Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Karlee Dawn Isfeld

A cross-continent exposition of geohazard risk management strategies

Master's thesis in Geotechnics and Geohazards
Supervisor: Yutao Pan (NTNU)
Co-supervisor: James Michael Strout (NGI)
June 2022

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Abstract

Geohazards are among the top contributors of worldwide disaster consequences and are a growing concern for society with the increase in economic losses through the past 50 years (UNDRR, 2022). Individual and societal risk to geohazards, such as landslides, floods and avalanches, are evaluated and mitigated worldwide on an ongoing basis. The funding for risk reduction is limited, and geohazard mitigations compete with other pressing demands such as day to day operations, safety and expansion of our society.

Traditional engineering identifies, qualifies and quantifies the risk of geohazards. Who is responsible for implementing risk management and setting thresholds? What involvement and education do community members have? How do these answers and techniques differ across nations and regions in relation to policies, guidelines and initiatives? These questions are explored through a cross-continent exposition of geohazard risk management strategies. Three countries, Norway, Canada and Guatemala, are researched through their development of geohazard risk management in terms of policies, guidelines, institutions and initiatives.

Three case studies are presented, one from each country, to explore the geohazard risk management strategies. To simply write about the policies, guidelines and initiatives of geohazard management does not do justice the complexity of the task of implementing such management techniques in practice. The collaboration between experienced practitioners and local authorities, the engagement of citizens, the gaps in the systems which cause inefficiencies or components of the risk management to be overlooked or ignored – these are all details better identified through studying these risk management techniques in practice.

This research explores the contributing factors in managing and mitigating geohazard risk, highlights the commonalities and differences between regions around the world, identifies gaps and opportunities and contributes to the discussion on effectively managing and communicating geohazard risks among risk analyzers, engineers and decision makers.

Key future studies could extend this research to more countries, review the funding and insurance schemes for geohazards in each country and study the compatibility and feasibility of implementing the practices of the United Nations Global Risk Assessment Framework methodology.

Key Words: Geohazards, risk management, policy development, case studies

Sammendrag

Geofarer er blant de største bidragsyterne til verdensomspennende katastrofer som kan gi enorme skadekonsekvenser. Bekymringen i samfunnet for slike farer er økende, ettersom de har ført til en økt trend i økonomiske tap de siste 50 årene (UNDRR, 2022). Individuell og samfunnsmessig risiko for geofarer, som jordskred, flom og snøskred, evalueres og reduseres på verdensbasis fortløpende. Finansieringen for risikoreduserende tiltak er begrenset, og bevilgning av midler til formålet konkurrerer med andre presserende krav som daglig drift, sikkerhet og utvidelse av samfunnet vårt.

Tradisjonell ingeniørvitenskap identifiserer, kvalifiserer og kvantifiserer risikoen for geofarer. Hvem er ansvarlig for å implementere risikostyring og sette terskelverdier? Hvilket engasjement og kunnskap har samfunnsborgerne? Hvordan er disse løsningene og teknikkene forskjellige på tvers av nasjoner og regioner i forhold til politikk, retningslinjer og initiativer? Disse spørsmålene utforskes gjennom en utredning på tvers av kontinenter av risikostyringsstrategier for geofarer. Tre land, Norge, Canada og Guatemala, forskes på gjennom deres utvikling av risikostyring for geofarer når det gjelder policyer, retningslinjer, institusjoner og initiativer.

Tre casestudier presenteres, en fra hvert land, for å utforske ulike strategier for risikostyring av geofarer. Å kun beskrive policyene, retningslinjene og initiativene til håndtering av geofarer rettferdiggjør ikke kompleksiteten i oppgaven med å implementere slike håndteringsmetoder i praksis. Samarbeidet mellom erfarne utøvere og lokale myndigheter, engasjementet til innbyggerne, hull i systemene som fører til ineffektivitet eller komponenter i risikostyringen som blir oversett eller ignorert – dette er alle detaljer som bedre identifiseres ved å studere risikostyringsteknikkene i praksis.

Dette studiet utforsker de medvirkende faktorene til å håndtere og redusere risiko knyttet til geofarer, fremhever fellestrekk og forskjeller mellom regioner rundt om i verden, identifiserer hull og muligheter og bidrar til diskusjonen om effektiv håndtering og kommunikasjon om geofarerisiko blant risikoanalysatorer, ingeniører og beslutningstakere.

Viktige fremtidige studier kan utvide denne forskningen til flere land, gjennomgå finansierings- og forsikringsordningene for geofarer i hvert land og studere kompatibiliteten og gjennomførbarheten av å implementere praksisene til FNs globale rammeverk for risikovurdering.

Stikkord: Geofarer, risikostyring, policyutvikling, casestudier

Preface

This report fulfills the 30-credit thesis requirement for the Geotechnics and Geohazards Master of Science in Engineering degree from the Norwegian University of Science and Technology (NTNU). This thesis was written through the Faculty of Engineering within the Civil and Environmental Engineering Department.

This project is in the scope of the Climate 2050 Center for Research-Based Innovation pilot project at Trollstigen with co-supervision from the Norwegian Geotechnical Institute (NGI) and collaboration with the Norwegian Public Roads Administration (NPRA). Significant contributions were provided by BGC Engineering Inc. (BGC) and the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) Natural Disaster Response division.

Longyearbyen, 2022-06-14

Karlee Dawn Isfeld

Acknowledgements and dedication

A very special thanks to James for taking me under his wing in Norway. Thanks for the mentorship, time in the field, tireless support and thoughtful review. Thanks to NGI for treating me like one of their own and providing a creative and inspiring place for me to write my thesis. Thanks to Yutao for trusting my enthusiasm, always listening intently and giving helpful feedback. To Matt, without you this fruitful web of continents, industry, research centers, academics and consulting would not have been spun. And not only that, but above all else, thanks for being an unwavering friend and mentor along the way. Thanks to Alex and Edy for hours of your generous time, sharing ideas and knowledge, but most of all sharing in my passion to bridge the gap between engineers and decision makers for a safer, more equitable world. Amanda, thanks for taking on the chore of translating my abstract to Norwegian with the same warm welcome you showed me at NGI. And thanks to Tore and Halgeir for being open to my ideas and academic interests. Thanks to the institutions whose commitment to collaboration will undoubtedly improve the safety and wellbeing of our society – NGI, NTNU, BGC, UN and NPRA.

