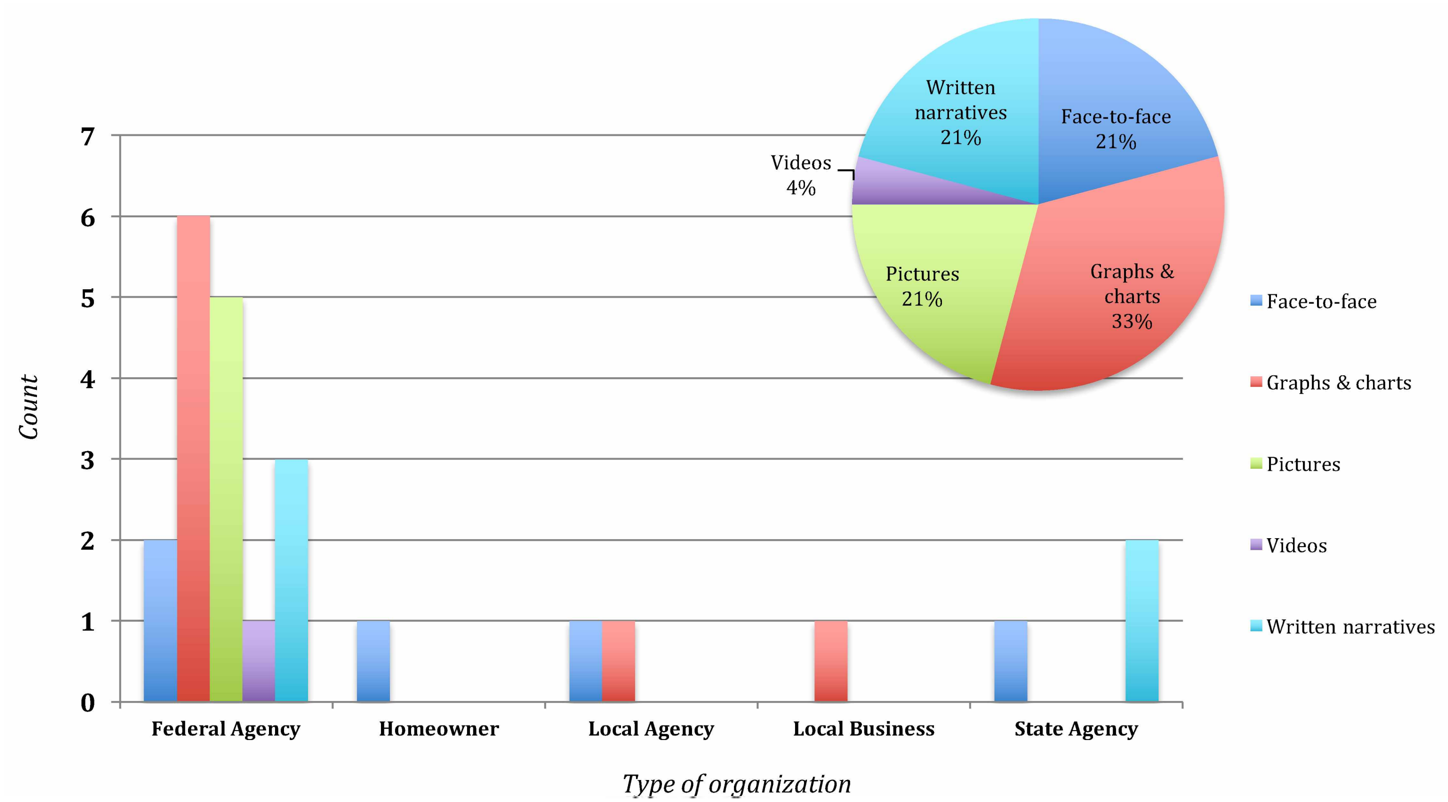

Figure 1.8. Snow Glacier interviewee (n=13) preferred formats to receive GLOF information.

Results from the Snow Glacier case study (n = 13) regarding interviewees preferred formats to receive GLOF information, by type of organization (bar chart). Interviewees could list multiple preferred formats, thus the results are not limited to the number of interviewees. The pie chart is an aggregated representation of all interviewee responses. In aggregate, graphs and charts were the most preferred format (33%) across all types of organizations, followed by a three-way-tie between graphs and charts (21%), face-to-face communication (21%), and written narratives (21%).

Table 1.1. Interviewed stakeholder groups by case study and type of organization.

All the stakeholder groups that were represented in both case studies (Suicide Basin and Snow Glacier) as well as their type of organization classification. Stakeholder groups with an * represent groups identified as information providers in this study.

Stakeholder group	Suicide Basin case study	Snow Glacier case study	Type of organization
US Forest Service	X	X	Federal Agency
US Geological Survey*	X	X	Federal Agency
City and/or Borough	X (City and Borough of Juneau)	X (Kenai Peninsula Borough)	Local Agency
NWS Weather Forecast Office*	X (Juneau Office)	X (Anchorage Office)	Federal Agency
Electric Department	X (Alaska Electric Light and Power)	X (Seward Electric Department)	Local Agency
Homeowners	X	X	Homeowner
Private tour operating companies	X	X	Local Business
US NWS Alaska-Pacific River Forecast Center*	X		Federal Agency
Juneau Empire (local newspaper)	X		Local Agency
Juneau Public Works Department	X		Local Agency
Juneau Fire Department	X		Local Agency
University of Alaska Southeast*	X		State Agency
US NWS Local Weather Observer		X	Local Agency
Alaska Department of Fish and Game, Division of Habitat		X	State Agency
Alaska State Parks		X	State Agency

Table 1.2. Number of interviewees by type of organization.

Number of interviewees by type of organization, for each case study. The Suicide Basin case study was separated by year (2018 and 2019) in this table to show the breakdown of interviewees each year.

Type of organization	*Suicide Basin 2018*	*Suicide Basin 2019*	*Snow Glacier 2019*
Homeowner	5	7	1
Interested Citizen	1	0	0
Federal Agency	9	4	7
Local Agency	10	4	2
Local Business	5	2	1
State Agency	3	3	2
Total	*33*	*20*	*13*

Table 1.3. Comparison of interviewee use and understanding of Suicide Basin information products, by type of organization.

Use and understanding of the applicable information products in the Suicide Basin case study, for the cumulative case study (n= 35), by type of organization. N_seen is the percentage of each stakeholder group who has seen a specific information product, N_used is the percentage of each stakeholder group who has used a specific information product, and N_ease is the average ranking of each stakeholder group of how easy it is to understand a specific information product, on a scale of 1 to 5 with 5 being the easiest.

	NWS Hydrograph			NWS Inundation Map			NWS Flood Statement			USGS Timelapse Camera			USGS Stream Gage		
	N_seen (%)	*N_used (%)*	*N_ease*	*N_seen (%)*	*N_used (%)*	*N_ease*	*N_seen (%)*	*N_used (%)*	*N_ease*	*N_seen (%)*	*N_used (%)*	*N_ease*	*N_seen (%)*	*N_used (%)*	*N_ease*
Federal Agency	100	100	4.6	100	89	3.7	89	89	4.4	100	89	3.9	78	78	3.9
Home-owner	100	100	4.9	100	86	4.8	71	71	5.0	71	71	4.8	71	71	4.0
Local Agency	91	91	4.1	55	45	3.3	73	73	5.0	91	82	4.8	91	91	4.6
Local Business	100	50	3.8	25	25	3.3	50	25	5.0	75	25	3.5	25	25	2.8
State Agency	100	100	5.0	100	67	5.0	100	100	4.7	100	100	5.0	100	100	4.7
Interested Citizen	0	0	NA	0	0	NA	100	0	NA	100	100	5.0	0	0	NA

Table 1.4. Comparison of interviewee use and understanding of Snow Glacier information products, by type of organization.

Use and understanding of the applicable information products in the Snow Glacier case study, for the cumulative case study (n= 13), by type of organization. N_seen is the percentage of each stakeholder group who has seen a specific information product, N_used is the percentage of each stakeholder group who has used a specific information product, and N_ease is the average ranking of each stakeholder group of how easy it is to understand a specific information product, on a scale of 1 to 5 with 5 being the easiest.

	NWS Hydrograph			NWS Flood Statement			USGS Stream Gage			Civil Air Patrol Photos		
	N_seen (%)	*N_used (%)*	*N_ease*	*N_seen (%)*	*N_used (%)*	*N_ease*	*N_seen (%)*	*N_used (%)*	*N_ease*	*N_seen (%)*	*N_used (%)*	*N_ease*
Federal Agency	100	100	5.0	100	100	5.0	100	100	5.0	86	86	5.0
Homeowner	0	0	NA	100	100	5.0	0	0	NA	0	0	NA
Local Agency	50	50	5.0	0	0	NA	50	50	5.0	50	50	5.0
Local Business	0	0	NA	100	100	5.0	100	100	5.0	0	0	NA
State Agency	50	50	5.0	100	100	5.0	50	50	5.0	0	0	NA

Table 1.5. Percentage of interviewees by case study who utilize GLOF information products on a daily basis before, during, or after a GLOF event.

Percentage of interviewees by case study, the cumulative Suicide Basin case study (n = 35) and the Snow Glacier case study (n = 13), which used each GLOF information product identified in this research on a daily basis before, during, or after a GLOF event. NA refers to products that were not part of / relevant to a specific case study.

Information product	*Suicide Basin case study (n = 35)*	*Snow Glacier case study (n = 13)*
NWS Hydrograph	77%	38%
NWS Inundation Map	31%	NA
NWS Flood Statement	60%	54%
USGS Timelapse Camera	54%	NA
USGS Stream Gage	60%	54%
Civil Air Patrol Photos	NA	0%

1.10 Appendices

Appendix I: List of interview questions for the Suicide Basin case study

Background information:

Name:
Home address (please provide zip code at very least):
Affiliation:
Title:
Degree of education (check highest):
- Middle school
- High school
- Bachelor's
- Master's
- Ph.D.

Field of study:

Interview questions (for both information providers and affected party):

1. Did you experience the 2018 Suicide Basin outburst flood event? (Y/N)

2. What about other Suicide Basin flood events? (Y/N)

3. Have you experienced another flood event, either in Juneau or elsewhere? (Y/N)

4. On a scale of 1-5, with 5 being very familiar, how familiar are you with Suicide Basin?

5. On a scale of 1-5, with 5 being very familiar, how familiar are you with the concept of glacial outburst flooding?

The next questions will ask about your familiarity and use of different data products. Please place a checkmark next to the answer that best characterizes your experience with these products.

6. Have you ever seen the following data products (check all that apply):
    - NWS APRFC hydrograph
    - NWS inundation map
    - USGS time lapse camera
    - USGS water gage

7. Have you ever used the following data products (check all that apply):
    - NWS APRFC hydrograph
    - NWS inundation map
    - USGS time lapse camera
    - USGS water gage

8. *If yes, how often?*
    - Daily
    - Weekly
    - Monthly
    - 3 to 4 times a year
    - 1 to 2 times a year
    - Never

Separate question for each product

9. Why do you use this specific product?

Separate question for each product

10. On a scale of 1-5, with 5 being the easiest, how easy to understand is this product?

11. What is your preferred method of information provision? Order by preference, with 1 being the most preferred.
    - Graphs and charts
    - Pictures
    - Videos
    - Text and written narratives
    - Audio messages
    - Face-to-face communication

12. What is your preferred medium to receive information? Order by preference, with 1 being the most preferred.
    - Text messages
    - Social media
    - Email
    - Flyer and paper handouts
    - Phone calls

13. What are you looking to gain from participating in this research?

Regarding new products (2019 interviews only):

1. Is the new NWS Suicide Basin page more or less intuitive for you?
    - Please describe.

2. Is the proposed historical Suicide Basin page more or less intuitive for you?
    - Please describe.

3. Are you more or less inclined to use the new NWS Suicide Basin page?
    - Please describe.

4. Are you more or less inclined to use the proposed historical Suicide Basin page?
    - Please describe.

5. Does the current information landscape help you in addressing your concerns with understanding Suicide Basin and GLOF?
    - Why or why not?

6. Do you see yourself using these news products moving forward?
   - If yes, for what purpose?
   - If not, why not?

7. What challenges do you face with trying to access information regarding Suicide Basin and GLOF?

8. What are effective ways, in your opinion, to better understand GLOF and other hydrological data?

9. Does having information on uncertainty make these products more or less useful to you?
   - Why or why not?

10. Do you have any recommendations for how uncertainty can be best communicated, in your opinion?
    - If yes, can you please provide an example or suggestion?

11. Do you see risk and uncertainty as separate or similar?

12. Do you find you have the information necessary to make informed decisions related to GLOF?
    - Please explain.

Only for information providers (2019 interviews only):

1. What was most surprising to you about the stakeholder feedback you received last Fall?

2. How did you use the stakeholder feedback from last Fall to develop the changes and new features as part of this iteration?
   - Please explain.

3. Did you find the stakeholder feedback you received useful in better understanding stakeholder needs?
   - If not, what was challenging in trying to understand the stakeholder feedback?

4. Is there any way stakeholders can improve their feedback for their next iteration?

5. Is there anything specifically you want feedback on and/or can stakeholders provide their feedback in a different manner?

Appendix II: List of interview questions for the Snow Glacier case study

Background information:

Name:
Home address (please provide zip code at very least):
Affiliation:
Title:
Degree of education (check highest):

- Middle school
- High school
- Bachelor's
- Master's
- Ph.D.

Field of study:

Interview questions (for both information providers and affected party):

1. Did you experience any Snow Glacier dammed release event? (Y/N)
    - If yes, which one(s)?

2. Have you experienced another flood event, either in the Kenai or elsewhere? (Y/N)

3. On a scale of 1-5, with 5 being very familiar, how familiar are you with Snow Glacier?

4. On a scale of 1-5, with 5 being very familiar, how familiar are you with the concept of glacial dammed release?

The next questions will ask about your familiarity and use of different data products. Please place a checkmark next to the answer that best characterizes your experience with these products.

5. Have you ever seen the following data products (check all that apply):
    - NWS APRFC hydrographs
    - NWS flood advisory or flood watch statements
    - USGS gages along the Snow and Kenai River systems
    - Civil Air Patrol photos of Snow Glacier

6. Have you ever used the following data products (check all that apply):
    - NWS APRFC hydrographs
    - NWS flood advisory or flood watch statements
    - USGS gages along the Snow and Kenai River systems
    - Civil Air Patrol photos of Snow Glacier

7. *If yes, how often? (please note if there is any difference between product(s) used)*
    - Daily
    - Weekly
    - Monthly
    - 3 to 4 times a year
    - 1 to 2 times a year
    - Never

Separate question for each product(s) selected

8. Why do you use this specific product?

Separate question for each product(s) selected

9. On a scale of 1-5, with 5 being the easiest, how easy to understand is this product?

10. What is your preferred method of information provision? Order by preference, with 1 being the most preferred.
    - Graphs and charts
    - Pictures
    - Videos
    - Text and written narratives
    - Audio messages
    - Face-to-face communication

11. What is your preferred medium to receive information? Order by preference, with 1 being the most preferred.
    - Text messages
    - Social media
    - Email
    - Flyer and paper handouts
    - Phone calls

12. Would a timelapse image or video of the Snow Glacier dammed lake be of relevance to your decision-making regarding these flood events?

13. Would an inundation map of the Snow Glacier-affected floodplain be of relevance to your decision-making regarding these flood events?

14. Would it be helpful to see all of the hydrographs of the affected lake and river gages from Snow Glacier on one webpage?

15. What are you looking to gain from participating in this research?

16. Do you know of anyone else who would be interested in participating in this project and/or should be included as part of the interviews?

Separate questions, just for information developers:

1. What kinds of stakeholder feedback are you interested in receiving as part of this research?

2. Are you willing or able to incorporate stakeholder feedback into your tools and products as part of this research?

Chapter 2: Sea ice hazard data needs for Search and Rescue (SAR) in Utqiaġvik, Alaska[1]

2.1. Abstract

Sea ice dynamics, such as sea ice convergence and landfast break-out events, can cause individuals and vessels to be trapped or beset in the ice, posing major hazards for Arctic marine operators and first responders. Search and rescue (SAR) for these events can be challenging, depending on weather and maritime conditions such as low visibility and large wave action. This research investigated the use of radar, satellite, and other tracking data for sea ice and weather conditions in maritime-related SAR operations in Alaska. Specifically, we looked into how sea ice and weather data and models can help support emergency responders by analyzing a case study of a SAR event for a missing small vessel offshore from Utqiaġvik (formerly, Barrow) in July 2017. This research consisted of: 1) an archival analysis of the SAR communication email threads and official U.S. Coast Guard case file associated with the SAR event and 2) an analysis of interviews with individuals involved in the SAR event. We analyzed themes related to the timeline of the event, the use of scientific products in decision-making, challenges to data use, and lessons learned for future SAR events. Interviews were conducted over the course of fall 2017 and spring 2018 to explore how this SAR event unfolded and also SAR data needs more broadly. Information user data needs in this study were defined as those related to supporting an emergency response. This research holds implications for future use and uptake of modeling data in local SAR operations in Utqiaġvik specifically and potentially across the Arctic. For example, one of the main findings from this research is that while there exists a breadth of data sources that could potentially be applied in a SAR context, many of these resources are not known to SAR operators. Furthermore, many of these resources were created for a specific scientific purpose and are not readily available for a SAR situation. Given that local SAR operators are predominantly the first line of response to maritime emergencies in Northern Alaska, the ability to share and provide a set of resources to support SAR operators is critical, particularly in a rapidly changing Arctic.

---

[1] Abdel-Fattah, D., S. Trainor, N. Kettle, A. Mahoney. Sea ice hazard data needs for Search and Rescue in Utqiaġvik, Alaska. Decisionmaking for Sustainability Volume II: Building Common Interests in the Arctic Ocean with Global Inclusion. *Springer.* **In press (2020).**

2.2. Introduction

Arctic sea ice cover and extent has seen dramatic decreases in recent years. Recent analysis has shown a 14% per decade decline in summer sea ice extent due to record-high decreases in sea ice extent since 2012 (Stroeve & Notz, 2018). It is predicted that there will be an ice-free Arctic Ocean during summer months before the year 2050 (Stroeve & Notz, 2018). Although sea ice retreat translates into more open water, sea ice still serves as a formidable hazard. As the seasonal Arctic sea ice extent has diminished and thinned over the past few decades, research has found that sea ice motion is increasingly more responsive to changes in geostrophic wind as well as the mean ocean current (Kimura & Wakatsuchi, 2000; Kwok, Spreen, & Pang, 2013). Furthermore, the stability of landfast ice is compromised due to increasingly warmer air temperature and varying snowfall rates, which leads to thinner landfast ice, increasing the risks for those who traverse sea ice for hunting, fishing, and exploration (Dumas, Carmack, & Melling, 2005; Eicken & Mahoney, 2015; Flato & Brown, 1996).