Now lastly to my sister, my biggest supporter. Thank you for the encouragement to take the leap across the ocean, the check-ins along the way and surely the celebration when I return home.

Brighton, this thesis is dedicated to you. Maybe one day you can dedicate your master's thesis back to me.

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List of Abbreviations

ALARP	As Low As Reasonably Practicable
ANCOLD	Australian National Committee on Large Dams
APLL	Annual probable life loss
BC	British Columbia
BC MOTI	British Columbia Ministry of Transportation and Infrastructure
BGC	Bruce Geotechnical Consulting
CERRPED	Empowered Communities in Small Landslide Risk Reduction
CHERP	The Canadian Hazards Emergency Response & Preparedness Research Initiative
CONRED	Coordination of National Reduction of Disasters
DBQ	Directorate for Building Quality in Norway
DSB	Norwegian Directorate for Civil Protection
EFSA	European Food Safety Authority
EGBC	Engineers and Geoscientists BC
FN	Frequency-Number
fN	Probability-Number
GAR	Global Assessment Report
GCMA	Guatemala City Metropolitan Area
GRAF	Global Risk Assessment Framework
HSE	Health and Safety Executive
IDNDR	International Decade for Natural Disaster Reduction
InSAR	Interferometric Synthetic Aperture Radar

INSIVUMEH	National Institute of Seismology, Volcanology, Meteorology and Hydrology
ISO	International Organization for Standardization
MJC	Maximum justifiable cost
NGI	Norwegian Geotechnical Institute
NPRA	Norwegian Public Roads Administration
NRC	National Reconstruction Committee
NRK	Norsk rikskringkasting AS
NTNU	Norwegian University of Science and Technology
NVE	The Norwegian Water Resources and Energy Directorate
OCHA	United Nations office for the Coordination of Humanitarian Affairs
ODA	Overseas Development Assistance
PDI	Probability of Death to an Individual
PH	Annual probability of the hazard occurring
PLL	Probable Life Loss
PLL	Possible Life Loss
PS:H	Spatial probability that the landslide will reach the individual
PT:S	Temporal probability that the individual will be present when the landslide occurs
QC	Quebec
QRA	Quantitative Risk Analysis
RDEK	Regional District of East Kootenay
SDG	Sustainable Development Goal
UBC	University of British Columbia
UN	United Nations
UNDRR	United Nations office of Disaster Risk Reduction
V	The vulnerability, or probability of loss of life if an individual is impacted
VLL	Value of Life Loss
VSL	Value of a statistical life

1 Introduction

1.1 Geohazards: a growing concern for society

The climate is changing. The likelihood, frequency and intensity of extreme weather events are increasing and so are disasters. The number of disaster events are projected to increase at a rate of 40% between 2015 and 2030, illustrated in Figure 1-1 (UNDRR, 2022). The population of the world is growing, and more infrastructure and settlements are being developed in areas of existing hazards, particularly within marginalized populations.

Due to the increase of disaster events and density of population, society will face challenges unseen before. More multi-hazard and compounding events and more socioeconomic stress with less time to recover between events. Now, more than ever, society needs to utilize the interconnectedness to catalyze substantial development in geohazard risk management to prepare for, mitigate against and build back stronger.

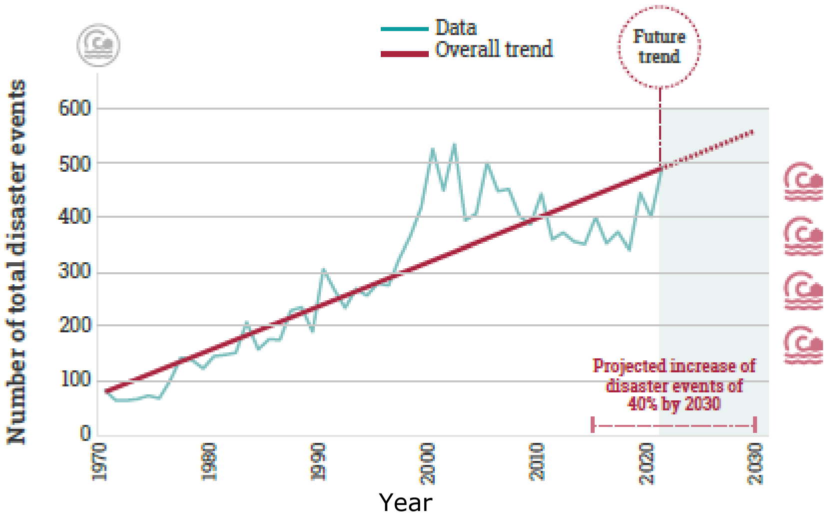


Figure 1-1. Number of disaster events 1970-2020 and projected increase 2021-2030 (UNDRR, 2022).

Through international initiatives and local efforts over the last few decades, society has managed to reduce the number of deaths from disasters in an exponential manner (Figure 1-2). Now, to reduce the increasing economic damages (Figure 1-2) and affected people (Figure 1-3), a shift needs to be made to more efficiently and frequently focus on disaster preparedness, resilience and risk reduction.

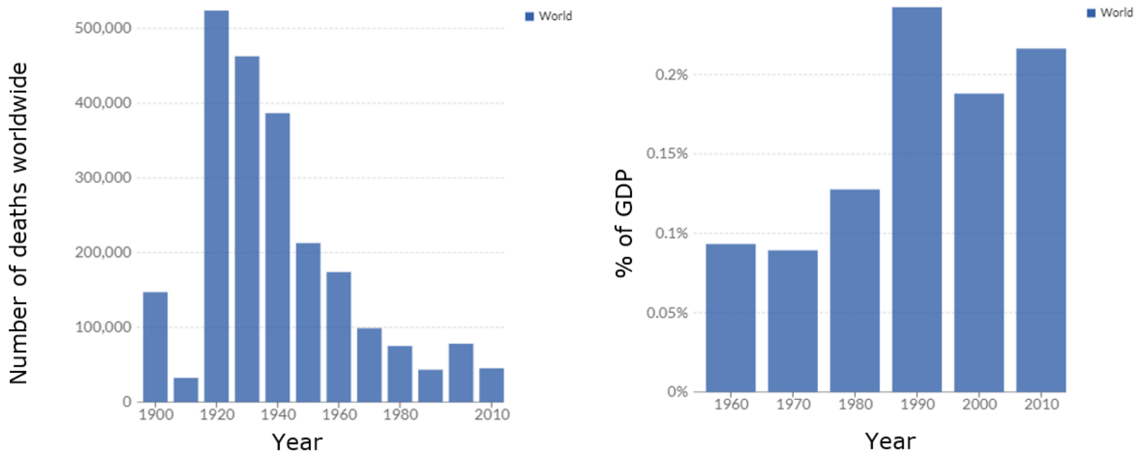


Figure 1-2. Number of deaths and economic damages due to disasters, decadal average. Disasters include all geophysical, meteorological and climate events including earthquakes, volcanic activity, landslides, drought, wildfires, storms and flooding (Guha-Sapir, 2021).