Understanding sea ice conditions and making decisions regarding the use of and travel across sea ice is an integral part of Indigenous communities in the Arctic as well as other vested sea ice users such as the maritime and shipping industry (Inuit Circumpolar Council 2008; Durkalec et al. 2015; Pizzolato et al. 2014). Sea ice conditions are changing in a multitude of ways beyond just its diminishing extent. These changes have different implications for different animals and people that use Arctic sea ice. For example, the continued loss of multiyear ice constitutes a loss of habitat for marine mammals who rely on this specific type of sea ice, for example, ringed seals (Kovacs, Lydersen, Overland, & Moore, 2011). Beyond ecosystem impacts, changes in Arctic marine mammal populations and distributions also affect subsistence hunting, which directly affect Indigenous communities (Lovvorn, Rocha, Mahoney, & Jewett, 2018).[2]

The later onset of sea ice formation, particularly landfast ice, has contributed to less stable and less predictable sea ice, which impacts Indigenous communities across the Arctic who rely on sea ice for hunting and travel during the winter (Mahoney, Eicken, Gaylord, &

---

[2] It is important to note regional differences exist regarding marine mammal populations. Changes in a marine mammal population in one area is not necessarily generalizable across the Arctic; for example, recorded declining polar bear population in the Hudson Bay area compared to increases seen in the polar bear population in the Alaskan Beaufort Sea area during similar periods of monitoring (Kovacs et al. 2011).

Gens, 2014). Delays in and more variable sea ice formation also exposes coastal communities to high winter wave action, which poses hazards and threats to communities, such as increased coastal erosion and flooding and hazardous maritime conditions (Barber et al., 2018; Overeem et al., 2011). These changes also impact industries – such as the offshore oil and gas industry – and therefore economies in the region, which rely on sea ice forecasts and measurements to assess access to and conduction of offshore drilling operations (Galley, Else, Prinsenberg, Babb, & Barber, 2013).

There is a clear need for data on changing sea ice conditions, to not only understand the sea ice changes taking place, but to also address the breadth of communities, ecosystems, and services these changes impact (Kettle et al., 2019). Traditional local knowledge (TLK) in conjunction with weather, water, ice, and climate data can provide a valuable resource for sea ice-related decision-making (Jeuring et al., 2019; Tremblay et al., 2006). There has been an increase in recent years in Arctic information providers that extend well beyond the national sea ice and meteorological services across the region (Knol et al., 2018). The development of various decision support tools to provide information on weather, water, ice, and climate data has spurred research and discussions on not only the operability and interoperability of these tools but more importantly the need for co-production with local and end users in the development of these tools (Jeuring et al., 2019; Knol et al., 2018). Co-production in the context of this chapter is defined as developing a service or product in an equal and reciprocal relationship between information providers and people using a service or product such that both sets of actors become effective agents of change (Fenwick, 2012). Co-production of decision support tools, particularly in an Arctic context, fosters tools that are better equipped to meet users' needs, bridging the science-to-policy interface and research-to-operations gap (Jeuring et al., 2019; Robards et al., 2018).

Beyond understanding different user needs, understanding different user contexts is important in the development of decision support tools. There is a diverse and therefore complex constellation of groups that use Arctic sea ice such that their interpretations and responses to drivers of change and exposure to hazardous conditions are based off their unique backgrounds. These different user groups thus experience variable vulnerability, exposure, and adaptive capacity to hazardous situations (Bennett, Blythe, Tyler, & Ban, 2016). In the Arctic, adaptive capacity is partially knowledge-based and grounded in TLK, but it is also influenced by knowledge gained from scientists, governments, and other decision makers (Parlee & Furgal, 2012). Decision support tools can therefore help increase a user's adaptive capacity, particularly if they are developed in a co-production manner and take into account various and different user needs.

In this chapter, we explore the use of TLK, various decision support tools, and weather, water, ice, and climate data by different user groups during a Search and Rescue (SAR) incident off the coast of Utqiaġvik, Alaska in July 2017. The six main user groups interviewed in this study were: the US Coast Guard, commercial operators, the North Slope Borough, research / data providers, local SAR, and subsistence hunters. This SAR event presented a novel opportunity to analyze the use of different information resources, particularly university-developed information products, by different user groups in an Arctic Alaska SAR context, which, to the best of our knowledge, has not previously been done. We analyzed which information products each user group used during the incident and why these products were chosen. We compared information use by user groups, taking into account a user group's needs and contexts based on their decision-making related to temporal, spatial, and organizational cultural scales. In this chapter, we discuss the reasons why various information resources are or are not used. In addition, we discuss the implications of our findings, potential limitations of this study as well as room for further research and expansion.

2.2.1. Case study background

There are three main types of sea ice hazard events: landfast breakout events, sea ice convergence events, and speed events. Landfast breakout refers to when grounded pressure ridges become ungrounded such that the ice detaches from the shoreline and drifts off (Jones et al., 2016). Sea ice convergence occurs when ice is pushed together by winds or currents such that internal ice stress keeps the ice from moving ("Dynamics | National Snow and Ice Data Center," n.d.). Speed events are when anomalously high rates of ice drift cause ice to collide with and damage vessels (Eicken et al., 2018). Between September 2006 and September 2017, findings from the Utqiaġvik Sea Ice Radar revealed that 245 sea ice convergence events occurred near Utqiaġvik (Kettle et al. 2018). These types of hazardous sea ice events have a consistent presence in the Utqiaġvik area and can pose significant hazards to maritime operators, particularly small vessels. Search, rescue, and response to these events can also be challenging, due to harsh and inclement weather and maritime conditions such as low visibility and fast currents. This specific case study investigates a SAR event in which a missing vessel was caught in a high-speed current event amongst drifting packed ice.

At approximately 2:30 am local time (GMT-8) on July 19, 2017, a fourteen-foot open top motor-powered boat went dead in the water approximately ten miles north of Point Barrow, Alaska among a drift ice pack. The boat had on board one adult and four children under the age of thirteen. Volunteers, the North Slope Borough SAR team, and the US Coast Guard (USCG) conducted a search to find the missing vessel and persons. Several university scientists who helped determine the vessel's drift from its point of last known location also supported the SAR effort. All five people aboard were safely found at 12:00 am (GMT-8) July 20, 2017. Figure 2.1 outlines some of the main events that took place during the SAR event.

2.3. Methods

2.3.1. Materials and methodology

The main objective of this research was to understand why seven different information products were or were not used by each user group during this specific SAR event as well as identify the differences, if any, between different user groups and the information products they used. This research investigated seven different information products used by six different user groups (Figure 2.2) during the SAR event. We engaged a mixed methodology to achieve the research objectives which involved 1) archival analysis of the SAR communication email threads and official US Coast Guard case files associated with the SAR event and 2) conducting semi-structured interviews (n=17) with different individuals involved directly or indirectly with the SAR event. Both methods are described in further detail below. We identified seven different information resources and products that were provided and/or used during the SAR event. Table 2.1 lists and provides a detailed description of each identified information resource and product.

2.3.2. Method 1: Archival analysis

We analyzed the e-mail communication (16 e-mails) among 16 individuals involved in the SAR event, which were obtained in August 2017. A university Arctic scientist who was in Utqiaġvik at the time of the event, initiated email communication with other Arctic researchers regarding the SAR event, given the urgency of the event and their desire to help support the local SAR effort. Specifically, the researcher reached out to a number of different Arctic researchers for support in estimating the location of the missing vessel based off potential drift. The review of the email communication was used to identify the interviewees for the interview portion of this research, identify the data products that were shared regarding the SAR event, and create a preliminary timeline of events (Figure 2.2). In addition to the email communication, the USCG case file was analyzed (MISLE reference number: 1089697, provided by USCG District 17 SAR Coordinator) to help reconstruct the timeline of events as well as provide information on the USCG's role in the SAR event and the information products used by the USCG during the event.

2.3.3. Method 2: Stakeholder interviews (n=17, 100% response rate)

Potential interviewees were selected based on a snowball sample, which began with the list of individuals identified in the archival analysis (Handcock & Gile, 2011). Interview participants spanned different stakeholder groups, specifically Arctic researchers, North Slope Borough employees, subsistence hunters, maritime commercial operators, North Slope Borough and volunteer local SAR responders, and the USCG (Figure 2.2). It is important to note that many interviewees spanned multiple stakeholder groups; for example, some subsistence hunters, North Slope Borough employees, and North Slope Borough and volunteer local SAR responders spanned multiple stakeholder groups. For the purpose of this study, we used perspectives from each of their self-identified groups.

In addition, local SAR was deemed as an information user group in this study since there is an implicit need to consume information and make decisions based off that information as an emergency responder during a SAR event. There was a larger number of interviewees from the researcher / data provider group due to speaking to each of the different data providers. Given the small community in Utqiaġvik, having comparable number of interviewees for the other stakeholder groups was not possible. A semi-structured interview protocol was used to ask the interviewees about: the SAR event, data provision – what type of data was provided and why, data use – what type of data was used in the SAR event and why, and the enabling and challenging factors in data provision and data use in a general SAR context.

Notes from the interviews were coded twice by one coder, approximately one year apart, to identify information on the aforementioned themes. Given the sensitive nature of the case study, detailed notes were taken during the interviews (n=17) instead of being recorded and transcribed in order to increase comfort for interviewees. Grounded theory analysis was used to analyze the transcriptions and notes from the interviews and develop a coding structure (Charmaz & Belgrave, 2012). Codes were developed to identify which information products were utilized by each user, any reasoning as to why information products were or were not used by a user, as well as challenges to utilizing information products, particularly in a SAR context. Interviews were analyzed using qualitative content analysis for themes related to the timeline of the event, the use of scientific products in decision-making, challenges to data use, and lessons learned for future SAR events (Mayring, 2004). Interviews were then coded to identify themes related to enabling and challenging factors in data sharing and use in an Arctic SAR context. Ten factors, five enabling factors and five challenging factors, were identified from the interviews. Each factor needed to have been mentioned and coded in at least two interviews in order to be included in the factors list, which is found in Table 2.6.

2.4. Findings

Based on the archival analysis and stakeholder interviews regarding the July 19, 2017 SAR event, the following three sections summarize the major findings from our analysis.

2.4.1. What information was provided and/or accessed and why?

TLK of wind and ocean conditions was provided by the local SAR team to help pinpoint the initial search radius for the local SAR effort that began the morning of July 19. Information from windy.com (a weather forecast application, which provides visualizations of outputs from different weather models) was also accessed by the local SAR team to help determine wind direction. The USCG Search and Rescue Optimal Planning System (SAROPS), the system used across USGS nationwide, was accessed to plan the USCG SAR response. Lastly, information from the four university-developed data and modeling tools were provided to the local SAR team over the course of the SAR event, once the group of university Arctic researchers was notified of the incident (Table 2.2).

2.4.2. What information was used and why

Of the six different stakeholder groups we interviewed, we identified three groups as information users for this specific SAR event: local SAR, subsistence hunters, and the US

Coast Guard. Since commercial operators were not involved in this specific SAR event, they are not included in the analysis of the SAR event. Two of the identified information user groups are also information providers, namely, subsistence hunters due to the wealth of TLK within this community as well as the US Coast Guard, since they are providers of the SAROPS platform. The local SAR team predominantly consists of individuals and community members that are extremely well versed in TLK. Many members of the local SAR team are subsistence hunters themselves, as well as well-established, respected members of the community, who therefore can, and do, serve as information providers.

Of the seven different information products and resources provided or accessed during the SAR event, only three were explicitly mentioned as being utilized during this SAR event (Table 2.4). TLK, windy.com, and SAROPS were primarily used due to the SAR responders' familiarity and positive previous experiences with these information resources and products, as well as due to the organizational culture and procedural mandates in utilizing these products in some cases. However, several interviewees mentioned that although the four university products that were shared with the SAR responders were not explicitly used by the SAR team (i.e. accessed directly by the SAR team), information was generated from these products and provided to the SAR team. This information helped to ascertain, inform, and confirm decisions that were being made by the SAR responders, specifically with the local SAR response team. This was done via communication between the university researchers (predominantly via email but also phone calls and text messages) and members of the local SAR response team. This indirect use of the four university products is accounted for in Table 2.4 below.

As one interviewee mentioned, there were unusual wind patterns during this event, which made estimating the missing vessel's location particularly challenging. The offshore nature of this SAR event is what triggered the request, sent out by a university researcher who was in Utqiaġvik at the time, for modeling the missing vessel's location via university products. None of the interviewees "regretted" reaching out to the broader scientific community. In fact, one interviewee mentioned this SAR event showed the "untapped potential of the science community in Utqiaġvik." As one interviewee stated, "traditional knowledge works very well on land and in the near shore area but farther out to sea, a lot of the guys are still building their knowledge base, so when it comes to offshore SAR, we find that capacity in general hasn't expanded to the degree of sea ice retreat." One of the main reasons the university products were not explicitly used in this SAR event was the amount of time it took to get the information to and from the scientists. As one of the scientists involved in the SAR event mentioned, "if we had gotten the message out to the science community earlier in the day, we could have had a chance to better help."

We were not able to determine whether information from the four university-developed tools was used by the US Coast Guard team since we were not able to speak with the specific US Coast Guard team members involved in this SAR event.

2.4.3. Other identified information resources and products

Over the course of our interviews, several other information resources and products were identified. In addition to the seven products identified for this study, each information user group identified at least two additional information resources and products they utilize for sea ice hazard awareness and/or response. Three products in particular were used by more than one information user group, as seen in Table 2.5 below, which shows the additional information resources identified by interviewees.

Regarding the additional information resources and products that were identified, commercial operators mentioned that the Marine Exchange of Alaska offered the ability to see information posted by other vessels, which is particularly useful when those vessels have recently been through ice. Commercial operators also noted that when Shell was operating in Northern Alaska, they would share a lot of information on ice conditions with the commercial maritime community, as well as advise the US Coast Guard, on occasion, of ice conditions. As the interviewee put it, "there was a lot of communication about sea ice when Shell was around."

Interviews with Local SAR mentioned that the Barrow Sea Ice Radar was utilized quite frequently when it was operational. It has not been in operation since 2017 and therefore was not used in this SAR event. However, it was utilized in 2014 to help track the drift of missing persons on a landfast ice breakout floe, the first time in which the sea ice radar was utilized for a SAR search. However, the limiting factor of the sea ice radar is its range, up to 6 miles from the coast of Utqiaġvik, which as one interviewee stated, "is barely past what we can already see with our eyes." Another interviewee stated that "a lot of cruise ships are just out of the radar's range," which in the event of a cruise ship-related SAR event, an unlikely but potentially calamitous SAR scenario, would render it unhelpful. These findings were also affirmed in our interviews with subsistence hunters.

The importance of community and individual interactions was highly stressed in interviews with both local SAR and subsistence hunters. One interviewee mentioned that roughly 90 percent of information for SAR missions comes from knowing which people have knowledge of certain areas; "I already know who I want to talk to and what I want to know from them depending on where a search is taking place."

2.4.4. The enabling and challenging factors in data sharing and data use

We identified five factors (E1 – E5), which enabled information product use, and five factors (C1 – C5), which created challenges in information product use. Familiarity with information or information provider (E1) and previous positive experiences with information and information provider (E2) were found to be enabling factors among all the interviewee groups. E2, E3, and E5 are linked to each other. Trust (E3) and previous positive experiences (E5) working with an information product or provider, such as windy.com and specific university researchers, increased an information user's perceived reliability of a specific information product or provider. In some cases, some information users have institutional mandates to utilize specific information products (E4), such as the US Coast in terms of using SAROPS to plan a SAR mission, which automatically generates a search grid for the USCG responders. Local SAR also has long-standing experience relying on TLK (E4), among themselves but also among the community, when planning a SAR response.

Commercial operators and US Coast Guard were not readily aware of some the university-based information products (C1); local SAR and subsistence hunters were aware of some of the products, if not directly, then indirectly via contact with university researchers or the North Slope Borough. Satellite imagery data and even weather data is not provided in near-enough real-time where it can be used for real-time decision-making, especially in the Arctic, where weather can change very rapidly within a matter of minutes; in some cases, even hourly data is not good enough, from a reliability perspective (C2). One interviewee mentioned that though it is great to see new information always coming online, it is hard to truly rely on products (C3), especially when you have had experiences where a "website changes and where we once had reliable information to go to, the link is now broken and we cannot find where it went." Other accessibility challenges (C3) that were mentioned involved information products that are Internet-based; Internet bandwidth is increasingly limited the further you go out to sea. Any information product with imagery or consistent Internet connection is difficult, or impossible to use, due to bandwidth limits. Accessibility problems however are not just limited to the sea. As one interviewee said, "the Internet is really slow here in Utqiaġvik, especially for Facebook."

Procedural policies and organizational culture can also inhibit the use of information resources and products (C4), especially new ones. As one interviewee mentioned, "I have trust in the science and the broader system – I use it on a daily basis – but some of the others might be hesitant" while another interviewee stated that instruments used by "operational agencies often become stagnant due to the tendency to buy the same thing over and over because it 'works' but meanwhile, technology has evolved."

Lastly, regarding how an information product is not designed or readily applicable for a SAR context (C5), Figure 2.3 shows the plotted location estimates provided by HIMOAS, the Chukchi Sea Surface Current HF Radar, and the ice-tracking drifters. The estimates from the Chukchi Sea Surface Current HF Radar group were in closest proximity (23 nautical miles) to where the missing vessel was retrieved. Though the surface velocity data from the HIOMAS model was only 24 nautical miles from where the missing vessel was retrieved, the estimate was more southward in comparison to the data from the Chukchi Sea Surface Current HF Radar group. It is important to note that the information from the ice-tracking drifter was provided less as a means to locate the missing vessel but rather to understand surface current speed and wind direction. Given that none of these information products were developed to provide estimated locations of a single object based off past data, the fact that it was indeed possible to modify each product to generate this information is notable and commendable, particularly in a short period of time (see SAR event timeline in Methods section). However, there is a need for optimizing and automating some of these processes, should they be used for other SAR events, where time and accuracy are of the essence.

2.5. Discussion

It is becoming increasingly apparent on a local, national, and an Arctic-wide scale that there is a need to model and forecast sea ice hazards, as well as a need to communicate this information to both sea ice users and rescue operators (Bridges, 2017). The SAR community in particular has recognized the necessity to actively pursue sea ice hazard research as pack ice and fast ice can limit the mobility of rescue vessels (Clark & Ford, 2017; Ford & Clark, 2019; Smith, 2017). Information on both current conditions (real-time to 2-day forecasts) and future conditions (1 to 2 month forecasts) in the Arctic Ocean is important to get a sense of both current and projected sea ice-related hazards. However, looking at sea ice melt and retreat is not enough to understand its implications on the Arctic maritime environment. Information on ice thickness, landfast ice stability, ice velocity (e.g. ice drift), as well as weather-related conditions such as atmospheric pressure, wind direction and speed, and ocean currents are important to get a holistic understanding of changes to sea ice and its potential impact on animal, human, and vessel movement in the Arctic (Eicken & Mahoney, 2015). Within this overarching context of information needs for sea ice-related SAR, we summarize the three main findings from our case study below.