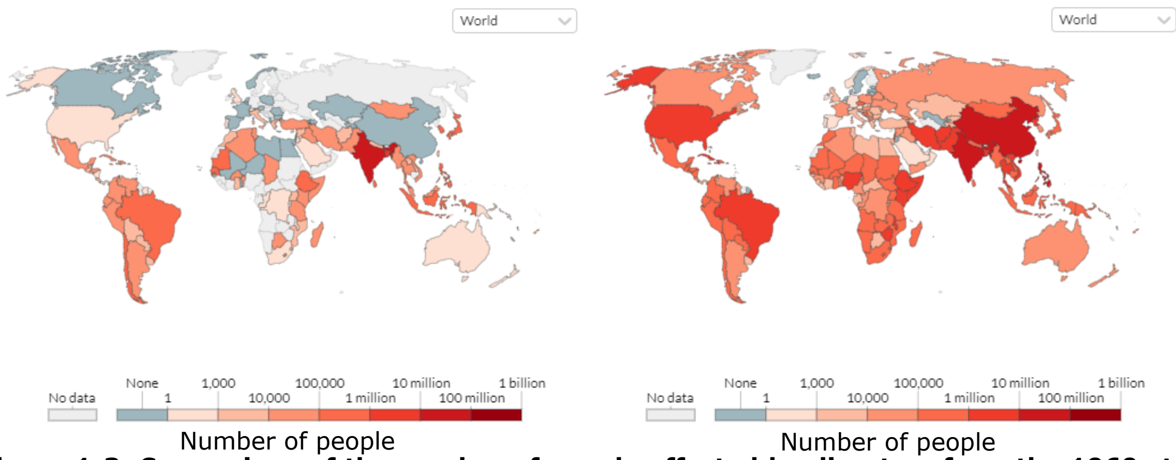


Figure 1-3. Comparison of the number of people affected by disasters from the 1960s to 2010s (Guha-Sapir, 2021).

There needs to be a transition from not only responding to disasters but also creating a society in which communities and nations are prepared for the disasters through monitoring, education and community involvement where communities are reducing their risk by implemented policies and guidelines for new infrastructure as well as prioritizing the mitigation of known risk. Figure 1-4 reveals a stark contrast between the large amount spent on emergency response versus the disproportionately small amount on disaster prevention, preparedness and reconstruction rehabilitation.

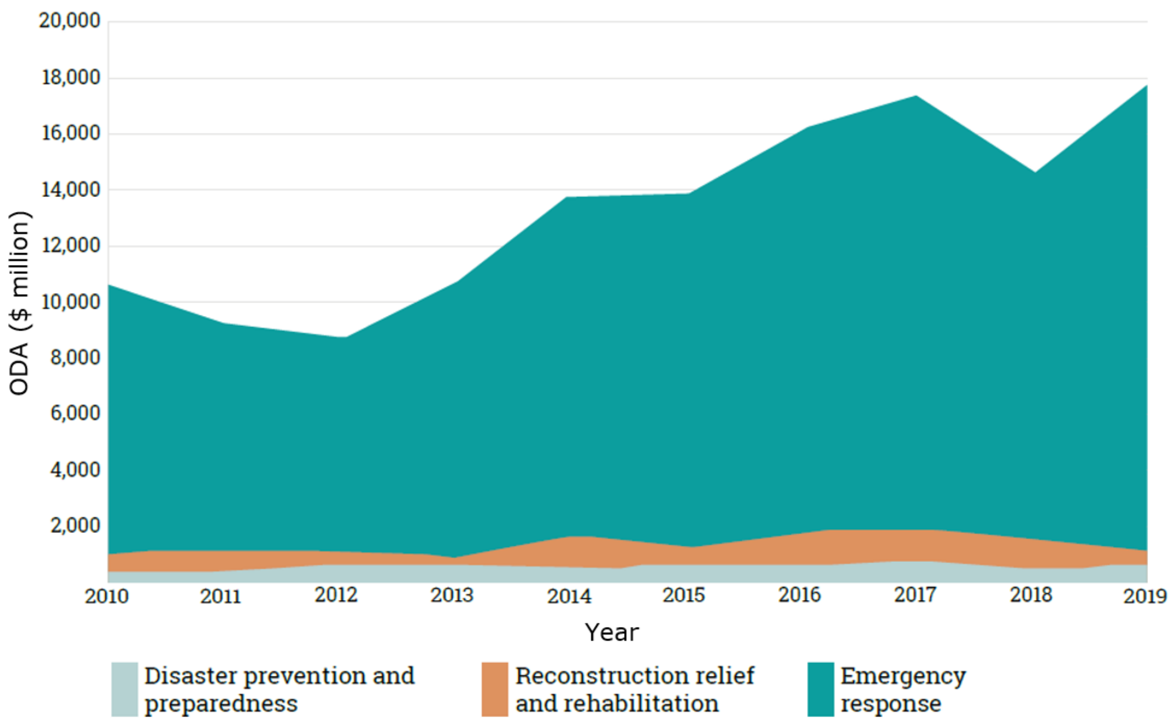


Figure 1-4. Disaster-related financing: Overseas Development Assistance (ODA) for prevention and preparedness, funding for reconstruction relief and rehabilitation and emergency response ($ million), 2010-2019 UNDRR (2022).

1.2 Research objectives

Geohazards are among the top contributors of worldwide disaster consequences that are managed and mitigated on a local and regional basis. There have been books (Anderson and Holcombe, 2013), articles (Fell, 1994), story maps (Humstad and Dahle, 2021) and even video games (Mossoux et al., 2016) attempting to understand and communicate risk of geohazards. Individual and societal risk to geohazards which can cause disasters, such as landslides, floods and avalanches, are evaluated and mitigated worldwide on an ongoing basis. The funding for risk reduction is limited, and geohazard mitigations compete with other pressing demands such as day-to-day operations, safety and expansion of our society.

Traditional engineering identifies, qualifies and quantifies the risk of geohazards. When this information is passed onto decision makers, how does this assessment transform into an understanding of how much should be done to reduce the risk of the geohazard? Who is responsible for implementing risk management and setting thresholds? What involvement and education do civilians have? How do these answers and techniques differ across nations and regions in relation to policies, guidelines and initiatives?

This thesis will explore the questions above and include the following:

- Introduce the concept of geohazard risk management and tell the narrative of the origin and development,
- Summarize common elements in risk management frameworks for geohazards used throughout the world,
- Describe quantitative risk analysis and the difference from qualitative risk analysis,
- Highlight risk evaluation parameters and criteria,

- Outline the possible components of geohazard risk mitigation strategies,
- Review the current state of practice for risk mitigation for geohazards in Norway, Canada and Guatemala including policies, guidelines, and initiatives,
- Highlight the geohazard risk mitigation techniques with case studies from the respective countries,
- Conclude with remarks on the differences of strategies from each country, barriers and challenges of geohazard management in these societies along with strengths and gaps, identify opportunities for cross-region adaptation of methods and practice and lastly comment on suggestions for continuation of research.

This research explores the contributing factors in managing and mitigating geohazard risk, highlights the commonalities and differences between regions around the world, identifies gaps and opportunities and contributes to the discussion on effectively managing and communicating geohazard risks among risk analyzers, engineers and decision makers.

This thesis progresses three sustainable development goals (SDGs) (Figure 1-5). By strengthening geohazard risk mitigation, the number of deaths and people affected by disasters will reduce, contributing to SDG 1: No Poverty. By reducing economic losses and developing resilient infrastructure and communities, cities and communities will become more sustainable, in line with SDG 11: Sustainable Cities and Communities. By creating an exposition of the geohazard risk management techniques of different countries, local and national governments can be inspired to implement geohazard risk reduction techniques that are forward thinking and adaptable to the changing climate, advancing SDG 13: Climate Action.

Figure 1-5. Sustainable development goals addressed in this thesis (UN, 2019).

The report is structured in four chapters such that the reader will gain a deeper understanding of what geohazard risk management is (Chapter 2). Then, the reader will be informed about the current state-of-practice for geohazard risk management within Norway, Canada and Guatemala (Chapter 3) and relate the understanding of geohazard risk management with the state-of-practice through relevant case studies (Chapter 4). Lastly, the reader will explore the discussion of the strengths and challenges of the geohazard management techniques of these countries, ponder areas for improvement on the state-of-practice and review potential future studies (Chapter 5). A summary of the thesis will be given in the final chapter (Chapter 6).

1.2.1 Chapter 2: Geohazard management evolution and background theory

The report begins with a literature review to develop an understanding of geohazard risk management and the intricacies within it. The history of geohazard risk management throughout the world is unfolded. Then, common elements within risk management frameworks are explained step-by-step. Furthermore, multi-hazard risk management frameworks are introduced and how they build upon the general framework first described. Following the risk management frameworks, the difference between quantitative and qualitative risk analysis is presented and details of the quantitative method are highlighted.

Next, parameters for risk evaluation, risk evaluation criteria and risk management strategies are explained. The purpose of reviewing these in detail is first for a more in depth understanding of the components of geohazard risk management, but further to highlight the complexity of risk management and its components. These concepts will be demonstrated within case studies. Since each of these criteria and parameters are debated and evolving within literature, there is reference to key papers and articles which study each of them further, if the reader wishes to explore any particular aspect or concept of risk management in more detail.

1.2.2 Chapter 3: Geohazard management state-of-pratice exposition

Chapter 3 and the following chapters focus on the geohazard management techniques of three nations – Norway, Canada and Guatemala. The countries were chosen, in part, due to the authors connection to and familiarity with them, but also since all three face many compounding geohazards that have caused economic destruction and death to citizens (Guha-Sapir, 2021). In Norway, floods, snow and rock avalanches, earthquakes and quick clay landslides contribute to the most economic and life loss (DSB, 2019). In Canada, earthquakes, floods and debris flows are among the most destructive (Sassa et al., 2013). And in Guatemala, hurricanes, earthquakes, extreme weather and subsequent landslides along ravines are the main culprits (Faber, 2016). These hazards are forecasted to increase in severity and frequency with the rapidly changing climate (UNDRR, 2022). This exposition is not intended to be a direct comparison of these three countries. They all have different mixtures of population density, land size, climate, economics, development and culture.

It would be unfair to assume each of these countries should or could manage geohazards in the same manner – Norway being relatively small in population, Canada being the second largest country in land mass of the world, and Guatemala being a developing nation. It is rather an opportunity to showcase how different societies address geohazard risk management and identify strengths and gaps of each countries' techniques by studying them one next to each other.

The exposition reviews the geohazard management history and state-of-practice for Norway, Canada and Guatemala. It maps policies, guidelines, initiatives and major events each country has in relation to geohazards. The exposition tells the narrative of how these countries have been affected by, and responded to, geohazards through history and the events along the way that have driven geohazard risk management efforts.

1.2.3 Chapter 4: Supporting case studies

To simply write about the policies, guidelines and initiatives of geohazard management does not do justice the complexity of the task of implementing such management techniques in practice. The collaboration between experienced practitioners and local authorities, the engagement of citizens, the gaps in the systems which cause inefficiencies or components of the risk management to be overlooked or ignored – these are all details better identified through studying these risk management techniques in practice.

This chapter will review three case studies from the countries chosen in the exposition above. The Norwegian case study gives detail of the many steps, policies, thorough risk analysis and citizen engagement that the Norwegian approach to geohazard risk management possesses. However, it also highlights the difficulty the local authorities have to allocate funding to geohazards, even when presented with an adverse risk analysis. The study area is a mountain pass in west central Norway with a road that is a national treasure, named Trollstigen in Norwegian, or the Troll's Ladder in English. It climbs with switchbacks up towering rock walls and waterfalls with a constantly busy tourist center at the top.