2.5.1. Different data needs and decision contexts for each information user group

Figure 2.4 describes the main information needs identified for sea ice decision-making in a coastal waters SAR context. These information needs spanned across the four identified information user groups in this study. However, depending on an information user's knowledge and familiarity of the area, familiarity with and previous use of an information product, as well as the situational context itself, some information needs can be inferred or are not relevant to a specific situation. For example, in the case of the SAR event analyzed in this study, information on landfast ice stability and open leads was irrelevant since not only was the missing vessel was stuck in a drifting ice pack over 30 nautical miles from shore, but ice concentration in general was low. Thus, though Figure 2.4 provides an overview of the main information needs for sea ice decision-making, actual information needs vary and depend on each SAR context.

2.5.2. Single information resource cannot meet all informational needs

We found in the context of this case study that a single resource cannot meet the needs of all sea ice information user groups. A multitude of different informational products and resources need to exist to meet each respective user needs, which including varying spatial and temporal information needs. This finding is in-line with what existing literature on information resource use and development (Jeuring et al., 2019; Knol et al., 2018; Petrich & Eicken, 2009; Tremblay et al., 2006). Therefore, access to a suite of resources, including

TLK, scientific information, as well as operational resources, can help overcome these challenges and can potentially better serve SAR needs. There is clear benefit though from generating information from a number of different resources (Knol et al., 2018). However, this puts the onus on information providers to address the situational context in and around Utqiaġvik, where Internet connectivity and data availability can be limited or non-existent, similar to other areas where there is a gap in data availability and potential data use (Dinku et al., 2014). Issues with Internet connectivity can impede a user's ability to utilize an information resource or product, which was an identified challenging factor in our research. Many of the identified information resources in this research are dependent on an Internet connection, which constrains their ability to be used when vessels are out in Arctic waters, where there is limited / no Internet bandwidth (Larsen et al., 2016).

Beyond Internet connectivity, data availability is also limited for further offshore areas, particularly beyond the scope of radars and trackers. Some ocean-based data products also may not be available in the wintertime when there is ice present and all data products can be subject to data outages due to weather and inclement conditions. Existing information products and resources are used by SAR operators due to their familiarity, trust, and/or mandate to use certain resources or products. However, there are gaps in information this current suite of utilized products and resources provide, particularly for further offshore areas that potentially could be met with the additional use of other information. There is merit therefore to leveraging different products to validate, interpolate, and extrapolate information against one another, in order to create a comprehensive suite of sea ice hazard decision-making data, especially for further offshore SAR events where there is limited data available.

2.5.3. Available resources not used due to lack of familiarity, developed trust, and perceived reliability

A number of different information resources and products are available to help meet information needs; our research identified and investigated the use of seven different information resources and products, as well as at least a dozen other information resources relevant for the community of Utqiaġvik. There is a breadth of potential data sources that could potentially be applied in a SAR context. However, based on our interview findings, many of these resources are not known to SAR operators, particularly those developed by university and other research institutions. This was one of the challenging factors we identified in our findings. Only three out of the seven identified information products or resources were used in this specific SAR event, which was primarily due to information user's lack of familiarity with these products. However, another challenging factor is that many of these resources were created for a specific purpose; they are not ready to be applied in a SAR situation as-is. All of the information derived from university-based data produced for this event required some level of pre- or post-processing, or separate individual analysis by university researchers, in order to be adapted for this specific SAR need; in this case, estimating the potential drift of a missing vessel.

2.5.4. Recommendations

A targeted and systematic way for SAR operators to utilize and draw upon the various sea ice hazard information products and resources available can help support the local SAR community in future SAR events, especially when immediate information is necessary. Future SAR efforts can benefit from a more streamlined process of data sharing and engagement, in order to maximize time. For example, a "code-red" email listserv that would be sent out to all data providers could be one way to help support SAR efforts as well as the preparation of a number of existing data resources to be "SAR ready," should they need to be utilized in a SAR effort. Data products, specifically those developed by universities, were used in ways for which they were not designed during this SAR effort. Yet, they were adapted to meet the demand. Optimizing some of these products for future use could be a highly applicable and useful contribution to further improving SAR responses moving forward. This can be done by incorporating different stakeholder decision contexts in current products and leveraging existing information networks to integrate additional information (Kettle et al., 2019).

Beyond creating SAR-relevant data, the following quotes (Figure 2.5) were taken from a number of different interviews to show the varied need for different data and data formats for the variety of sea ice information users in Arctic Alaska. The need for continued and comprehensive sea ice research and sea ice data development is critical to furthering our understanding of the changing Arctic. However, there is also a clear benefit for the co-production of these resources with local communities. It is very important to note that distinct and sustained efforts need to be undertaken by all actors to integrate TLK with science products. Our findings have shown that TLK plays a critical role in understanding sea ice conditions as well as monitoring the changes happening to sea ice over time. Braiding TLK with science products will ensure not only their relevancy to local communities across the Arctic but also serve to honor the important knowledge and understanding to be gained from this very valuable and venerated information source found across the Arctic. Furthermore, research has indicated that products developed using co-production not only increases their relevancy but also their usability (Dilling & Lemos, 2011; Kettle et al., 2019).

2.5.5. Limitations and potential future research

Due to the small sample size (n = 17) of our interviews, no statistical analyses were conducted, hence this study was qualitative. Furthermore, while we spoke with the general local SAR and USCG teams, we were not able to speak with the actual SAR responders for this event from both teams, which limited our ability to say which information was or was not used by the response teams. To respect the privacy and anonymity of our respondents, given the small size of the community in Utqiaġvik, we refrained from providing any detailed information on the interviewees. Lastly, this research was a pilot study to investigate the use of the seven identified information products in a specific SAR event. Over the course of the interviews, we identified additional information products that are used by information users. Future research could conduct additional interviews to analyze systematically why and how these additional information products are used.

This study was an analysis of a single case study. The analysis of a historical SAR event provided insight and helped to improve our understanding of a SAR response. Although it was very illuminative, our findings cannot be generalized without further research on other SAR events related to sea ice. Further analysis of other SAR events, in Utqiaġvik, in Arctic Alaska, as well as the broader Arctic, is important to see if these findings can extend to other contexts. Expanding this research to a broader set of events can be especially helpful in investigating whether there have been any changes to SAR data needs over time. Specific events should be identified in conjunction with local communities as well as emergency responders and operators in order to ensure the findings are pertinent to those the research affects the most.

In addition, further research on the relationship between information providers and information users in an Arctic SAR context can help to expand upon some of the findings from this work. Particularly given that TLK can both be provided and used in a SAR context, this opens up the opportunity to explore the ensuing cyclical relationship between information providers and information users but also between information users (Figure 2.6). In general, there is a move away from the "traditional" linear relationship between information providers and information users, particularly in the weather, water, ice, and climate information realm, which calls for further research into how information is both shared and used in this sector (Beck, 2011; Haavisto et al., 2020; Jeuring et al., 2019; Knol et al., 2018).

2.6. Conclusion

As more sea ice-related risks arise for individuals and vessels, this has direct implications for maritime operators, including subsistence hunters, and rescue operators, such as national Coast Guards and local SAR (U.S. Coast Guard 2015). Research is currently underway to understand these risks better and their effects on the maritime environment. For example, the broader project this research is a part of, the U.S. Arctic Domain Awareness Center (ADAC)-funded project, *Developing Sea Ice and Weather Forecasting Tools to Improve Situational Awareness and Crisis Response in the Arctic,* seeks to create an early notification system for sea ice-related hazards (Kettle et al., 2019). The early warning system is designed to support U.S. Coast Guard and local SAR operators in the North Slope of Alaska.

However, there is both need and merit to work with other Arctic communities and contexts on such a topic, as there are lessons learned, similarities, and differences across the Arctic that when looked at together, can only help to increase our understanding of the changing sea ice landscape (Hovelsrud, Poppel, Van Oort, & Reist, 2011). Co-production research of Arctic weather and sea ice services is well underway in Canada and Scandinavia (Armitage et al., 2011; Dale & Armitage, 2011; Jeuring et al., 2019). Collaborating with other researchers and research institutes on a pan-Arctic sea ice hazards assessment, as well as a study of the various weather and sea ice services that are the most beneficial to information users, would be a strong demonstration of science diplomacy and collaboration within the changing Arctic.

2.7. References

Armitage, Derek, Fikret Berkes, Aaron Dale, Erik Kocho-Schellenberg, and Eva Patton. 2011. "Co-Management and the Co-Production of Knowledge: Learning to Adapt in Canada's Arctic." *Global Environmental Change* 21 (3): 995–1004. https://doi.org/10.1016/j.gloenvcha.2011.04.006.

Barber, D.G., Babb, D.G., Ehn, J.K., Chan, W., Matthes, L., Dalman, L.A., Campbell, Y., Harasyn, M.L., Firoozy, N., Theriault, N. and Lukovich, J.V. 2018. "Increasing Mobility of High Arctic Sea Ice Increases Marine Hazards Off the East Coast of Newfoundland." *Geophysical Research Letters* 45 (5): 2370–79. https://doi.org/10.1002/2017GL076587.

Beck, Silke. 2011. "Moving beyond the Linear Model of Expertise? IPCC and the Test of Adaptation." *Regional Environmental Change* 11 (2): 297–306. https://doi.org/10.1007/s10113-010-0136-2.

Bennett, Nathan James, Jessica Blythe, Stephen Tyler, and Natalie C Ban. 2016. "Communities and Change in the Anthropocene: Understanding Social-Ecological Vulnerability and Planning Adaptations to Multiple Interacting Exposures." *Regional Environmental Change* 16 (4): 907–26.

Bridges, Robert. 2017. "Risks and Damages Caused in Ice Navigation." *Encyclopedia of Maritime and Offshore Engineering*, 1–12.

Charmaz, Kathy, and Liska Belgrave. 2012. "Qualitative Interviewing and Grounded Theory Analysis." *The SAGE Handbook of Interview Research: The Complexity of the Craft* 2: 347–65.

Clark, Dylan G., and James D. Ford. 2017. "Emergency Response in a Rapidly Changing Arctic." *CMAJ*. Canadian Medical Association. https://doi.org/10.1503/cmaj.161085.

Dale, Aaron, and Derek Armitage. 2011. "Marine Mammal Co-Management in Canada's Arctic: Knowledge Co-Production for Learning and Adaptive Capacity." *Marine Policy* 35 (4): 440–49. https://doi.org/10.1016/j.marpol.2010.10.019.

Dilling, Lisa, and Maria Carmen Lemos. 2011. “Creating Usable Science: Opportunities and Constraints for Climate Knowledge Use and Their Implications for Science Policy.” *Global Environmental Change* 21 (2): 680–89.

Dinku, Tufa, Paul Block, Jessica Sharoff, Kinfe Hailemariam, Daniel Osgood, John del Corral, Rémi Cousin, and Madeleine C Thomson. 2014. “Bridging Critical Gaps in Climate Services and Applications in Africa.” *Earth Perspectives* 1 (1): 15. https://doi.org/10.1186/2194-6434-1-15.

Dumas, Jacqueline, Eddy Carmack, and Humfrey Melling. 2005. “Climate Change Impacts on the Beaufort Shelf Landfast Ice.” *Cold Regions Science and Technology* 42 (1): 41–51. https://doi.org/10.1016/j.coldregions.2004.12.001.

Durkalec, Agata, Chris Furgal, Mark W. Skinner, and Tom Sheldon. 2015. “Climate Change Influences on Environment as a Determinant of Indigenous Health: Relationships to Place, Sea Ice, and Health in AnInuit Community.” *Social Science and Medicine* 136–137 (July): 17–26. https://doi.org/10.1016/j.socscimed.2015.04.026.

“Dynamics | National Snow and Ice Data Center.” n.d. Accessed November 28, 2019. https://nsidc.org/cryosphere/seaice/processes/dynamics.html.

Eicken, Hajo, Andrew Mahoney, Joshua Jones, Thomas Heinrichs, Dayne Broderson, Hank Statscewich, Thomas Weingartner, Martin Stuefer, Tom Ravens, and Mark Ivey. 2018. “Sustained Observations of Changing Arctic Coastal and Marine Environments and Their Potential Contribution to Arctic Maritime Domain Awareness.” *Arctic* 71: 1–15.

Eicken, Hajo, and Andrew R Mahoney. 2015. “Sea Ice: Hazards, Risks, and Implications for Disasters.” In *Coastal and Marine Hazards, Risks, and Disasters*, 381–401. Elsevier.

Fenwick, Tara. 2012. “Co-Production in Professional Practice: A Sociomaterial Analysis.” *Professions and Professionalism* 2 (2): 1–16.

Flato, Gregory M., and Ross D. Brown. 1996. “Variability and Climate Sensitivity of Landfast Arctic Sea Ice.” *Journal of Geophysical Research: Oceans* 101 (C11): 25767–77. https://doi.org/10.1029/96JC02431.

Ford, J., and D. Clark. 2019. “Preparing for the Impacts of Climate Change along Canada’s Arctic Coast: The Importance of Search and Rescue.” *Marine Policy* 108 (October). https://doi.org/10.1016/j.marpol.2019.103662.

Galley, Ryan J, B G T Else, S J Prinsenberg, D Babb, and D G Barber. 2013. “Summer Sea Ice Concentration, Motion, and Thickness Near Areas of Proposed Offshore Oil and Gas Development in the Canadian Beaufort Sea—2009.” *Arctic*, 105–16.

Haavisto, Riina, Machiel Lamers, Rick Thoman, Daniela Liggett, Jorge Carrasco, Jackie Dawson, Gita Ljubicic, and Emma Stewart. 2020. “Mapping Weather, Water, Ice and Climate (WWIC) Information Providers in Polar Regions: Who Are They and Who Do They Serve?” *Polar Geography*, January, 1–19. https://doi.org/10.1080/1088937X.2019.1707320.

Handcock, Mark S, and Krista J Gile. 2011. “Comment: On the Concept of Snowball Sampling.” *Sociological Methodology* 41 (1): 367–71.

Hovelsrud, Grete K., Birger Poppel, Bob Van Oort, and James D. Reist. 2011. “Arctic Societies, Cultures, and Peoples in a Changing Cryosphere.” *Ambio* 40 (SUPPL. 1): 100–110. https://doi.org/10.1007/s13280-011-0219-4.

Inuit Circumpolar Council. 2008. *The Sea Ice Is Our Highway: An Inuit Perspective on Transportation in the Artic*. Inuit Circumpolar Council (Canada).

Jeuring, Jelmer, Maaike Knol-Kauffman, and Anders Sivle. 2019. “Toward Valuable Weather and Sea-Ice Services for the Marine Arctic: Exploring User–Producer Interfaces of the Norwegian Meteorological Institute.” *Polar Geography*, October, 1–21. https://doi.org/10.1080/1088937X.2019.1679270.

Jones, Joshua, Hajo Eicken, Andrew Mahoney, M V Rohith, Chandra Kambhamettu, Yasushi Fukamachi, Kay I Ohshima, and J Craig George. 2016. “Landfast Sea Ice Breakouts: Stabilizing Ice Features, Oceanic and Atmospheric Forcing at Barrow, Alaska.” *Continental Shelf Research* 126: 50–63.

Kettle, Nathan P. 2018. Developing sea ice and weather forecasting tools to improve situational awareness and crisis response in the Arctic. Presented at ADAC Customers and Partners Roundtable. February 22, 2018.

Kettle, Nathan P., Dina Abdel-Fattah, Andrew R. Mahoney, Hajo Eicken, Lawson W. Brigham, and Joshua Jones. 2019. "Linking Arctic System Science Research to Decision Maker Needs: Co-Producing Sea Ice Decision Support Tools in Utqiaġvik, Alaska." *Polar Geography*, December, 1–17. https://doi.org/10.1080/1088937X.2019.1707318.

Kimura, Noriaki, and Masaaki Wakatsuchi. 2000. "Relationship between Sea-Ice Motion and Geostrophic Wind in the Northern Hemisphere." *Geophysical Research Letters* 27 (22): 3735–38. https://doi.org/10.1029/2000GL011495.

Knol, Maaike, Peter Arbo, Paula Duske, Sebastian Gerland, Machiel Lamers, Olga Pavlova, Anders Doksæter Sivle, and Stein Tronstad. 2018. "Making the Arctic Predictable: The Changing Information Infrastructure of Arctic Weather and Sea Ice Services." *Polar Geography* 41 (4): 279–93. https://doi.org/10.1080/1088937X.2018.1522382.

Kovacs, Kit M., Christian Lydersen, James E. Overland, and Sue E. Moore. 2011. "Impacts of Changing Sea-Ice Conditions on Arctic Marine Mammals." *Marine Biodiversity* 41 (1): 181–94. https://doi.org/10.1007/s12526-010-0061-0.

Kwok, R., G. Spreen, and S. Pang. 2013. "Arctic Sea Ice Circulation and Drift Speed: Decadal Trends and Ocean Currents." *Journal of Geophysical Research: Oceans* 118 (5): 2408–25. https://doi.org/10.1002/jgrc.20191.

Larsen, Lars-Henrik, Beate Kvamstad-Lervold, Kjetil Sagerup, Victoria Gribkovskaia, Alexei Bambulyak, Rune Rautio, and Tor Einar Berg. 2016. "Technological and Environmental Challenges of Arctic Shipping—a Case Study of a Fictional Voyage in the Arctic." *Polar Research* 35 (1): 27977. https://doi.org/10.3402/polar.v35.27977.

Lovvorn, James R, Aariel R Rocha, Andrew H Mahoney, and Stephen C Jewett. 2018. "Sustaining Ecological and Subsistence Functions in Conservation Areas: Eider Habitat and Access by Native Hunters along Landfast Ice." *Environmental Conservation* 45 (4): 361–69.

Mahoney, Andrew R., Hajo Eicken, Allison G. Gaylord, and Rudiger Gens. 2014. "Landfast Sea Ice Extent in the Chukchi and Beaufort Seas: The Annual Cycle and Decadal Variability." *Cold Regions Science and Technology* 103 (July): 41–56. https://doi.org/10.1016/J.COLDREGIONS.2014.03.003.

Mayring, Philipp. 2004. "Qualitative Content Analysis." *A Companion to Qualitative Research* 1: 159–76.

Overeem, Irina, Robert S. Anderson, Cameron W. Wobus, Gary D. Clow, Frank E. Urban, and Nora Matell. 2011. "Sea Ice Loss Enhances Wave Action at the Arctic Coast." *Geophysical Research Letters* 38 (17): n/a-n/a. https://doi.org/10.1029/2011GL048681.

Parlee, Brenda, and Chris Furgal. 2012. "Well-Being and Environmental Change in the Arctic: A Synthesis of Selected Research from Canada's International Polar Year Program." *Climatic Change* 115 (1): 13–34.

Petrich, Chris, and Hajo Eicken. 2009. "Growth, Structure and Properties of Sea Ice." In *Sea Ice*, 23–77. Oxford, UK: Wiley-Blackwell. https://doi.org/10.1002/9781444317145.ch2.

Pizzolato, Larissa, Stephen E.L. Howell, Chris Derksen, Jackie Dawson, and Luke Copland. 2014. "Changing Sea Ice Conditions and Marine Transportation Activity in Canadian Arctic Waters between 1990 and 2012." *Climatic Change* 123 (2): 161–73. https://doi.org/10.1007/s10584-013-1038-3.

Robards, M. D., H. P. Huntington, M. Druckenmiller, J. Lefevre, S. K. Moses, Z. Stevenson, A. Watson, and M. Williams. 2018. "Understanding and Adapting to Observed Changes in the Alaskan Arctic: Actionable Knowledge Co-Production with Alaska Native Communities." *Deep-Sea Research Part II: Topical Studies in Oceanography* 152 (June): 203–13. https://doi.org/10.1016/j.dsr2.2018.02.008.

Smith, Timothy. 2017. "Search and Rescue in the Arctic: Is the US Prepared?" RAND.

Stroeve, Julienne, and Dirk Notz. 2018. "Changing State of Arctic Sea Ice across All Seasons Changing State of Arctic Sea Ice across All Seasons." *Environ. Res. Lett* 13: 103001. https://doi.org/10.1088/1748-9326/aade56.

Tremblay, Martin, Christopher Furgal, Violaine Lafortune, Caroline Larrivée, Jean-Pierre Savard, Michael Barrett, Tuumasi Annanack, N Enish, P Tookalook, and B Etidloie. 2006. "Communities and Ice: Bringing Together Traditional and Scientific Knowledge." *Climate Change: Linking Traditional and Scientific Knowledge*, 289.

U.S. Coast Guard. 2015. "Arctic Strategy Implementation Plan." Washington, D.C.

2.8 Figures and tables

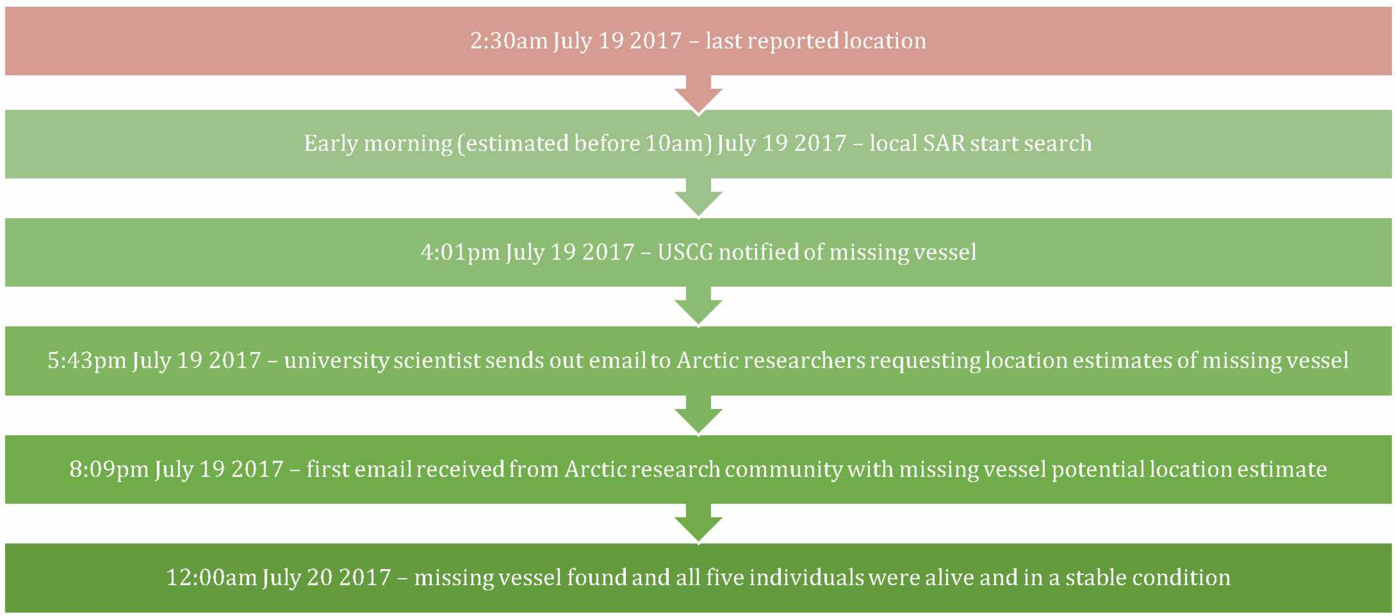

Figure 2.1. Summary of main events during July 19 2017 SAR event.

The main events of the July 19 2017 SAR event analyzed in this study. At ~2:30am local time on July 19, 2017, a 14 foot open egg top shell boat, powered by a 90 horse power Yamaha motor, went dead in the water approximately 10 miles north of Point Barrow, Alaska among a drift ice pack. The boat had on board one adult and four children under the age of 13. Volunteers, the North Slope Borough Search and Rescue team, and the US Coast Guard (USCG) conducted a search to find the missing vessel and persons. Their efforts were supported by several university scientists who helped determine the vessel's drift from its point of last known location. All five persons aboard were safely found at 12:00am local time July 20, 2017.

Figure 2.2. Primary interviewee stakeholder group, self-identified (n = 17).

Different stakeholder groups identified via an archival analysis of the SAR event and interviewed (n = 17) for this study. Some interviewees spanned multiple stakeholder groups. For the purposes of this study, we used their perspectives regarding each group, hence the larger n (21) via the figure.

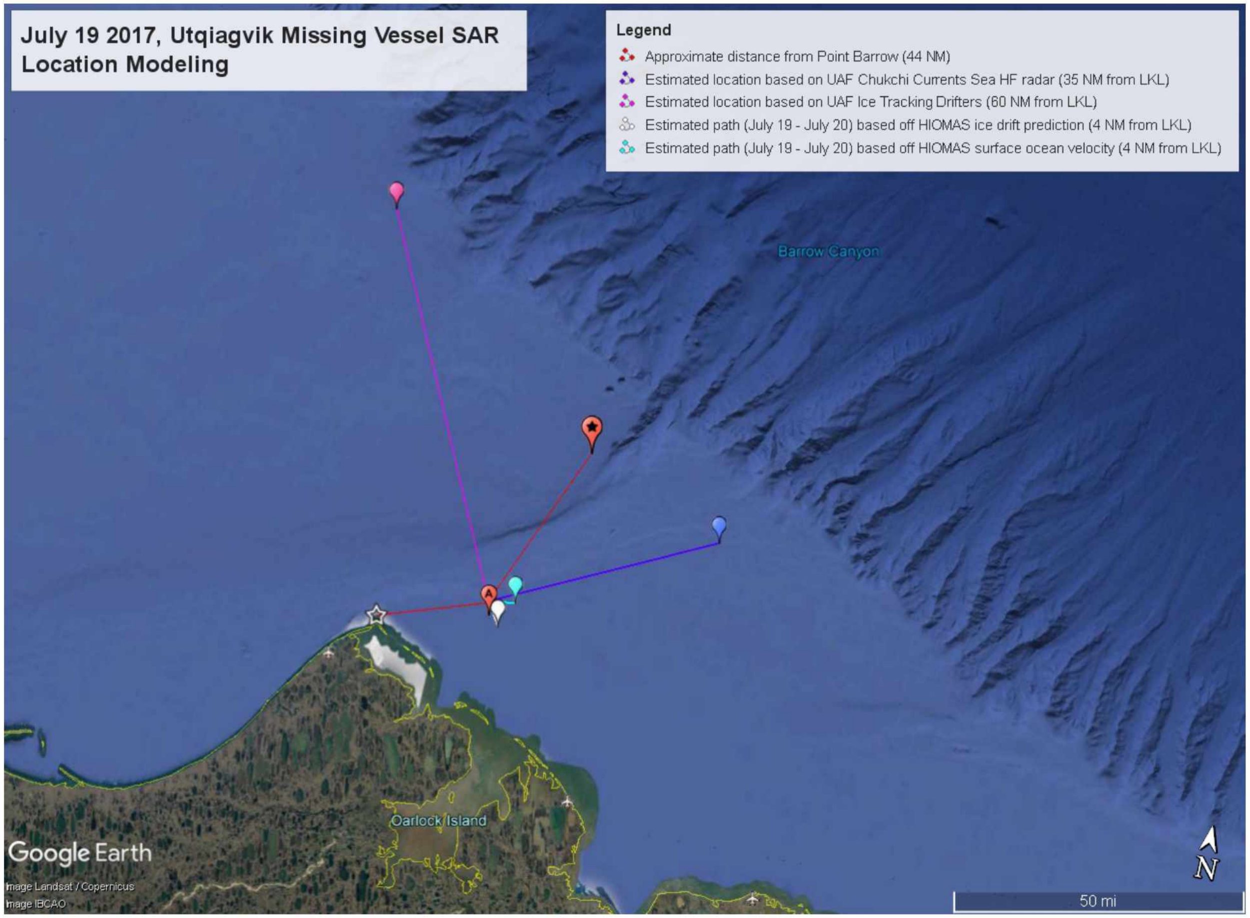

Figure 2.3. Plot of location predictions provided by university researchers during SAR event, against point of last known location for the missing vessel as well as its retrieval location.

Analysis of the location predictions provided via the four university-developed products analyzed in this research, against the point of last known location (LKL) for the missing vessel (point A, red balloon) as well as its ultimate retrieval location (starred point, red balloon). Though none of the product estimated the retrieval point, they helped to indicate ocean current direction and a general search grid, despite having very little information to work off (e.g. only one point of LKL, almost 12 hours prior to when the models were run (see Figure 2.

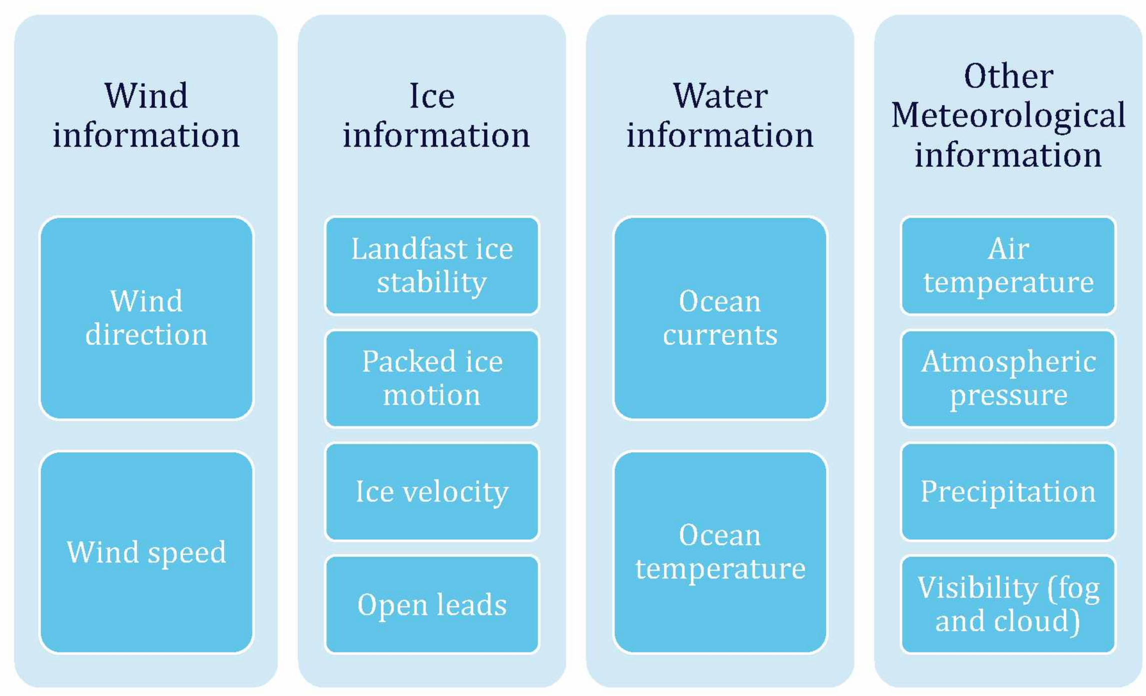

Figure 2.4. Information needs regarding sea ice decision-making in a SAR context.

Summary of the main information needs, identified via the stakeholder interviews for this case study research, that individuals need to assess for sea ice-related decision-making. It is important to note that all of these information needs may not always be relevant depending on the situation.

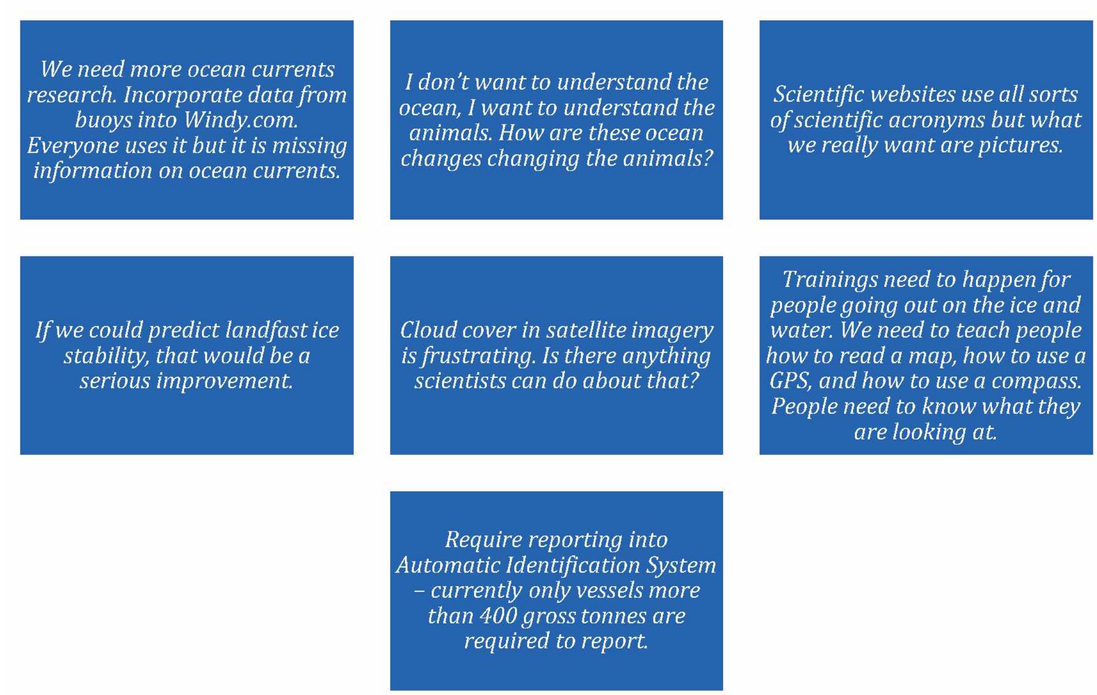

Figure 2.5. Recommendations for future sea ice hazard research.

Several quotes that were garnered from the stakeholder interviews that were conducted for this case study research, about how to develop better sea ice hazard-related information products as well as bolster better sea ice hazard decision-making.

Table 2.1. Weather- and sea ice-related information provided for the July 19, 2017 SAR effort.

Seven different weather and sea ice-related information resources and products that were investigated as part of this case study research. Information on the data provider for each information resource or product as well as the information provided, how it can be accessed, its refresh rate, and general format are provided below.

Information Product or Resource	Information Provider	Information Provided	Access	Refresh Rate	Format	Notes
International Arctic Buoy Programme (IABP)	University of Washington	Buoy (ID, skin temperature when available), ice concentration, sea level pressure, sea surface temperature	Online (requires Internet)	Daily (every morning), Monthly (once a month)	Map (dynamic, online) or table (.dat)	Buoys report on the hour but can be changed to every 15 minutes
High-Resolution Ice-Ocean Modeling and Assimilation System (HIOMAS)	University of Washington	Hindcast and forecast of Arctic Ocean currents, sea ice, and change	Online (requires Internet)	6 hours	Via Arctic ERMA mapping tool	Hindcasts and forecasts can be optimized and created in an hour
Chukchi Sea Surface Currents High Frequency (HF) Radar	University of Alaska Fairbanks	12-hour animation as well as daily maps	Online (requires Internet)	Every hour (during open water season)	Map (dynamic, online) or raw data files (KML, PNGs, and KMZ)	Though the radar does not overwinter, ice drifting buoys have data during winter season (send GPS data every hour)
Windy.com	Windy	Wind, rain, snow, temperature, and cloud movement data	Online (requires Internet)	Between 6 to 12 hours depending on data source	Online webpage and phone application (Android and iPhone)	Ocean current information not available for Arctic Alaska
Traditional and local knowledge (TLK)	North Slope Borough local community	Information related to travel, ocean, and sea ice conditions	In-person, can be shared online or via distance communication			
Ice Tracking Drifters Mapping Tool	University of Alaska Fairbanks	Ice drifter location (from deployment, to current, and end destination)	Online (requires Internet)	Consistently (precise interval not yet identified)	Online map	Drift rates can also be provided as a text file
Search and Rescue Optimal Planning System (SAROPS)	U.S. Coast Guard (USCG)	Drift probability, probability grid for search area, probability of success metric	Only accessible via USCG Intranet	Consistently (precise interval not yet identified)	Charts, maps, text files, shapefiles, and KMZ files	SAROPS exports can be created by USCG Headquarters

Table 2.2. University-developed data and modeling tools provided in SAR event.

Description of the four university-developed data and modeling tools that were provided in this SAR event, focusing on the type of information each product provides.

University-developed data and modeling tools	*Information provided*
University of Washington International Arctic Buoy Programme	Provides real-time meteorological and oceanographic data from Arctic buoys
University of Washington High-Resolution Ice-Ocean Modeling and Assimilation System (HIOMAS)	Provides surface ocean velocity and ice drift prediction
University of Alaska Fairbanks (UAF) Chukchi Sea Surface Current High Frequency Radar	Measures surface currents
UAF ice-tracking drifters	Provides data on the speed and direction of ice

Table 2.3. Information users and information providers during SAR event by stakeholder group.

Identification of which of the five main stakeholder groups involved in the analyzed SAR event were information users, information providers, or were both during the SAR event.