The Canadian case study will reveal the decentralized decision-making process for risk management that is currently state-of-practice in Canada. The setting for this case study is in the Rocky Mountains of south-western Canada at the Cold Spring Creek fan in the Fairmont Hot Springs community. The case study follows the risk evaluation and mitigation options presented with reference to surrounding communities to suggest thresholds and suitable mitigation.

The Guatemalan case study is a story of motivated, knowledgeable citizens living in unfavourable conditions. Here the policy restricting building near ravines holds little weight, and due to the lack of governing authority, is rarely enforced. The study is located in informal settlements on the margins of the capital of Guatemala, Guatemala City, where even though geohazard risks are threatening homes, the benefits and opportunities being near the city outweigh the risks.

1.2.4 Chapter 5: Discussion on findings and future studies

The discussion and future studies is perhaps the most important chapter. What can be done with the information gathered and the cases studied? What significance does this have in practice? And what can be done next to continue to propel geohazard risk management to cultivate safe and flourishing societies living amongst the hazards in an equitable way?

The discussion will begin with a review of the state-of-practice of geohazard risk management in Norway, Canada and Guatemala. It then analyzes the barriers and challenges the countries face while tackling geohazard risk, calling on the case studies as reminders. Further, areas of improvement for the state-of-practice, both for each country but also taking a step back and looking at the condition of the state-of-practice worldwide.

Future studies are recommended to fill in the gaps of the limitations to the thesis, from research questions that have arose from this study and to carry on the work attained in this thesis.

1.3 Limitations to the thesis

This thesis is limited to provide a general overview of geohazard risk management techniques and criteria, with a focus on risk evaluation and mitigation, not hazard or consequence analysis. The author explains the concepts of geohazard risk management, however it is not in the scope to feature one particular criteria or parameter in fine detail. Papers have been sourced throughout the report for further readings on these concepts and techniques, as well as mentions of niche concepts that were not explained in this report.

The exposition is limited to three selected countries to showcase an array of geohazard management techniques. This is due to the consideration of added value versus muddling the significance of the differences. The author encourages other such expositions to be completed on more sets of countries to identify their gaps and strengthen their risk management strategies.

The case studies of geohazard risk assessment and mitigation are limited to published knowledge. The most pertinent analyses and considerations of each case study are chosen from the reports by the author. The discussion is of the author's own opinions and encourages thought and deliberation from readers.

It is also of note that even though this thesis is interdisciplinary, it is written from the perspective of an engineer, not social scientist, risk analyst or decision maker.

1.4 Fundamental terminology

The terminology surrounding hazards and risk are evolving and adapting to the development of new knowledge and new challenges society faces. The terminology herein is representative of the state-of-practice at the time of this report. It is to be understood these terms are continually refined and debated but were chosen by the author as the most applicable and true for this study.

The terminology used in this thesis is sourced from the Global Assessment Report on Disaster Risk Reduction published by UNDRR (2022) and is consistent with the United Nations General Assembly "Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction", an update of the "2009 UNISDR Terminology on Disaster Risk Reduction" (United Nations, 2016).

A hazard is a process that may cause loss of life, injury, health impacts, property damage, social and economic disruption or degradation to the environment. Hazards can be of single, sequential or combined origin and effect. Each is characterized by the location, intensity or magnitude, frequency and probability. Multi-hazard takes into account the potential interrelated effects of hazards that occur simultaneously, sequentially or cumulatively over time. Hazards span all systems and have, for example, environmental, technological, hydrological, chemical and social origins. In fact, over 300 hazard types that can contribute to disasters have been outlined by UNDRR and the International Science Council (UNDRR, 2020). This report will focus on geological hazards.

Geological or geophysical hazards, called geohazards for the remainder of the report, are hazards which originate from internal earth processes. Some examples include earthquakes, volcanic activity, landslides, rockslides and debris flows.

The vulnerability to an individual, community or system is the physical, social, economic and environmental factors that create conditions that increase their susceptibility to the impact of the hazards. The exposure is when people or infrastructure are located in the areas of the hazards. The capacity is the combination of the attributes and resources available to an organization, the community or society to manage and reduce risk and be resilient. Capacity can include infrastructure, community knowledge and skillsets and social relationships and leadership.

Risk is considered as the potential for impact a hazard may have to a system, society or community in a specific period of time. This is determined probabilistically and is a function of the hazard(s) being evaluated, the exposure, vulnerability and capacity of that which is at risk. A simple illustration of hazard versus risk is in Figure 1-6.

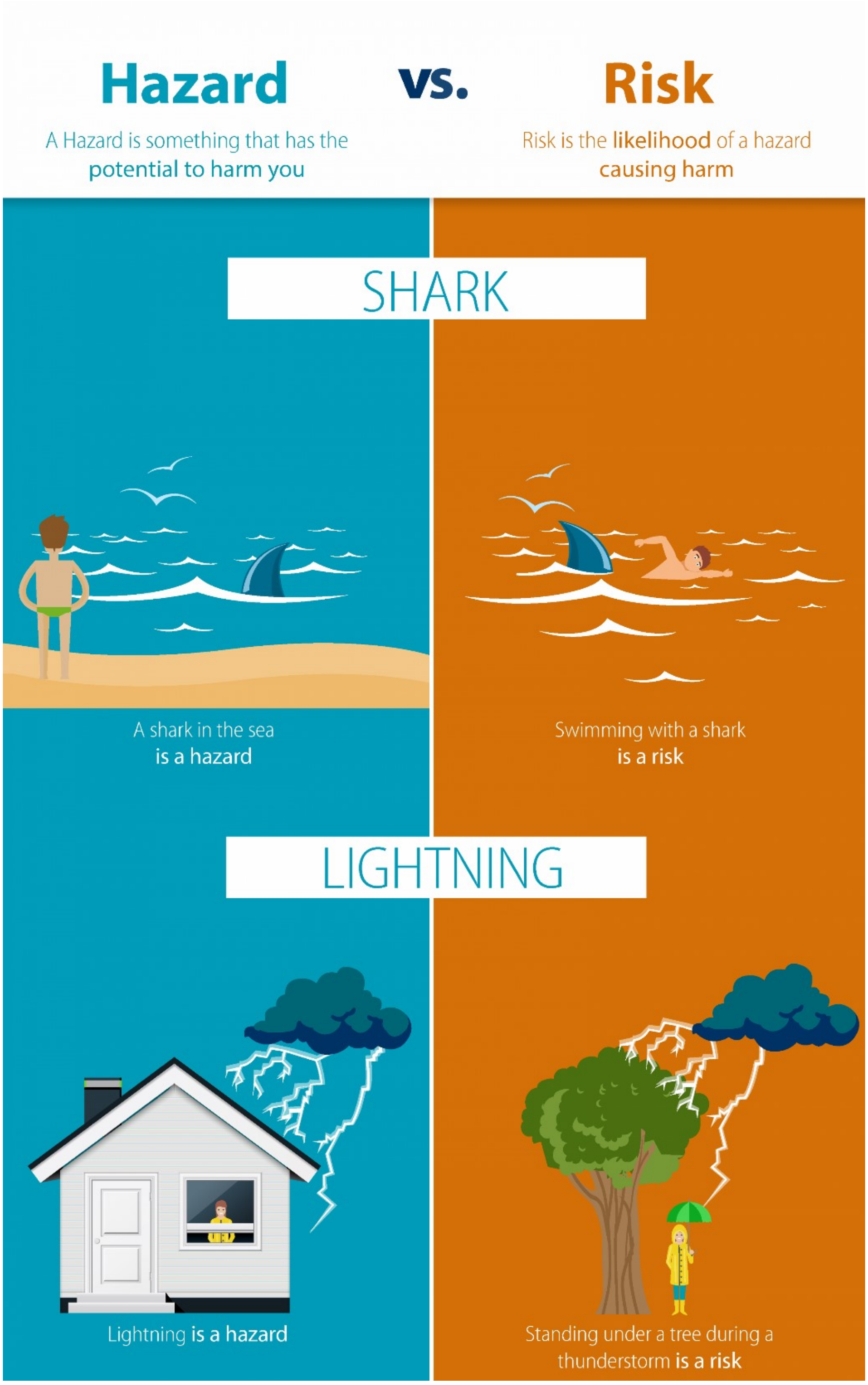


Figure 1-6. Illustration of the concept of hazard versus risk (EFSA, 2016).

A disaster is a serious disruption of how a community or society functions due to hazardous events leading to human, material, economic and or environmental losses and impacts. The effect of the disaster is sometimes immediate and localized, but more often it is widespread and lasts for an extended period of time. The effect may exceed the capacity of the community or society to cope solely with its own resources and may require external assistance. A disaster can result from a geohazard risk event if not mitigated effectively.

The consequence is the result of the hazard affecting the people, infrastructure or society. The consequence can have physical effects, such as losing a home or a road being damaged, but it is important to remember hazards can have economical, social, psychological, cultural and environmental consequences as well.

Here is a simple example scenario of a landslide event to put into real life perspective and solidify the understanding of the fundamental terminology. The hazard, or more specifically the geohazard in this case, is a valley slope that has a mapped debris flow hazard zone fanning out to the flat land at the base of the slope. The vulnerability is there is a community which lives and works at the base of this valley slope. The exposure is the homes and infrastructure are located in the mapped hazard zone. The capacity of this community includes an early warning system to identify if the landslide could be active, information sessions for the community to learn about the potential landslide and be prepared if evacuation was needed and the emergency route plans for evacuation. The risk may be classified as a probability that 100 homes are destroyed in a 1 in 1000-year debris flow event.

The disaster would be the unfortunate event that a 1 in 1000-year debris flow event did indeed happen and surrounding communities were called upon to house the displaced community members and help rebuild the houses in a safe area. The consequence would be the loss of homes, the worry of the community members that they will never be safe and the cultural losses of the community being destroyed. However, due to the preparation and capacity of the community, all lives were saved and they had the funds to build back up their community better.

For further explanation and understanding of this terminology and examples, it is recommended to read the Global Assessment Report on Disaster Risk Reduction by UNDRR (2022).

2 Geohazard management evolution and background theory

2.1 Geohazard risk management origin and development

Geohazard risk management is the act of assessing and mitigating the risk of geohazards regarding society, individuals and the environment. It includes the components of risk assessment, monitoring and reduction.

Quantifying geohazard risk means classifying the probability of an event, which is the hazard, and identifying the degree to which elements are exposed and their capacity and preparedness to react to and recover from a disaster, also known as the vulnerability. Managing and mitigating this risk requires evaluating multiple risk scenarios, identifying the uncertainty of these estimates and comparing risks to prioritize funding and resource allocation.

The importance of risk management for geohazards was highlighted by Casagrande (1965), was reemphasized in the 1980's by Whitman (1984) and became state-of-practice in the 1990's, with publications from around the world addressing the need for risk analysis and management (Fell (1994), Fell and Hartford (1997), ERM-Hong Kong (1998)). In 1994, the United Nations (UN) held a World Conference on Natural Disaster Reduction where they created guidelines for the prevention, preparedness and mitigation of natural disasters (IDNDR, 1994).

Since then, countries, communities, industries and institutions have adopted their own methodologies for evaluating and managing geohazard risk influenced by the culture, severity or frequency of hazards, funding and other competing elements at risk to the population. In 2005, the UN created an updated framework, the Hyogo Framework for Disaster Risk Reduction (UNISDR, 2007). This was created for an increased and more cohesive use in the terminology and methodology within hazard management, focusing on reducing the impact of the hazard (Mizutori, 2020).

Once again in 2015, the UN made an action plan focusing on reducing the risk of disasters, called the Sendai Framework for Disaster Risk Reduction (Sendai Framework). The objectives of the development of the Global Risk Assessment Framework (GRAF), an initiative within the Sendai Framework, are to increase the access and availability of quality hazard risk data and support countries to build capacity and network for hazard risk evaluation, decision making and mitigation (UNDRR, 2015).

The purpose of GRAF is to foster a more integrated risk assessment and decision-making process across systems and industries. The goal is for GRAF to be able to be used in humanitarian efforts, public sectors and private investments to foster collaboration between risk analysts, engineers, the general public, decision-makers, investors and policy makers. GRAF is intended to establish a methodology useable by, and desirable for, all who encounter and make decisions on disaster risks. It is currently in it's formation and pilot phases (UNDRR, 2021).