Stakeholder Group	*Information User*	*Information Provider*
Local Search and Rescue	X	
North Slope Borough		X
Subsistence Hunter	X	X
Research / Data Provider		X
US Coast Guard	X	X

Table 2.4. Information resources and products used during SAR event by information users.

Identification of which information resources and products were used by the information users (Local Search and Rescue and the US Coast Guard) identified for this specific SAR event via our stakeholder interviews. Products that are mentioned below as being *indirectly* used refer to how, in several instances, we were told these products helped support the SAR event. However, since we did not have the ability to talk with the specific SAR responders who potentially utilized these products, we cannot determine if information derived from these products was simply passed along to the relevant SAR responders or if the SAR responders directly accessed the products themselves.

	IABP	HIOMAS	HF Radar	Windy.com	TLK	Ice Drifters	SAROPS
Local Search and Rescue	*Indirect*	*Indirect*	*Indirect*	X	X	*Indirect*	
US Coast Guard				X			X

Table 2.5. Other utilized information resources and products by stakeholder group, identified during interviews.

Other information resources and products used by each stakeholder group, that stakeholders indicated they use over the course of our interviews. The products outlined in bold below denote products that were identified by more than one stakeholder group. In total, four products were reported as being used by more than one stakeholder group. It is important to note stakeholders indicated they use these products in general and not specifically for the analyzed SAR event.

Commercial Operators	*Local Search and Rescue*
- Canadian Ice Navigators (when travelling in Canadian waters) - Communication with other vessels that travel the same routes - **Satellite imagery from NASA MODIS website** - **NOAA ASIP** - Marine Exchange of Alaska - Flying in personnel to physically assess landfast ice stability	- Community members - **University of Alaska Fairbanks Barrow Sea Ice Radar** - Alaska Eskimo Whaling Commission - **Satellite imagery from NASA MODIS website**
Subsistence Hunters	*US Coast Guard*
- Facebook - **University of Alaska Fairbanks Barrow Sea Ice Radar** - Barrow Whaling Captain Commission	- NOAA Buoys - **NOAA ASIP**

Table 2.6. Enabling and challenging factors in data sharing and data use in Arctic SAR context.

Identified enabling and challenging factors regarding data sharing and data use in a general Arctic SAR context. These factors were identified via the stakeholder interviews using grounded theory analysis, in which the stakeholder interviews were initially coded to identify broad themes and then subsequently coded (one year later) to further refine and develop the ten factors, five enabling and five challenging, listed and discussed below.

Enabling factors	***Challenging factors***
E1. Familiarity with information or information provider	C1. Lack of awareness of information resource or product's existence
E2. Previous positive experiences with information or information provider	C2. Infrequent information update or refresh
E3. Trust in information or information provider	C3. Inaccessibility of information resource or product
E4. Mandate to, or legacy of, using an information resource or product	C4. Procedural policies or organization culture barriers
E5. Reliability of information or information provider	C5. Information product not designed or readily applicable for a SAR context

Chapter 3: Application of structured decision-making in cryospheric hazard planning: theoretical case study of Bering Glacier surges on local state planning in Alaska[1]

3.1. Abstract

Surging glaciers are glaciers that experience rapidly accelerated glacier flow over a comparatively short period of time. Though relatively rare worldwide, Alaska is home to the largest number of surging glaciers globally. However, their impact on the broader socioecological system in the state is both poorly understood and under researched. We investigated how the surge patterns of Bering Glacier in Alaska have potential devastating effects on the local ecological biodiversity of its watershed via a structured decision-making analysis of the different possible consequences. Specifically, this analysis was conducted to explore the various outcomes of a Bering Glacier surge particularly if humans have an increased presence near the glacier due to the area potentially becoming a state park. This work explored the benefit of applying decision and risk analysis methodologies in a cryosphere context, to better understand the socioeconomic impact of glacier surges. We also emphasize the need for integrated biophysical and socioeconomic analyses when it comes to understanding glacier hazards. Our research highlights the importance of understanding and researching the biophysical changes as well as the management and decision-making frameworks for glaciated regions in Alaska, in order to create adaptation strategies that are holistic and that encompass the range of possible outcomes.

[1] Abdel-Fattah, D., L. Ekenberg, S. Trainor, R. Hock, M. Lindberg. Application of structured decision-making in cryospheric hazard planning: theoretical case study of Bering Glacier surges on local state planning in Alaska. *Group Decision and Negotiation.* **In preparation (2020).**

3.2. Introduction and background

This paper is a purely methodological study of applying structured decision-making, a decision and risk analysis method, to a theorized example of a multi-stakeholder decision regarding the development of a state park in the Bering Glacier system in Alaska. The methodology and theorized case study application was developed to show the benefits of using a structured decision-making approach in a large structural uncertainty (e.g. system-wide uncertainty) cryosphere hazard context, which to our knowledge has not been done before. Given the success of structured decision-making in other environmental management settings, we assert that the application of this process can be used in cryospheric hazard settings, such as glacier surges. The structured decision-making process utilized in this paper are the six steps of the PrOACT model from (Hammond et al., 2015): 1) clarify the decision context, 2) define objectives and measures, 3) develop alternatives, 4) estimate consequences, 5) evaluate trade-offs, and 6) implement, monitor, and review.

Risk and decision analyses for cryospheric hazards is a novel arena that has just recently started to be explored in the risk and decision analysis literature (Kougkoulos et al., 2018). Alaska has one of the largest concentrations of ice in the world apart from the Greenland and Antarctic ice sheets (Pfeffer et al., 2014). This paper discusses how structured decision-making can support multi-stakeholder decision-making regarding potential socioecological hazards in a glacial context, focusing on a specific glacier type common in Alaska: surge-type glaciers. Changes to the Bering Glacier, a surge-type glacier and one of the largest glaciers in Alaska, hold implications for the broader socio-cryospheric system, the socioecological system in cold regions (Carey et al., 2015). We therefore also discuss the necessity, and suggest avenues, of further decision and risk analysis research regarding potential socio-cryospheric impacts of glacier hazards in Alaska.

3.2.1. Surging glaciers

Glacier surging is when a glacier's flow is accelerated very rapidly over a comparatively short period of time, from a few months to years, and is often associated with considerable advances of the glacier's terminus (Cogley et al., 2011). Glacier surging is a quasi-periodic glacial phenomenon, which, in addition to the surge phases, consists of quiescent phases during which the glacier does not surge and which typically last some decades at a time (Cogley et al., 2011). During a surge, flow acceleration can reach 10 to 100 times normal ice velocity, which typically results in the fast transfer of large quantities of ice from the upper reaches of the glacier towards its terminus (Burgess, Forster, & Larsen, 2013). Surging glaciers represent a small percentage of the world's glacier population (less than 1 percent) but constitute potential hazards, particularly if they advance and cutoff valleys and/or trigger glacial lake outburst floods (Sevestre & Benn, 2015). Importantly, though glacial surge processes are not well understood, they present a unique opportunity to understand glacier dynamics due to surges being largely triggered by sub-glacier dynamics rather than by external factors, such as climate (Benn & Evans, 2014).

In Alaska, there are at least 300 identified surge-type glaciers – a glacier that has the propensity to surge (Sevestre & Benn, 2015). Furthermore, Alaska has one of the highest concentration of surge-type glaciers in the world (Burgess, Forster, & Larsen, 2013). Surge-type glaciers in Alaska typically experience surges that lasts between two to three years (Meier & Post, 1969). The time period between surges, the quiescence phase, is also relatively short in Alaska, lasting anywhere between 20 and 30 years, compared to other regions (50 – 500 years) (Benn & Evans, 2014). Given the short time period of surging glaciers in Alaska, the surges themselves tend to be also quite rapid. Though most of Alaska's surging glaciers are far from human populations, glacier surges can impact human and physical systems as well as ecosystems, the latter particularly due to their impacts on surrounding biodiversity. A notable example of a surge-type glacier in Alaska is the Bering Glacier (Figure 3.1).

3.2.2. Bering Glacier surges

The Bering Glacier system is the largest surge-type glacier, outside the ice sheets (Burgess, Forster, Larsen, & Braun, 2012). It is also the largest temperate surge-type glacier globally (Crossen & Noyles, 2010). Though Bering Glacier is retreating rapidly, five notable surges have been recorded for the glacier during the past century: ~1900, ~1920, ~1938 – 1940, 1957 – 1967, and 1993 – 1995 (Molnia & Post, 2010). A smaller surge was also recorded in 2008 to 2011 (Burgess et al., 2012). Data on the Bering Glacier's surges shows that the glacier's quiescence phase lasts about 20 years (Roush, Lingle, Guritz, Fatland, & Voronina, 2003).

Bering Glacier's cycle of retreat and surging has significant implications for the area's surrounding hydrology. The Bering Glacier's surge advances and subsequent retreats dramatically affected the lakes and rivers surrounding during the glacier's surge in the early 1990s ("Yakataga Area Plan," n.d.). Though Vitus Lake, Bering Glacier's proglacial lake, expanded to over 202 km^2 during Bering Glacier's post-surge retreat in the early 1990s, the 1994 – 1995 surge caused Bering Glacier to regain most of Vitus Lake ("Yakataga Area Plan," n.d.). The 1995 Yakataga Area Plan discussed how scientists, given the high tides (approximately > 2 m) entering via Seal River into Vitus Lake, expect the lake to ultimately open up to the Gulf of Alaska ("Yakataga Area Plan," n.d.). The increased tidal influx will create not only a fjord where Vitus Lake once was but is also projected to cause Bering Glacier to retreat up to 57 km in the next 50 to 100 years ("Yakataga Area Plan," n.d.). However, recent models have shown that though Vitus Lake will continue to significantly expand in size and volume, the rapid retreat of Bering Glacier and its freshwater contribution to Vitus Lake as well as other factors make it more likely that tidal influxes will become less significant (Josberger, Shuchman, Meadows, Jenkins, & Meadows, 2010; Josberger, Shuchman, Meadows, Savage, & Payne, 2006).

3.2.3. Socioecological impacts of Bering Glacier surging

Though Bering Glacier experiences rapid advances during its glacier surges, it has been experiencing rapid retreat since its last surge (2008 - 2011), which has a direct impact on its surrounding physical and ecological system. However, Bering Glacier's rapid retreat is surprisingly under researched from a socioecological perspective. Though the glacial retreat and glacier surges of Bering Glacier has been of notable interest from a glaciology perspective, there is comparatively little research done on how these changes affect the surrounding socioecological system. For example, Vitus Lake is becoming more and more saline due to tidal influxes from Seal River, creating potential research opportunities to study a freshwater to marine transition for salmon runs and bird rookeries ("Yakataga Area Plan," n.d.). However, little research has been done to date on these ecological changes. Freshwater biogeography of newly deglaciated areas is still not well understood (Weigner & von Hippel, 2010).

What makes Bering Glacier particularly interesting to study in this regard is that Vitus Lake has a relatively high fish species richness, given its size and the fact it is tidally influenced. This is unique given that most glacial lakes have typically low fish species (Weigner & von Hippel, 2010). If Vitus Lake continues to grow, as the Bering Glacier retreats, it could potentially foster an even more vibrant fish community; older lakes and streams are more likely to have more fish and more fish species diversity. Vitus Lake can be an ideal environment for coho salmon runs as the stickleback species pair, a food source for coho salmon, is the only known species, to our current knowledge, that exists in a proglacial lake in the world (Weigner and von Hippel 2010).

However, Bering Glacier is an extremely dynamic glacier that can have drastic destabilizing effects on its surroundings, which has implications for land and resource management decisions. The 1993 - 1995 surge of Bering Glacier completely destroyed the coho salmon runs in Vitus Lake (Weigner & von Hippel, 2010). Though the coho salmon have since returned, the full extent of the population recovery is not known.

The State of Alaska has potential plans – according to the 1995 Yakataga Area Plan – to open Bering Glacier as a state park as the glacier continues to recede as well as potentially allowing for the continued use of the glacially fed rivers and streams for sport fishing. If this plan is approved, it is unclear at the moment how the state will take into account future surges of the glacier, especially if the area will be used for recreational use. Specifically, more research needs to be done on whether Bering Glacier surges will potentially continue to destroy salmon and other fish populations each time they happen, and if so, how that would impact the recreational activities and local businesses that support sport fishing in this area from both an operational and economic perspective. Bering Glacier is due for another surge soon – its quiescence phase normally lasts 20 years and the last major surge was in 1993 – 1995. Though climate change may impact the magnitude of its next surge (Bering Glacier has retreated considerably since its last surge), more research is necessary to understand whether Vitus Lake is at risk for being drained once again if Bering Glacier surges, particularly if the area is under consideration by the State of Alaska for recreational and potentially economic gain.

Human impact and its effect on the Bering Glacier system's coho salmon population therefore need to be better understood. The US Bureau of Land Management is a key stakeholder interested in changes to the Bering Glacier system. The US Bureau of Land Management oversees competing land interests, such as land rights in the area that have been sold to corporations interested in exploring the area's oil and coal potential as well as the increasing ecotourism the area has seen in recent decades; two public use cabins have been built along Vitus Lake (Josberger et al., 2006). Human presence however has long been underway in the Bering Glacier area – sports fishing takes place on some of the rivers (Tsiu and Kiklichk rivers) coming out of Bering Glacier, but hunters, fishermen, and gold prospectors have been in the area since the early 1990s (Josberger et al., 2006). The increase in human activity can potentially affect the stickleback species pair – a food source for salmon – population, since it is particularly sensitive to human impacts on water quality and water withdrawals (Weigner and von Hippel 2010).

Given the relatively young population of the fish colonies in Vitus Lake and the surrounding watershed as well as the sensitivity of the stickleback species pair to human presence, research is needed to shed light on whether increased human activity in the Bering Glacier system can negatively impact this ecosystem if a state park is indeed created as well as what are the risks to the human community if Bering Glacier surges again.

3.2.3. Decision-making in environmental management

Structured decision-making is a collaborative, facilitated application of group decision-making (Gregory et al., 2012). Specifically, in the context of environmental management, structured decision-making allows for the utilization of analytical methods from the fields of decision analysis and applied ecology, as well as cognitive psychology and group negotiation (Gregory et al., 2012). Structured decision-making is based on the five steps of the PrOACT process which aim to identify: 1) problems, 2) objectives, 3) alternatives, 4) consequences, and 5) tradeoffs (Hammond, Keeney, & Raiffa, 2015). Each step of the structured decision-making process can have varying levels of rigor and complexity, depending on the nature of the decision and the incentives, resources, and time available (Gregory et al., 2012). Structured decision-making is meant to be used as a methodological, iterative framework for decision-making. Though the process and the iterative nature in particular may seem time-consuming, a key tenant of structured decision-making is that it does not have to be time-consuming. Thus, the process of structured decision-making is meant to be flexible as it is iterative. From complex modeling to intensive, long-term data collection to elicitations and interviews conducted over the span of a few days, the resources and effort involved in a structured decision-making process are dependent on the questions being asked and the decisions being made. The essence therefore of structured decision-making is to provide a transparent thinking process that helps to mitigate biases such that decision-making is undertaken in a consistent manner in order to attain high quality outcomes, after careful consideration of the range of relevant concerns. Given that structured decision-making is meant to be a collaborative group process, the definition of what is a quality outcome as well as what are the relevant concerns for stakeholders are meant to be defined as part of the process. Each process and set of definitions will therefore be unique to the individuals involved.

A study by van der Burg et al. (2016) looked into the use of a structured decision-making approach to help two Landscape Conservation Cooperatives (LCC) decide on what information to provide to conservation and other land decision-makers. The results of this study found that in order for information to be useful to decision-makers, they needed to understand how it could help them make or understand the effects of their decisions. They also found that a decision process of this kind can support elicitation of stakeholder needs, but that it cannot ensure that the decision ultimately reached is a good one. It is important to note that a "good decision" is something to be determined by the stakeholders involved in a structured decision-making process. However, following a "good process" in general is not enough to ensure a good outcome due to a number of factors. These include modeling shortcomings and negative dynamics in a decision context, such as the uncertainties associated with needs, perceptions, preferences, and group interactions, as well as institutional issues and other dynamic factors that already prevail or might arise during and after the process. It is therefore important to adapt the decision-making process to take these aforementioned factors, as well as the overarching context, into account in order to actively counter and address barriers and negative dynamics.

In general, structured decision-making requires long-term institutional commitment – whether at the individual or organizational level – in order to ensure the process is maintained and built upon in future decision-making. There is consequently the risk that future stakeholders and managers will not uphold the process (Gregory et al., 2012). In addition, it can be challenging to implement a structured decision-making approach in institutional settings that are not already transparent and committed to transparency as an organizational value (Gregory et al., 2012). It is therefore important to ensure that participants and beneficiaries have realistic and appropriate expectations of what can and cannot be achieved from a structured decision-making approach, to help sustain the longevity and proper application of the approach over time.

Ohlson et al. (2005) assessed how a structured decision-making approach supported forest managers in Canada in their development of climate change strategies at the local, regional, and national scale. Structured decision-making in this context provided easy-to-understand guidance that decision-makers required to develop and evaluate climate change adaptation strategies. Importantly, the structured decision-making process helped to contextualize for decision makers in this study that climate change is only one of several other issues that needs to be addressed in planning, helping decision makers realistically and actively evaluate various trade-offs. Ogden and Innes (2009) also applied a structured decision-making approach to the Canadian forestry sector, by assessing climate change vulnerabilities and adaptation options via eliciting knowledge from local forest practitioners. They found that though a focus on future decision-making – particularly related to climate change – is a part of planning, an understanding of current practices is important to ensure viable adaptation options are considered. A structured decision-making approach therefore helped to shed light on what are gaps between perceptions and actuality, which can potentially improve current and future planning.

Martin et al. (2011) looked into how structured decision-making can be applied for decision-making in a different sector. At the time of their paper, though structured decision-making was gaining traction in the conservation management sector, it had not yet been applied to the sea-level rise sector. This is largely due to structured decision-making generally assuming that the systems and processes at play are fairly stationary whereas in the sea-level rise sector, the processes at play are non-stationary and continuously changing. They found that though many of the structured decision-making tools can be adapted to a non-stationary system, optimizing solutions is more challenging, given the difficulty of capturing a problem with extreme dimensions.

Though the above examples and many others (Lienert, Scholten, Egger, & Maurer, 2015; Wilson & McDaniels, 2007) highlight the benefit of structured decision-making in elucidating realistic solutions for decision-making, particularly in light of complex challenges related to climate change, gaps exist in the literature for developing concrete methods that actively take into account the multitude of uncertainties related to climate change (Martin, Runge, Nichols, Lubow, & Kendall, 2009). Specifically, challenges exist with how to capture unintended or unforeseen consequences in structured decision-making approaches regarding large structural (e.g. environmental) uncertainty contexts (Martin et al., 2009; Nichols et al., 2011). This research methodology paper aims to actively address this gap, by looking into how a structured decision-making framework can be developed for a large structural uncertainty context, specifically a glacier surge context.