Despite these efforts to create a common approach, there are still differences on how societies and industries approach geohazard risk evaluation and management, and the tolerability levels of such risks. This literature review is structured such that it introduces common risk management frameworks, details the quantitative risk analysis method, reviews methods used to evaluate geohazard risk and discusses differing perspectives on common risk evaluation tools and their components.

An exposition of state-of-practice of the policies, guidelines, initiatives and thresholds within geohazard risk analysis and mitigation in Norway, Canada and Guatemala follows this literature review. After the exposition, three case studies are presented to highlight the similarities and differences between the countries and give the reader a sense of how these policies, or lack there of, play out in real world scenarios. An analysis of the barriers, challenges and areas for improvement in geohazard risk management are discussed.

The purpose of this literature review is to:

- Give an overview of common risk management frameworks and their components,
- Differentiate between qualitative and quantitative risk analysis,
- Describe in detail the parameters and criteria of risk evaluation,
- Highlight the difference between societal and individual risk assessment and evaluations and
- Outline the current state-of-practice within geohazard risk management.

2.2 Common elements in risk management frameworks

Risk management is an essential part of keeping societies safe, informed and prepared for geohazards. Though many have made iterations of geohazard risk management frameworks they all include defining the scope, assessing and evaluating the hazard, consequence and risk and determining if and how to mitigate the risk (examples in Fell and Hartford (1997), Leventhal (2007), VanDine (2012), Corominas et al. (2014) and ISO (2018)). Figure 2-1 displays a concise risk management framework.

The first step in risk management is identifying what the potential hazard is, what are the key consequences and goals to achieve, who are the stakeholders involved, what are the methods to be used and who is the team who will work together to manage the risk. This description is otherwise described as a scope definition and is essential for successful risk management.

Once the hazard and team have been identified, a thorough analysis of the hazard is to be completed. The available budget and resources likely restrict this portion of the risk management, however typically includes a characterization of the hazard mechanism, then details the frequency, magnitude and intensity of the hazard. The methods used for this analysis differ depending on the region, type of hazard assessment and the policies in place.

After the hazard has been analyzed and the area potentially at risk is defined, a consequence analysis is completed to characterize the elements at risk. These elements could be vulnerable populations, environmental elements or economic risks.

A variety of risk scenarios are then developed and evaluated against risk tolerance criteria. The methods for evaluating risk have been discussed and debated in literature through the years. The estimation of risk through monetary terms (utility-based) is a common method so the risk comparison can span multiple sectors and situations. Equity-based and technology-based methods are also being used. All three of these methods use societal risk and/or individual risk as parameters for evaluation. Detail of these methods and clarification of indices used are in Sections 2.5 and 2.6.

At this stage in risk management, the risk has been thoroughly assessed and mitigation solutions then need to be decided on. This is when mitigation and monitoring options are to be presented and implemented, and the estimation of residual risk is calculated.

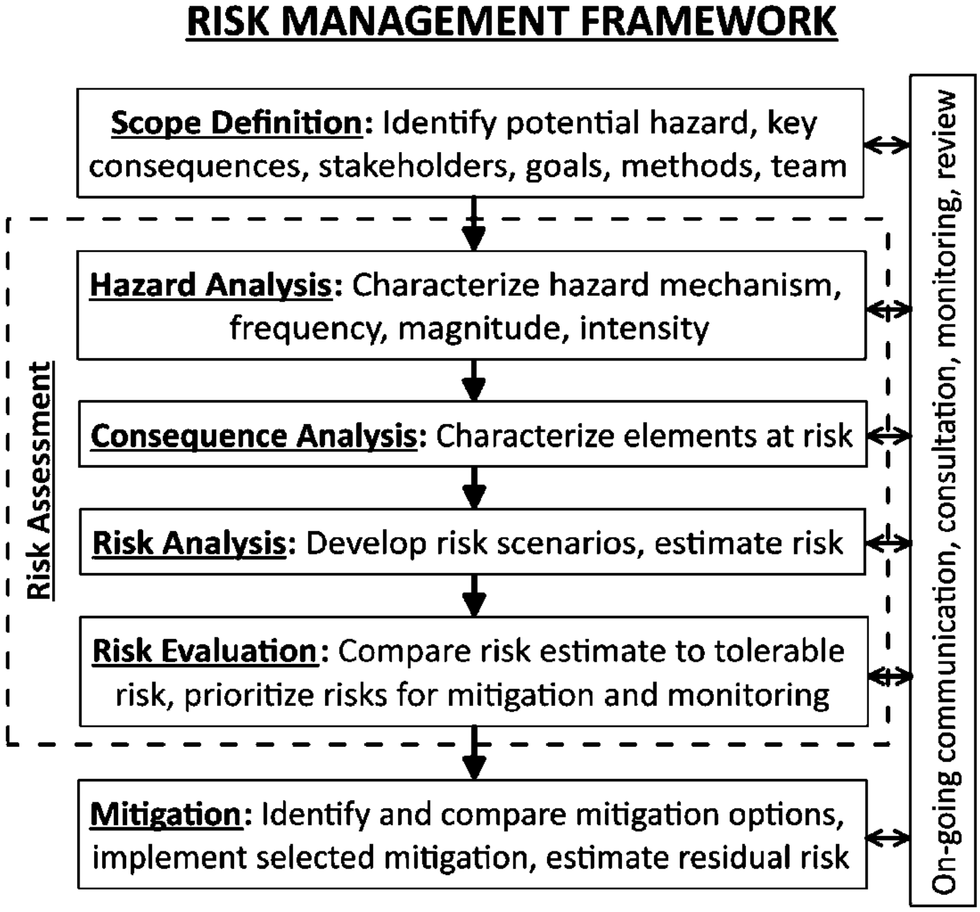


Figure 2-1. Landslide risk management framework (Strouth and McDougall, 2020).

The risk assessment process may be re-evaluated to ensure the mitigation is deemed sufficient for the goals identified in the scope. Finally, ongoing communication, monitoring of the risk and review of changing conditions are vital whenever a hazard is present and has the potential to impact society. Categories of risk management strategies are introduced in Section 2.8.

Following this literature review, a study of three countries' risk management strategies is in Chapter 3. Then, the development and outcome of evaluating geohazards in a risk management framework are displayed through the three case studies in Chapter 4.