3.2.4. The Bering Glacier case study

Decision-making regarding land and biodiversity management in a surging glacier floodplain is a cryospheric hazard situation that lends itself well to the application of a structured decision-making approach. The Bering Glacier case study is an interesting one to explore the application of structured decision-making since there are several unknown impacts, particularly regarding the timing of future glacier surges as well as the impact of increased human presence on the biodiversity of the area. Glaciers and glaciated areas such as the Bering Glacier system are areas of high scenic value. Trail systems and recreational areas – whether developed by city, state, or federal authorities – can therefore be present in the glacier surge floodplain and subsequently can be impacted or destroyed during a surge event. A structured decision-making approach can be a useful application to help relevant decision-makers assess the following questions:

1) What are the uncertainties associated with a surge event and how do these uncertainties impact management decisions?
2) Which stakeholders are impacted by a surge event and to what extent?
3) What are the impacts of human activity on the local biodiversity?
4) What are the various management decisions that can be undertaken, despite the uncertainties associated with a surge event and increased human presence in the area?

3.3. Methods

We utilized the existing literature to inform our understanding of the Bering Glacier system and the development of our theorized structured decision-making application. For clarifying the decision context step, we developed a problem statement in which we identified: the decision-makers who would make the decision, the reason for the decision and why it matters, the time period of the decision, as well as the constraints that need to be taken into consideration of the decision. We also identified the decision-makers, hereafter referred to as stakeholders, by not only their involvement in the decision process but also by the extent to which the decision would affect them as well (Table 3.1).

We defined the objectives for this structured decision-making application by identifying both fundamental and means objectives. Fundamental objectives are objectives that are essential to be met by any decision made while means objectives are those which help to achieve fundamental objectives. Measurable attributes were also developed to help quantify the achievement of an identified objective. We identified three possible decisions, hereafter referred to as alternatives, that were considered in this case study (Figure 3.2).

We estimated the possible outcomes, hereafter referred to as consequences, based off how we theorized each alternative achieving each of the identified objectives (Table 3.2). In order to compare each alternative and evaluate the trade-offs between each, we normalized all the alternatives using a standard min-max normalization score, $N_{Score}(X)$, which is standard practice.

$$N_{Score}(X) = (s_{ij} - \min(s_j) / (\max(s_j) - \min(s_j)) \qquad (1)$$

where s_{ij} represents a value in the set s_j and $min(s_j)$ represents the lowest value in the set sj and $max(s_j)$ represents the highest value in the set s_j (Fitts Cochrane, n.d.).

The alternative with the highest normalized score was ranked as the optimal decision from the consequence and trade-off analysis. We also conducted a decision tree analysis (Figure 3.3) to compare its results with results from the consequence and trade-off analysis (Tables 3.2 to 3.6). Each alternative is represented as a branch in a decision tree, and each decision node is given a probability of occurrence, terminating with an outcome. Each alternative was given an expected value, using the common expected value equation,

$$E(X) = \Sigma\, x_i p_i \qquad (2)$$

where the expected value E of a set of an alternative X, is the sum of each outcome x_i multiplied by its probability p_i.

The results from the decision tree analysis were then compared with the results from the consequence and trade-off analysis to evaluate whether the results were reproducible such that the same alternative was deemed as the optimal decision in both analyses.

3.4. Results

3.4.1. Clarify the decision context

Via our review of the literature on this topic as well as official state documents, we identified that the main goal of any decision regarding the Bering Glacier area is to maximize the scientific and scenic value of the area while minimizing the impact on local biodiversity. For the purposes of this study, given the large uncertainty associated when / if Bering Glacier will surge next (it is due to potentially surge again within the next 20 years), we limited our analysis to just the next 5 years, in order to be able to better parameterize the uncertainty surrounding the surge. Thus, the aforementioned decision context was taken into consideration with the potential surge of Bering Glacier, the state's budget, the current health of the coho salmon population present in the area, as well as the ability of the area to serve as a scientific and recreational resource in mind, as outlined in Figure 3.2 ("Yakataga Area Plan," n.d.).

Table 3.1 lists the stakeholders we considered for this study, based on their ability to not only affect the decision-making process but also the extent to which a decision would affect them as well. Given the remoteness of the Bering Glacier system, most of the stakeholders able to affect a decision in this context would be state and federal agencies mandated with overseeing or monitoring the area.

3.4.2. Clarify objectives and measures

Table 3.2 outlines the fundamental and means objectives we identified as part of our structured decision-making exercise as well as the measurable attributes for each objective, based on indicators that could be collected and measured for each objective. It is also important to note that all of the objectives were sought to be maximized.

3.4.3. Develop alternatives

Three alternatives (see boxes in Figure 3.2) were identified as potential solutions to meet the fundamental and means objectives, based on our assumptions from a review of the literature. They were: build a state park, manage and monitor biodiversity, as well as open up the area for commercial recreation access. The alternatives were not mutually exclusive and were thus considered as portfolio options with some elements in common. We were interested to see which alternative was the most optimal considering the impacts (see hexagons in Figure 3.2) and uncertainty (see oval in Figure 3.2) of the decision, as informed by our review of the literature (see Introduction section). It is important to note that the only notable uncertainty in this study was whether Bering Glacier would surge during the next 5 years. Building a state park was the only alternative that influenced all the identified impacts.

3.4.4. Estimate consequences

Tables 3.3 to 3.5 relay the process of consequence table analysis. We first provided values for each alternative for how they would contribute to the four identified objectives (Table 3.3). According to the measurable attributes and their scales as well as our understanding of the Bering Glacier system context, we provided values for each alternative.

Next, we converted all the consequences values to a 10 point scale so that we could assess if there were any objectives that were irrelevant; meaning for each alternative, each value for said objective was the same (Luo & Cheng, 2006). We found that the "striving to model the next surges of the Bering Glacier" objective was irrelevant, given its equal value across all three alternatives (Table 3.4). We therefore removed this objective from further analysis and consideration.

We normalized the remaining consequences in order to compare them against one another using Equation (1) (Table 3.5). In doing so, "build state park" emerged as the optimal alternative.

3.4.5. Evaluate trade-offs

Once the consequences were normalized, we conducted a sensitivity analysis of the alternatives by adding weights to each objective, in order to ensure that the optimal alternative elucidated after normalization was not due, or sensitive, to an underlying dominant objective(s) (Table 3.6). We weighed each objective based on our perceived importance of each objective concerning how it would meet the fundamental objective assessed in this study, which was "ensure local biodiversity of the Bering Glacier area." Therefore, "ensuring local biodiversity" was the highest weighted objective (50%) followed by "continuing scientific research" (30%) and "building scenic value" (20%). After the weights were applied, we were able to create a cumulative score for each alternative, based on summing all the objectives value for each alternative. In doing so, we found that the "manage and monitor biodiversity" alternative was the most optimal, with a score of 0.58, followed by "build a state park" (0.51) and "open area for commercial access" (0.25).

3.4.6. Implement, monitor, and review

Lastly, we checked to see if the results from our consequence table were reproducible by conducting a decision tree analysis (Figure 3.3). Given the complexity of the uncertainty of the Bering Glacier surge, we conducted a decision tree analysis primarily to see whether managing and monitoring biodiversity was worth the effort, given the potential of the area to experience another glacier surge soon. We assigned the theorized probabilities according to the range of possibilities based off our knowledge and understanding of the Bering Glacier context. The outcomes – the effect on stickle back species pair – were theorized based on the literature regarding their sensitivity to human impacts (Weigner & von Hippel, 2010) and did not include any observational data.

Once the decision tree was created, we calculated expected value based on Equation 2 for managing and monitoring biodiversity (E(yes)) and for not managing and monitoring biodiversity (E(no)). In doing so, we obtained the following results:

$$\mathbf{E(yes)} = 0.1(1) + 0.01(0) + 0.7(7) + 0.5(5) + 0.5(5) + 0.3(3) + 0.5(4) + 0.3(3) + 0.3(3) + 0.1(1) = \mathbf{14.8}$$

$$\mathbf{E(no)} = = 0.1(1) + 0.01(0) + 0.9(10) + 0.7(8) + 0.7(8) + 0.5(6) + 0.5(6) + 0.3(4) + 0.3(4) + 0.1(2) = \mathbf{28.9}$$

The expected value in this context was minimum direction – we wanted to see *less* of an effect on stickleback species pair. The expected value for managing and monitoring biodiversity was lower than that for not managing and monitoring biodiversity (14.8 < 28.9). Therefore, the decision tree analysis confirmed the same results of the consequence table analysis – that managing and monitoring biodiversity was the optimal solution.

3.5. Discussion

Surging glaciers are a unique part of the Alaskan cryosphere. However, their impact on the broader socioecological system in the state is both poorly understood and under researched. It is as important to understand the management frameworks as the biophysical changes that are taking place in glaciated regions, to create adaptation strategies that are both holistic and realistic of the actual situation in these regions.

This paper assessed a number of different scenarios regarding the potential surge patterns of Bering Glacier, which can have potential devastating effects on the local ecological biodiversity of its watershed, particularly if humans have an increased presence near the glacier due to the area potentially becoming a state park. We utilized a structured decision-making theoretical exercise to explore the effect of three different management alternatives on the Bering Glacier area: build a state park, manage and monitor biodiversity, and open up the area for commercial recreation access.

What was interesting from the findings was the assurance of managing and monitoring biodiversity as the optimal solution that was derived from this exercise, which potentially suggests the decision to build a state park is not necessarily a binary decision. Rather, by ensuring the local biodiversity is well protected and monitored, this opens up the opportunity for decision makers to explore other possibilities, such as the development of a state park, but within the confines of an established ecosystem preservation effort.

Structured decision-making can help to illuminate a variety of options for decision-makers faced with making decisions with little information or even large uncertainty. This paper helped to show how utilizing a decision-making methodology, despite very large uncertainty surround the Bering Glacier's potential next surge, does not need to immobilize decision-making processes. Rather, by considering options and consequences in a transparent and holistic process, decisions can be made and amended, as part of the iterative process structured decision-making promotes. It should be noted that the decision analytical approach is simplified in several respects to demonstrate the general idea. The general framework can straightforwardly be adapted to considerably more elaborate methods and processes, such as the ones proposed in, e.g., (Danielson & Ekenberg, 2019; Danielson, Ekenberg, & Larsson, 2020).

Although a structured decision-making approach can be advantageous to decision-makers in this Bering Glacier case study, there are factors associated with utilizing such an approach that can nonetheless lead to a structured decision-making "failure." Namely, if there is no long-term institutional buy-in and commitment to utilizing such an approach year-after-year in decision-making, the benefits of employing a structured decision-making approach will be short-lived and perhaps even non-existent. Furthermore, if there are stakeholders who deeply contest some, if not all, of the potential decision-making alternatives, the ability to accurately carryout a structured decision-making decision will be greatly compromised and potentially completely blocked. Lastly, if decision-makers ultimately find the uncertainties associated with a surge event to be too large to optimize any, or all, potential alternative solutions, it will not be possible to use a structured decision-making approach to help flesh out viable alternatives given the large, and non-parameterizable, uncertainty.

3.5.1. Review of the structured decision-making method in a cryospheric hazard context

Our methodology application suggests that structured decision-making can lend itself well to analyzing stakeholder needs and objectives regarding cryospheric hazards. Importantly, the use of structured decision-making can potentially support stakeholders to arrive at well-informed decisions regarding cryospheric hazard management. Particularly in contexts where there is not an ample amount of scientific information or observational data available to assess the socioecological impacts of these types of hazards, such as in the Bering Glacier case study, our theoretical application of structured decision-making was nonetheless conclusive and robust, in that the results were reproducible.

The results from the consequence table analysis however suggest the need to validate our findings with stakeholder inputs. The optimal decision, after normalizing the variables, was "build a state park." However, after conducting our sensitivity analysis via employing a weighting scheme, the optimal decision was "manage and monitor biodiversity." We were able to reproduce this result via the decision tree analysis, which potentially indicates the robustness of this result. Nonetheless, without utilizing actual stakeholder inputs, we cannot ascertain that these findings are reflective that this is the optimal decision. As with all quantitative decision analysis models, stakeholder elicitation is an important part of validating results from quantitative models.

However, the results of our study show the potential merits of employing structured decision-making to help empower stakeholders to arrive at a decision, despite limited information. The power of structured decision-making lies less in its quantitative modeling abilities and instead, in its ability to serve as a transparent and group-based process, where different stakeholders come together to find common goals, such that they use this commonality, despite limited information, to arrive at a decision.

3.5.2. Limitations

This was a purely methodological study and because of such, there was no stakeholder engagement as part of this research. This limited our ability to confirm our assumptions regarding the objectives we identified in the consequence table analysis as well as the weighting scheme for each objective, that reflected the stakeholder importance of each objective. In addition, the values we utilized in the consequence table analysis as well as in the decision tree analysis were theoretical and were not validated by stakeholders. Given that we did not use stakeholder inputs, we could not conduct a more sophisticated weighting scheme analysis nor could we derive more precise estimations of the probabilities of occurrence for the various uncertainties analyzed in the decision tree analysis. However, for future research, it would be interesting to see if different weighting schemas could be applied, such as swing weighting. In addition, employing Bayesian analysis in the decision tree could be another method to test, for more comprehensive probability analysis, in future research.

3.5.3. Application to other glacier hazards scenarios and future research

Though the Bering Glacier case study discussed above focused on one ecological impact of the glacier's surging, cryospheric hazards can have an even more direct impact on communities. Glacial lake outburst floods, avalanches, landslides, and seasonal and long-term glacier runoff variability can greatly and potentially catastrophic impact downstream communities (Carey et al., 2015). Indirect impacts, such as what is shown in this case study, can also occur, particularly for communities that do not live near glaciers. Tourism economies, energy production, and food production can also be dependent on glacial run-off. Carey et al. offer a 3-part approach to ensuring that adaptation to cryospheric hazards is ultimately successful. This approach requires 1) understanding cryospheric hazards from a biophysical basis, 2) preventing disasters from occurring through risk management, and 3) reducing vulnerability by addressing socioeconomic factors that increase susceptibility to these events (Carey et al., 2014).

More research is necessary from both a physical science and a decision and risk analysis perspective to understand the changes to glaciers in Alaska as well as how these changes affect and impact socioecological systems and communities. Researching surging glaciers and their socioeconomic impact in Alaska can support further research efforts and understanding regarding the combined socio-cryospheric systems in Alaska. Longitudinal glacial data in Alaska, particularly for a large subset of glaciers, has been limited up until now due to the difficulty and demanding level of resources (i.e. time and money) that would be necessary to create a dataset like this. However, recent datasets have been created regarding surging glaciers – such as the worldwide surging glaciers inventory via data from the Randolph Glacier Inventory in addition to the glacier surface velocities map developed by the University of Alaska Fairbanks – providing an opportunity to do more macro-level research on surging glaciers and their impacts on communities in Alaska and elsewhere. Datasets such as these can be combined with community-level data (i.e. infrastructure, natural resources, and salmon runs maps) to understand what are potential areas of impact from glacier surges. Overlaying socioeconomic indicator maps against surging glacier information can provide insight to see which glaciers can potentially impact local communities, particularly from indirect effects. By identifying at a macro level the target areas of concern, more localized research and projects can consequently be undertaken to understand the local socio-cryospheric context more deeply, helping to pave the pathway to relevant and feasible adaptation and resilience strategies.

3.6. References

Benn, D., & Evans, D. J. A. (2014). *Glaciers and glaciation*. Routledge.

Burgess, E W, Forster, R. R., Larsen, C. F., & Braun, M. (2012). Surge dynamics on Bering Glacier, Alaska, in 2008-2011. *The Cryosphere*, *6*(6), 1251.

Burgess, Evan W, Forster, R. R., & Larsen, C. F. (2013). Flow velocities of Alaskan glaciers. *Nature Communications*, *4*, 2146.

Carey, M., Baraer, M., Mark, B. G., French, A., Bury, J., Young, K. R., & McKenzie, J. M. (2014). Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru). *Journal of Hydrology*, *518*, 60–70.

Carey, M., McDowell, G., Huggel, C., Jackson, J., Portocarrero, C., Reynolds, J. M., & Vicuña, L. (2015). Integrated Approaches to Adaptation and Disaster Risk Reduction in Dynamic Socio-cryospheric Systems. *Snow and Ice-Related Hazards, Risks and Disasters*, 219–261. https://doi.org/10.1016/B978-0-12-394849-6.00008-1

Cogley, J. G., Hock, R., Rasmussen, L. A., Arendt, A. A., Bauder, A., Braithwaite, R. J., … Nicholson, L. (2011). Glossary of glacier mass balance and related terms. IHP-VII Technical Documents in Hydrology, 86, 965.

Crossen, K. J., & Noyles, C. (2010). The raw beauty of Bering Glacier. *Geological Society of America Special Papers*, *462*, 1–12.

Danielson, M., & Ekenberg, L. (2019). An improvement to swing techniques for elicitation in MCDM methods. Knowledge-Based Systems, 168, 70–79.

Danielson, M., Ekenberg, L., & Larsson, A. (2020). A second-order-based decision tool for evaluating decisions under conditions of severe uncertainty. Knowledge-Based Systems, 191, 105219.

Fitts Cochrane, J. (n.d.). *Making Decisions with Multiple Objectives An Overview of Structured Decision Making Module H-Making Decisions with Multiple Objectives*.

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T., & Ohlson, D. (2012). *Structured decision making: a practical guide to environmental management choices*. John Wiley & Sons.

Hammond, J. S., Keeney, R. L., & Raiffa, H. (2015). *Smart choices: A practical guide to making better decisions*. Harvard Business Review Press.

Josberger, E. G., Shuchman, R. A., Meadows, G. A., Jenkins, L. K., & Meadows, L. A. (2010). Hydrologic processes of Bering Glacier and Vitus Lake, Alaska. *Bering Glacier: Interdisciplinary Studies of Earth's Largest Temperate Surging Glacier, Geological Society of America Special Papers*, *462*, 105–127.

Josberger, E. G., Shuchman, R. A., Meadows, G. A., Savage, S., & Payne, J. (2006). Hydrography and circulation of ice-marginal lakes at Bering Glacier, Alaska, USA. *Arctic, Antarctic, and Alpine Research*, *38*(4), 547–560.

Kougkoulos, I., Cook, S. J., Jomelli, V., Clarke, L., Symeonakis, E., Dortch, J. M., … Merad, M. (2018). Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2017.10.083

Lienert, J., Scholten, L., Egger, C., & Maurer, M. (2015). Structured decision-making for sustainable water infrastructure planning and four future scenarios. *EURO Journal on Decision Processes*, *3*(1–2), 107–140. https://doi.org/10.1007/s40070-014-0030-0

Luo, C.-M., & Cheng, B.-W. (2006). Applying Even-Swap Method to Structurally Enhance the Process of Intuition Decision-Making. *Systemic Practice and Action Research*, *19*(1), 45. https://doi.org/10.1007/s11213-005-9003-3

Martin, J., Runge, M. C., Nichols, J. D., Lubow, B. C., & Kendall, W. L. (2009). Structured decision making as a conceptual framework to identify thresholds for conservation and management. *Ecological Applications*, *19*(5), 1079–1090. https://doi.org/10.1890/08-0255.1

Martin, J., Fackler, P. L., Nichols, J. D., Lubow, B. C., Eaton, M. J., Runge, M. C., … Langtimm, C. A. (2011). Structured decision making as a proactive approach to dealing with sea level rise in Florida. *Climatic Change*, *107*(1–2), 185–202.

Meier, M. F., & Post, A. (1969). What are glacier surges? *Canadian Journal of Earth Sciences*, *6*(4), 807–817. https://doi.org/10.1139/e69-081

Molnia, B. F., & Post, A. (2010). Surges of the Bering Glacier. *Bering Glacier: Interdisciplinary Studies of Earth's Largest Temperate Surging Glacier*, 291–314.

Nichols, J. D., Koneff, M. D., Heglund, P. J., Knutson, M. G., Seamans, M. E., Lyons, J. E., … Williams, B. K. (2011). Climate change, uncertainty, and natural resource management. *The Journal of Wildlife Management*, *75*(1), 6–18. https://doi.org/10.1002/jwmg.33

Ogden, A. E., & Innes, J. L. (2009). Application of structured decision making to an assessment of climate change vulnerabilities and adaptation options for sustainable forest management. Ecology and Society, 14(1).

Ohlson, D. W., McKinnon, G. A., & Hirsch, K. G. (2005). A structured decision-making approach to climate change adaptation in the forest sector. The Forestry Chronicle, 81(1), 97–103.

Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., … Kienholz, C. (2014). The Randolph Glacier Inventory: a globally complete inventory of glaciers. *Journal of Glaciology*, *60*(221), 537–552.

Roush, J. J., Lingle, C. S., Guritz, R. M., Fatland, D. R., & Voronina, V. A. (2003). Surge-front propagation and velocities during the early-1993–95 surge of Bering Glacier, Alaska, U.S.A., from sequential SAR imagery. *Annals of Glaciology*, *36*, 37–44. https://doi.org/10.3189/172756403781816266

Sevestre, H., & Benn, D. I. (2015). Climatic and geometric controls on the global distribution of surge-type glaciers: implications for a unifying model of surging. *Journal of Glaciology*, *61*(228), 646–662.

van der Burg, M. P., Thomas, C. C., Holcombe, T., & Nelson, R. D. (2016). Benefits and limitations of using decision-analytic tools to assess uncertainty and prioritize landscape conservation cooperative information needs. Journal of Fish and Wildlife Management, 7(1), 280–290.

Weigner, H. L., & von Hippel, F. A. (2010). Biogeography and ecological succession in freshwater fish assemblages of the Bering Glacier Region, Alaska. *Bering Glacier: Interdisciplinary Studies of Earth's Largest Temperate Surging Glacier*, *462*, 167.

Wilson, C., & McDaniels, T. (2007). Structured decision-making to link climate change and sustainable development. *Climate Policy*, *7*(4), 353–370. https://doi.org/10.1080/14693062.2007.9685661

Yakataga Area Plan. (n.d.). Retrieved February 5, 2020, from http://dnr.alaska.gov/mlw/planning/areaplans/yakataga/

3.7 Figures and tables

Figure 3.1. Bering Glacier and Vitus Lake

Location of Bering Glacier in southern Alaska. Vitus Lake, Bering Glacier's proglacial lake and the home to a coho salmon population, is connected to the Gulf of Alaska via Seal River. Vitus Lake was completely overrun by the Bering Glacier surge in 1993 to 1995, which completely destroyed the coho salmon population. Lake Vitus could possibly be overrun again in future Bering Glacier surges.

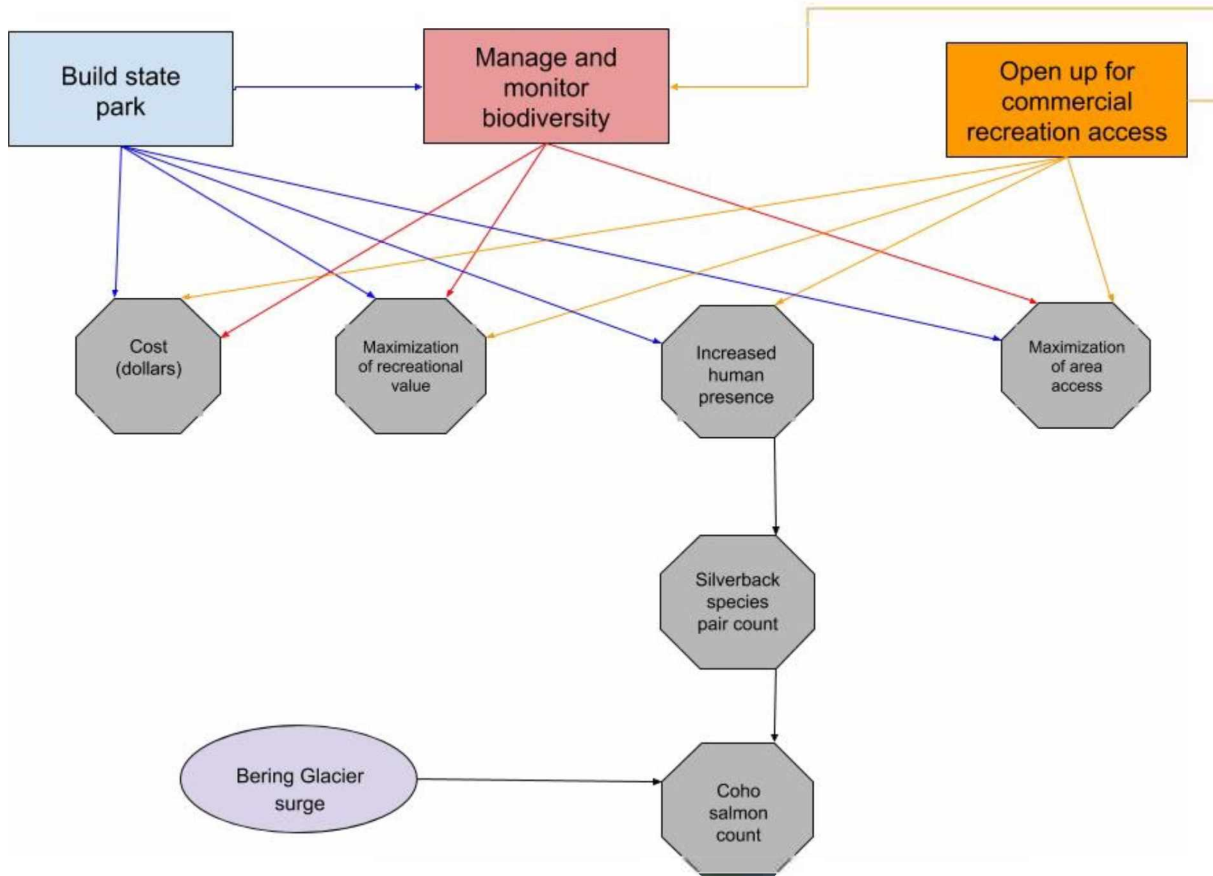

Figure 3.2. Influence diagram of developed alternatives.

Influence diagram depicting the three alternatives considered in this study (boxes), the values considered to help achieve the identified objectives (hexagons), and the uncertainties associated with the decision-making process (oval). Corresponding arrows showing the relationship between the different alternatives and objectives are color-coded accordingly. The uncertainty considered in this study, the Bering Glacier surge, predominantly affects the coho salmon count. We therefore considered it in context of its potential impact on the coho salmon population.

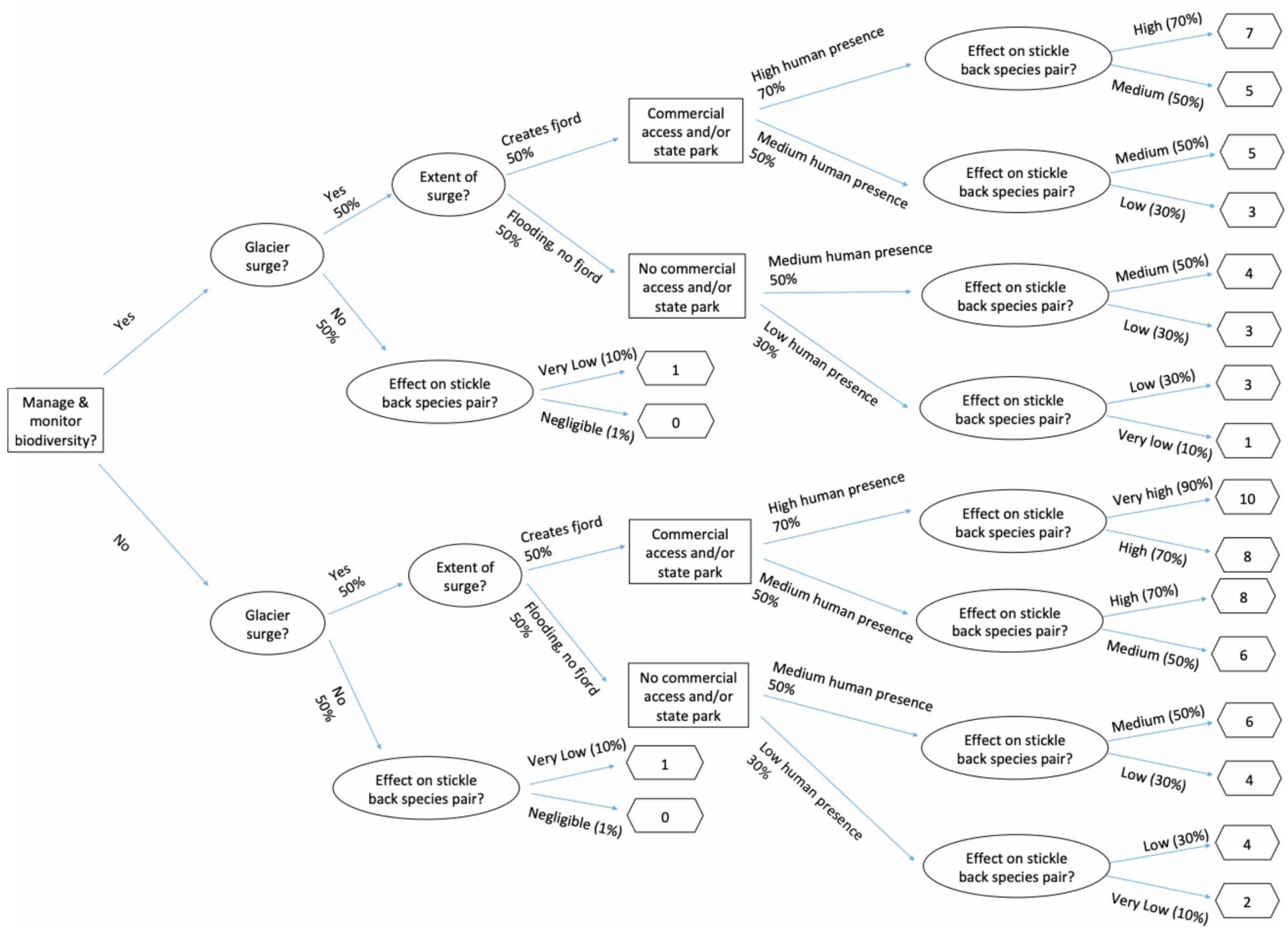

Figure 3.3. Decision tree analysis.

Figure 3.3. (Continued)

Decision tree analysis to assess the expected value of undertaking and not undertaking the *manage and monitor biodiversity* decision. Decisions undertaken in this analysis are represented as boxes. Given that opening a state park and the area for commercial access would both increase the human presence in the Bering Glacier area, they were put into the same decision box to simplify the decision tree analysis. Uncertainties are represented as ovals. Each uncertainty has an upper bound (top arm) and a lower bound (bottom arm) associated with it. The probabilities (percentages) used for each bound were determined based off a review of the literature and state documents. They are meant to signify the potential range of possibilities rather than serve as precise estimates of chance occurrence. Lastly, the outcome assessed in this decision tree analysis, the effect on stickleback species pair, is represented as a hexagon. This is a theorized 10-point scale, where 10 represents the highest negative impact on the stickleback species pair. The scale was determined via a review of the existing literature and state documents. Based on the decisions and upper and lower bounds associated with each set of uncertainties, each outcome reflects the extent to which the management decisions and the associated uncertainties affect the stickleback species pair.

Table 3.1. Identified stakeholders and their ability to affect and be affected by a decision.

Different stakeholder perspectives that were considered as part of this methodological application of structured decision-making. In structured decision-making, the goal is for all stakeholders to work together to reach a common decision. However, it is important to note each stakeholder's ability to affect the final decision, as well as how the decision can potentially impact each stakeholder. Given the small number of stakeholders, and the fact that most identified stakeholders are state or federal agencies, the ability of each stakeholder to affect the final decision was deemed as high for the purposes of this theoretical application. However, we identified that commercial recreational guides might not have as much as weight to affect the final decision, given that the development of a state park and any other land management-related decision would need to ultimately be implemented from the state or federal level.

Stakeholder	*Ability of Decision to Affect Stakeholder*	*Ability of Stakeholder to Affect Decision*
Alaska Department of Natural Resources	High	High
Bureau of Land Management (Alaska)	High	High
US Geological Survey (or other research science group such as the Alaska Division of Geological and Geophysical Survey)	High	High
Commercial recreation guides	High	Low
Alaska Department of Tourism	High	High
Alaska Department of Fish and Game	High	High

Table 3.2. Objectives and measurable attributes of a decision.

Identified objectives for this theoretical application of structured decision-making. The identified objectives were developed based off a review of the literature and state documents. Each objective is classified as either a fundamental or a means objective. Fundamental objectives are objectives that are essential to be met by a decision while means objectives help to achieve fundamental objectives. Measurable attributes were also developed to help quantify the achievement of an identified objective. Scale describes how a measurable attribute is measured and direction refers to whether an objective is sought to be maximized or minimized. All the objectives identified for this study were sought to be maximized.

Objective	*Type of Objective*	*Measurable Attribute*	*Scale*	*Direction*
Continue scientific research of the Bering Glacier area	Means	Number of field campaigns to Bering Glacier each year	Numerical	Maximize
Build scenic value of the Bering Glacier area	Means	Number of state parks or commercial recreational tours to Bering Glacier each year	Numerical	Maximize
Ensure local biodiversity of the Bering Glacier area	Fundamental	Population count of coho salmon and stickleback species pair	Low/Medium/High	Maximize
Strive to better model the next surge(s) of the Bering Glacier	Fundamental	Determination or approximation of next Bering Glacier surge	Yes/No	Maximize

Table 3.3. Initial consequence table.

Initial consequence table developed for this theoretical application of structured decision-making. Each objective, as identified in Table 3.2, is listed along with its measurable attribute and its goal. All objectives were sought to be maximized in this analysis. The three alternatives (see Figure 3.2) assessed in this study were: build state park, manage and monitor biodiversity, and open area for commercial access. A value was determined for each objective, based off the alternative. It is important to note these values are theoretical, however, they are grounded in logical assumptions regarding how each alternative would potentially impact each objective. For example, we sought to measure the achievement of the *continue scientific research of the Bering Glacier area* objective via the number of field campaigns to the Bering Glacier area. If a state park was built or if the area was open for commercial access, we assumed no changes would occur to the number of field campaigns (2). However, for the *manage and monitor biodiversity* objective, we assumed we would see an increase in the number of field campaigns, due to the need to collect observational data for management and monitoring decisions, hence, the assignment of 4 compared to 2 field campaigns. It is important to note the numbers chosen are not an indication of precise measurements but rather, an illustration of the relational differences between the values for each alternative.

		Alternatives (Decisions)		
Objective	*Goal*	**Build state park**	**Manage and monitor biodiversity**	**Open area for commercial access**
1. Continue scientific research of the Bering Glacier area *Measured by: number of field campaigns to Bering Glacier each year*	Maximize	2	4	2
2. Build scenic value of the Bering Glacier area *Measured by: number of state parks or commercial recreational tours to Bering Glacier each year*	Maximize	10	0	8
3. Ensure local biodiversity of the Bering Glacier area *Measured by: Population count of coho salmon and stickleback species pair*	Maximize	Medium	High	Low
4. Strive to better model the next surges of the Bering Glacier *Measured by: Strive to better model the next surge(s) of the Bering Glacier better model the next surge(s) of the Bering Glacier*	Maximize	Yes	Yes	Yes

Table 3.4. Consequence table accounting for irrelevant objectives.

Accounting for irrelevant objectives in the consequence analysis. Irrelevant objectives are objectives that carry the same value across all alternatives and thus can be removed from the analysis since they carry the same weight across all the outcomes. In addition, we converted the values for objectives 3 and 4 (see Table 3.3) to a 10-point scale, with 10 being the maximal value, in order to be able to assess the values for each objective against those of other objectives. One irrelevant objective was found, which was *strive to better model the next surges of the Bering Glacier.* Since this information is important for any management decision related to the Bering Glacier area, we assumed the same value (10) for each the alternatives and therefore removed it from further analysis, as it was deemed an irrelevant objective.

		Alternatives (Decisions)			
Objective	*Goal*	**Build state park**	**Manage and monitor biodiversity**	**Open area for commercial access**	**Notes**
1. Continue scientific research of the Bering Glacier area *Measured by: number of field campaigns to Bering Glacier each year*	Maximize	2	4	2	
2. Build scenic value of the Bering Glacier area *Measured by: number of state parks or commercial recreational tours to Bering Glacier each year*	Maximize	10	0	8	
3. Ensure local biodiversity of the Bering Glacier area *Measured by: Population count of coho salmon and stickleback species pair*	Maximize	6	10	2	
4. Strive to better model the next surges of the Bering Glacier *Measured by: Strive to better model the next surge(s) of the Bering Glacier better model the next surge(s) of the Bering Glacier*	Maximize	10	10	10	**Irrelevant Objective**

Table 3.5. Normalized consequence table.

Normalization of the values from Table 3.4, using Equation 1. Normalizing values helps to ensure that values can be compared across different objectives. Summing the normalized values for each alternative, we arrived at a cumulative alternative score for each alternative. Given the *maximize* goal for each objective, the largest cumulative score would indicate the optimal alternative. The *build state park* alternative was therefore the optimal decision from this analysis (1.67).

		Alternatives (Decisions)		
Objective	*Goal*	**Normalized - Build state park**	**Normalized - Manage and monitor biodiversity**	**Normalized - Open area for commercial access**
1. Continue scientific research of the Bering Glacier area *Measured by: number of field campaigns to Bering Glacier each year*	Maximize	0.11	0.33	0.11
2. Build scenic value of the Bering Glacier area *Measured by: number of state parks or commercial recreational tours to Bering Glacier*	Maximize	1.00	-0.11	0.78
3. Ensure local biodiversity of the Bering Glacier area *Measured by: Population count of coho salmon and stickleback species pair*	Maximize	0.56	1.00	0.11
Cumulative Alternative Score		***1.67***	*1.22*	*1.00*

Table 3.6. Normalized and weighted consequence table.

Sensitivity analysis of the normalized consequence analysis from Table 3.5. Based off our review of the literature and state documents, we found that the seemingly most important objective of land management in the Bering Glacier area is to *ensure local biodiversity*. We assumed a weight of 50% for this objective, to reflect our perceived stakeholder priority. We assumed, also based off our review of the literature and state documents, that the *continue scientific research* and *build scenic value* objectives were equally as important, though with the research interest in the area due to its glacier surge phenomenon, there is slightly more weight potentially for the *continue scientific research* objective. We therefore assigned a 30% weight to *continue scientific research* and a 20% weight to *build scenic value.* Summing the values for each alternative, inclusive of the weights for each value per objective, we found that *manage and monitor biodiversity* was the most optimal alternative (0.58).

		Alternatives (decisions)		
Objective	*Goal*	**Normalized - Build state park**	**Normalized - Manage and monitor biodiversity**	**Normalized - Open area for commercial access**
1. Continue scientific research of the Bering Glacier area *Weight: 30%*	Max	0.03	0.10	0.03
2. Build scenic value of the Bering Glacier area *Weight: 20%*	Max	0.20	-0.02	0.16
3. Ensure local biodiversity of the Bering Glacier area *Weight: 50%*	Max	0.28	0.50	0.06
Cumulative Alternative Score		0.51	**0.58**	0.25

Conclusions

This dissertation consisted of three case studies regarding decision-making and information use for cryospheric hazards in Alaska. I focused on three different cryospheric hazards: GLOFs, sea ice hazards, and glacier surges. My GLOF research took place in two GLOF-affected communities in Alaska, Juneau and the Kenai Peninsula, and my sea ice hazards research took place in Utqiaġvik, Alaska. Both of these research studies focused on how and why information resources and products are or are not used by stakeholders in a hazard context, specifically in flood events related to GLOFs or in a SAR event associated with sea ice. My glacier surge research was a methodology study, in which I tested whether a structured decision-making approach can be applied in a glacier surge context, specifically Bering Glacier, Alaska. The purpose of this methodology study was to investigate whether such an approach could support land and resource management decision-making for the surrounding Bering Glacier ecosystem.

This dissertation research was particularly unique in that decision-making regarding cryospheric hazards is an under-researched topic, despite the variety of human, economic, and ecosystem impacts these hazards have locally and globally. Furthermore, to my knowledge, this was the first time that stakeholder feedback was collected and assessed for specific GLOF and sea ice information products in a cryospheric hazard context, including for a SAR event in Arctic Alaska. In addition, the application of structured decision-making in a cryospheric hazard context has never been done before. The novel approaches presented in this dissertation helped to address the gap in the literature regarding stakeholder decision-making in cryospheric hazards, setting the stage for further research and contributions on decision-making in our changing cryosphere.

Main findings

The three case studies presented in this dissertation had unique, as well as crosscutting findings. Regarding my GLOF research – *The use of glacial lake outburst flood information products by stakeholders in Juneau and the Kenai Peninsula, Alaska* – I found that there is a variety of information products utilized by a variety of stakeholders in a GLOF context in Alaska. Similar information products exist for both Juneau and the Kenai Peninsula, namely due to the monitoring efforts by the NWS and USGS in each location. However, the use of these products varies between the two communities as well as across the spectrum of stakeholders in each community. In Juneau, there is a much broader awareness across all stakeholders of what GLOFs are in addition to what are the available GLOF information products. This can be associated with the public awareness and further monitoring efforts provided by University of Alaska Southeast researchers in Juneau, who conduct intensive monitoring efforts of Suicide Basin as well as provide community outreach and science communication via public talks and local media.

However, on the Kenai Peninsula, although there is perhaps less common knowledge associated with the scientific processes involved in GLOFs, there is a high level of community preparedness regarding their potential impacts. This is partially because the Kenai Peninsula, particularly in the downstream area from Snow Glacier, experiences recurrent high water events. As one interviewee aptly described, it therefore does not matter what is the source of a high water event, whether it is from a GLOF, increased precipitation or snowmelt, the community needs to respond. The only concern with this at-the-ready approach is that should there ever be a compounded GLOF, high water, and/or high rainfall event, the impacts from such an event would be much larger than any high water event seen thus far in the area. There is need therefore to distinguish the potential for more catastrophic impacts due to GLOFs.

One of the most important findings from this research for the scientific community is that stakeholders in a GLOF context want access to more information; scientific uncertainty or potential inaccuracies, as many stakeholders indicated, would not affect their confidence in or use of information products related to GLOFs. Rather, having access to more information, particularly from a long-term forecasting perspective, would be of interest to many stakeholders as it would help them better understand the processes at play, increasing their confidence to respond accordingly to an event. This was an interesting finding, especially as many stakeholders in both communities expressed an interest in learning more about what kind of uncertainties scientists face in forecasting GLOFs, and wanting to see that information incorporated in current and future information products. This can potentially be due to the fact that because GLOFs present hazardous, potentially catastrophic, impacts on their downstream communities, stakeholders want to have as much information as possible in order to feel prepared and able to judge their risks accordingly.

Regarding my sea ice hazards research – *Sea ice hazard data needs for Search and Rescue (SAR) in Utqiaġvik, Alaska* – I found that a number of enabling and challenging factors to information use exist. Compared to the GLOF hazard context, SAR requires immediate decision-making. Time is of the essence in a SAR event and therefore familiarity and trust in an information resource or data product plays an important role in whether it is utilized by emergency responders. Furthermore, some stakeholders – such as the US Coast Guard – are mandated to use specific information products to ensure consistency and accuracy across the organization. However, this can also create barriers for new information products or resources to be readily utilized or readily incorporated into existing processes. Integrating existing knowledge sources is also an important finding from my research, and one that confirms other findings from across the literature (Eicken & Mahoney, 2014; Kettle et al., 2019; Lovecraft et al., 2016; Lovecraft et al., 2013). TLK is an invaluable resource across the Arctic and particularly in Arctic Alaska and Utqiaġvik, community-based SAR responders, many of whom are holders of this knowledge, are the first in-line to respond to a search event. Sea ice hazard events in Arctic Alaska, especially in the nearshore area (~10 km from the coastline), are well understood from a TLK perspective. Collaboration between Indigenous communities and scientists in addition to the braiding of TLK and SAR information products can be very useful for other SAR responders, such as the US Coast Guard, that does not have a local presence in Arctic Alaska. Similarly, scientific information on further offshore areas can support both local search responders and the US Coast Guard in a SAR event. As we see increased sea ice retreat, it is likely that we will also see SAR events occurring further off-shore than typically seen in the past, which calls for potentially new information resources to understand further offshore ice, ocean, and weather conditions and new ways to access these resources as Internet access is currently limited in offshore, Arctic latitudes.

However, in order to have effective uptake of scientific information products for SAR in the Arctic, challenges related to Internet bandwidth and connectivity need to be addressed so that emergency responders can readily access information, particularly during a SAR response. Furthermore, many scientific information products are not ready to be used in a SAR response as-is; most of the university-developed information products analyzed as a part of this research required some level of pre- or post-processing by university researchers to generate the information necessary for the SAR event. Thus, automating these processes, so that SAR responders can utilize this information immediately or readily is important to ensure their uptake and sustained use by emergency responders.

Lastly, I tested the application of a structured decision-making approach to inform decision-making regarding land and resource management in the Bering Glacier area in my glacier surge case study, *Application of structured decision-making in cryospheric hazard planning: theoretical case study of Bering Glacier surges on local state planning in Alaska*. I found that utilizing a structure decision-making approach can be indeed relevant and useful for decision-makers in such a context. The most important finding from this research is how it illuminated that the geophysical processes at play in the Bering Glacier area – specifically, the potential glacier surges from Bering Glacier – are not the most important factors to take into consideration regarding land and resource management decisions for the area. Rather, specific management decisions regarding whether or not to manage the biodiversity in the region are what contribute the most to ecosystem impacts in the area, regardless of a glacier surge happening. This can be a surprising finding for many, where such a potentially catastrophic and uncertain hazard event seems to be what decision-making should be focused on. However, the decision to manage or not manage biodiversity is what ultimately met all the objectives to ensure the sustainability of the Bering Glacier region, even in the event of a glacier surge. One of the main findings therefore from this research is utilizing a decision and risk analysis approach, such as structured decision-making, can potentially help reduce decision-maker immobilization when they are faced with large and uncertain events, such as a glacier surge, in their decision context. This research nonetheless was a theoretical application of a structured decision-making approach and though the findings were conclusive, it is important to validate them with relevant stakeholders to ensure that the findings are indeed reflective of actual stakeholder needs.

In sum, regarding the two research questions (*RQ3.1* and *RQ3.2*) presented in the Introduction chapter in this dissertation, I found that regarding *RQ3.1) does parameterizing scientific uncertainty regarding a cryospheric hazard help a stakeholder in their decision-making*, in the context of the Bering Glacier surge, parameterizing scientific uncertainty regarding a glacier surge event was found to be irrelevant, given the emphasis on maintaining and monitoring biodiversity. In addition, with regards to *RQ3.2) does structured decision-making serve as an effective method to relay cryospheric hazard uncertainty in a manner that is understandable and useable to stakeholders*, structured decision-making was indeed found to be an effective method to incorporate the uncertainty of a glacier surge in a decision-making process.

Crosscutting case study findings

The first set of my overarching research questions for both the GLOF and sea ice case studies sought to understand what are the decision contexts that stakeholders have regarding cryospheric hazards, specifically: *RQ1.1) what are the decisions that stakeholders need to make regarding cryospheric hazards*, *RQ1.2) do these decisions differ by the type of the stakeholder*, and *RQ1.3) whether these decisions also differ by the type of cryospheric hazard*. To address *RQ1.1*, stakeholders need to make decisions prior, during, and after a cryospheric hazard event, as well as gage the probability and likelihood of an event taking place, in addition to develop an understanding of what are the long-term implications and projections of these events. For GLOFs, I found that there was a need for decisions to be made about all three of these contexts while from my sea ice hazards research, the emphasis was more on real-time decision-making, particularly during a SAR event.

Regarding *RQ1.2*, decisions differ by type of stakeholder, based on whether a stakeholder is an information provider or an affected party. Furthermore, within these two types of stakeholders, there are distinct decision differences, based off how closely a stakeholder is involved in or affected by a cryospheric hazard event. I also found regarding *RQ1.3* that decisions do not necessarily differ by the type of cryospheric hazard. Hazards ultimately require decisions that cycle between preparing and responding to a hazardous event. The main distinction I found was that there are different temporal and spatial scales to these decisions, depending on the type of hazard, its proximity to surrounding communities, the rapidity of a hazardous event, and the potential magnitude of its impact.

My second set of research questions was about what factors affect a stakeholder from using or not using a specific information product or resource in a cryospheric hazard context. I found that for *RQ2.1) to what extent does the manner in which information is presented affect the ability of a stakeholder to use a data product or data resource for decision-making*, irrespective of the cryospheric hazard, format and presentation of information were not necessarily barriers to a data product or resource being used. Given hazard potential, stakeholders are more concerned about whether information, in terms of its content, is helpful in their risk assessment and decision-making. There were several anecdotes shared in which stakeholder found creative solutions to understanding and utilizing certain information products, since they found the information content useful but they experienced challenges accessing or understanding it. It was not uncommon for stakeholders in both case studies to develop relationships with key information providers so they could ask them for their help in interpreting information. Several stakeholders across both case studies also mentioned they compile their own databases of information on previous GLOF or sea ice hazard events to keep track of trends.

If life, property, and livelihood are at risk, individuals have greater incentive to understand and interpret information to support their risk preparedness, regardless of how that information is provided. This does not mean that information providers should discount their responsibility for providing information in a format and in a manner that is understandable to a broad audience. Most stakeholders will turn to other sources, particularly to individuals who are knowledge about certain information, and will therefore not use a product if it does not meet their needs or is difficult to understand or access. This finding in particularly addresses *RQ2.2) what conditions drive stakeholders to seek additional information to make a decision and where do stakeholders turn for information in this context* and *RQ2.3) what are specific contexts and conditions that serve as barriers for stakeholders to use a data product or data resource.*

Research limitations and challenges

This research consisted of multiple case studies. Though much depth and insight can be gained from case study research, generalizations beyond the case studies, as well as determining causation between different variables within the case studies, is not possible. Given the uncertainty of when a GLOF will occur, I was not able to conduct a similar longitudinal (2-year) study for my Kenai Peninsula case study as for my Juneau case study since only one GLOF occurred on the Kenai Peninsula over the course of my PhD. Furthermore, small sample sizes for my interviews, particularly for my sea ice hazards research, did not allow for statistical analyses to be conducted. My Bering Glacier case study was also strictly a methodology paper and therefore did not involve stakeholder interviews to validate my assumptions about stakeholder values and priorities. However, my assumptions for my Bering Glacier work were still informed by real-life assumptions, via information found in the literature and multiple official documents on this topic.

Research implications and recommendations for future research

My research shows there is benefit in assessing stakeholder needs as well as their use of information products and resources, to improve cryospheric hazard planning. This research contributed to the literature on cryospheric hazards by utilizing use-inspired science and decision and risk analysis methods, to test the application of these well-established methods in a novel context.

Notably, my research was also applied; findings from my GLOF research in particular helped to inform and support efforts by the US National Weather Service, the US Geological Survey, and the University of Alaska Southeast to refine existing GLOF information products, as well as develop new products. I was able to assess stakeholder feedback in Juneau about these modified and new products. Stakeholders unanimously found they better met their needs. They also appreciated that their insights and feedback were taken seriously and incorporated by information providers. Although this is one case study, it does present a success story for co-production of knowledge regarding cryospheric hazards. This success calls for further research and similar projects to be done in other communities in order to compare results. With more research on co-production between stakeholders and information providers in a GLOF context, we can start to synthesize the similarities, differences, and challenges that exist across different contexts, helping to pave the way for a more generalized understanding of stakeholder information needs across the cryosphere.

In addition, my sea ice hazards research has implications for other Arctic countries that also face potential SAR efforts in the rapidly changing Arctic maritime context. Research on Arctic SAR in Norway and Canada in particular is underway, where joint and tabletop exercises on conducting SAR operations becoming increasingly important on the national front, as well as meteorological researchers and institutions looking into how sea ice and weather information can be better communicated to a broader public (Ford & Clark, 2019; Jeuring et al., 2019; Knol et al., 2018). Though many challenges exist, particularly from a funding perspective, the increased focus on SAR in the Arctic is gaining traction. Arctic SAR is one of the priorities of the Arctic Council's Emergency Prevention, Preparedness and Response (EPPR) Working Group, evident by the legally binding agreement on SAR in the Arctic that was signed into agreement by Arctic Council members in 2011. Given the global and national focus on SAR in the Arctic, more research is needed to highlight the needs and processes that happen on the ground in order to ensure the reality of local SAR is both emphasized and supported.

Lastly, decision and risk analysis is a well-established field of knowledge that is employed across a variety of sectors – environmental and others – to support informed decision-making and to make the decision process transparent, replicable, and accountable (Hammond et al., 2015). My glacier surge case study showed how utilizing such an approach could potentially help decision-makers in the cryosphere hazards space realize previously unidentified objectives, allowing them to take "better" decisions that can serve the fundamental needs of the communities. Structured decision-making and other decision and risk analysis methods help to illuminate hidden but critical objectives, which, without using such a process, may not be met. Further research on utilizing these methods, particularly from a predictive modeling perspective, would be highly beneficial to the cryospheric hazards sector. Increasingly, there is more research on how to parameterize large uncertainty in decision and risk analysis fields (Danielson, Ekenberg, & Larsson, 2020). The cryospheric hazards field would be an excellent area to apply these new approaches for parameterizing large uncertainty, given the range of scenarios regarding the occurrence of cryospheric hazard events but also their magnitude when they do occur.

References

Danielson, M., Ekenberg, L., & Larsson, A. (2020). A second-order-based decision tool for evaluating decisions under conditions of severe uncertainty. *Knowledge-Based Systems*, *191*, 105219.

Eicken, H., & Mahoney, A. R. (2014). Sea Ice: Hazards, Risks, and Implications for Disasters. In *Coastal and Marine Hazards, Risks, and Disasters* (pp. 381–401). https://doi.org/10.1016/B978-0-12-396483-0.00013-3

Ford, J., & Clark, D. (2019). Preparing for the impacts of climate change along Canada's Arctic coast: The importance of search and rescue. *Marine Policy*, *108*. https://doi.org/10.1016/j.marpol.2019.103662

Hammond, J. S., Keeney, R. L., & Raiffa, H. (2015). *Smart choices: A practical guide to making better decisions*. Harvard Business Review Press.

Jeuring, J., Knol-Kauffman, M., & Sivle, A. (2019). Toward valuable weather and sea-ice services for the marine Arctic: exploring user–producer interfaces of the Norwegian Meteorological Institute. *Polar Geography*, 1–21. https://doi.org/10.1080/1088937X.2019.1679270

Kettle, N. P., Abdel-Fattah, D., Mahoney, A. R., Eicken, H., Brigham, L. W., & Jones, J. (2019). Linking Arctic system science research to decision maker needs: co-producing sea ice decision support tools in Utqiaġvik, Alaska. *Polar Geography*, 1–17. https://doi.org/10.1080/1088937X.2019.1707318

Knol, M., Arbo, P., Duske, P., Gerland, S., Lamers, M., Pavlova, O., … Tronstad, S. (2018). Making the Arctic predictable: the changing information infrastructure of Arctic weather and sea ice services. *Polar Geography*, *41*(4), 279–293. https://doi.org/10.1080/1088937X.2018.1522382

Lovecraft, Amy L, Meek, C., & Eicken, H. (2016). Data portals as institutional bridges: Connecting scientific observations to stakeholder needs in sea ice social-environmental systems. *Arctic Observing Summit*, 15–18.

Lovecraft, Amy Lauren, Meek, C., & Eicken, H. (2013). Connecting scientific observations to stakeholder needs in sea ice social–environmental systems: the institutional geography of northern Alaska. *Polar Geography*, *36*(1–2), 105–125. https://doi.org/10.1080/1088937X.2012.733893