2.3 Multi-hazard risk management frameworks

Though the general framework from Section 2.2 is state-of-practice within geohazard risk management, there has been increased awareness for the need of a more wholistic, multi-hazard risk framework to be developed. This was recognized by van Westen et al. (2006), emphasized by Lacasse et al. (2012) and advanced by Corominas et al. (2014) in Figure 2-2.

The main advantages of the multi-hazard framework are the utilization of an inventory of hazards assessed together to understand the overall risk and how the hazards interact with each other. This array of hazards, for example, could be floods, landslides and earthquakes all threatening the same village and how one hazard could influence the probability of the other. This is in contrast to a risk assessment for a single hazard, where compounding risks may not be realized or evaluated. The details of the multi-hazard risk assessment process in Figure 2-2 will not be discussed in further in this study, however can be read in it's corresponding paper by Corominas et al. (2014).

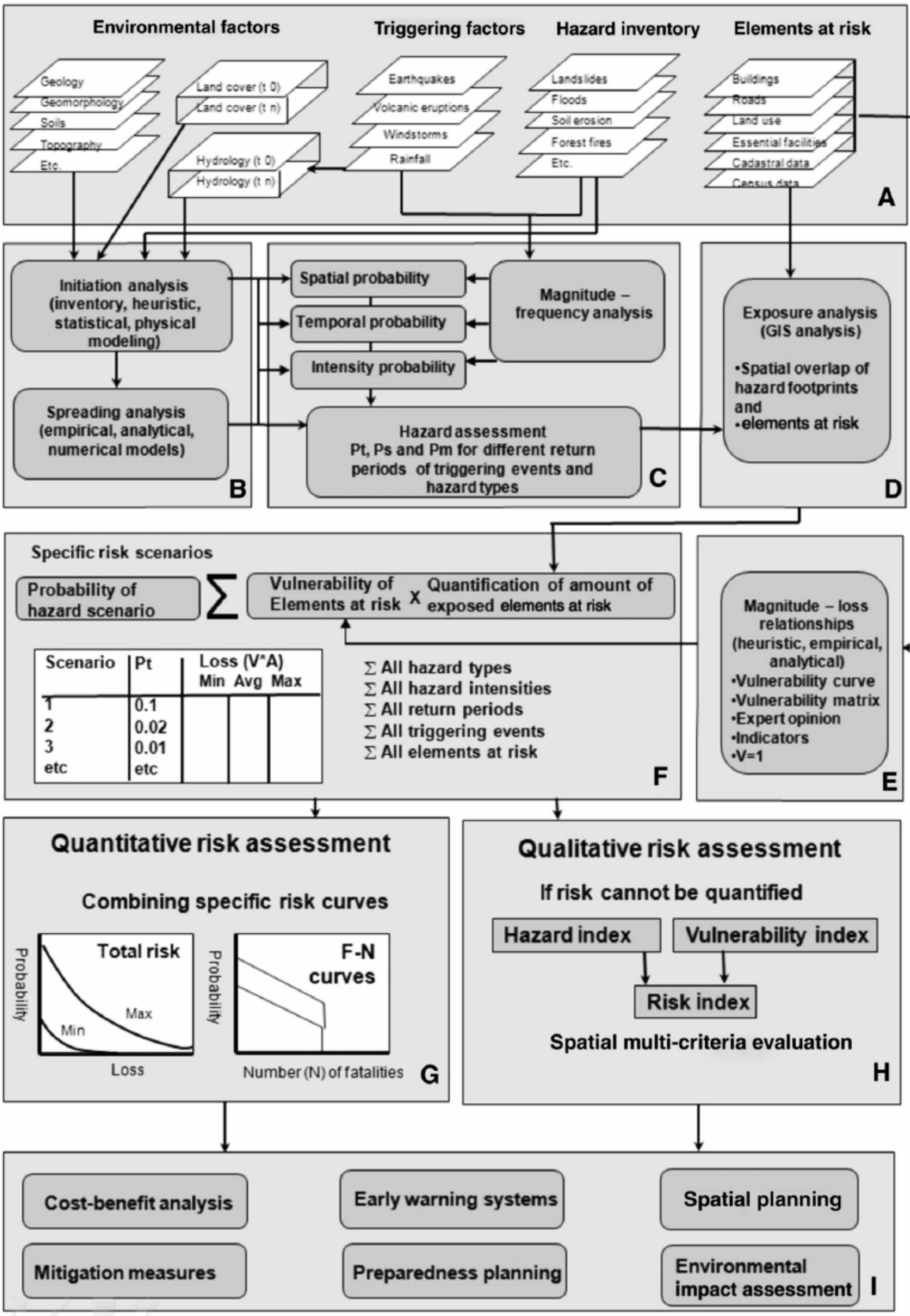


Figure 2-2. Framework of multi-hazard landslide risk assessment (Corominas et al., 2014).

The result of multi-hazard risk analysis framework helps bridge the gap between industries, technical experts and decision makers. It gives opportunity for a wholistic view of the hazards the region faces and the ability to prioritize the hazards and risk areas effectively.

As noted by Mizutori (2020), since the nature of risk is systemic, it is essential to move away from risk management and mitigation for separate components of risk, such as geographical, temporal or disciplinary, and instead move towards using coordinated approaches across sectors and countries. This need is highlighted and addressed in the United Nations office for Disaster Risk Reduction's initiation and development of the Global Risk Assessment Framework (UNDRR, 2015).

The stages of the framework of risk analysis evaluation and mitigation, in terms of methods, criteria and parameters used, will be the focus for the remainder of the literature review.

2.4 Quantitative risk analysis

A thorough analysis and evaluation of geohazard risk is essential to manage the risk from geohazards. Risk needs to be understood in the context of space and time, in other words, the expected frequency or probability of the event, and the intensity or magnitude of such an event. This is needed to understand whether or not the risk is tolerable or acceptable. To do this, a quantitative risk analysis (QRA) must be performed.

A QRA differentiates itself from a qualitative risk analysis by the extensiveness of the procedures used for analysis, the quantity and quality of input data, and the deliverable of the risk analysis. A QRA has the ability to use event trees (Figure 2-3), sensitivity analyses (Figure 2-4), probabilistic simulations to output probabilities, frequencies, magnitudes and impact of risk and specify uncertainties in the analysis (Figure 2-5). This is in contrast to a qualitative risk analysis, which typically uses weighted indices for risk categorization with expert judgement to create a probability impact chart (Figure 2-6). The qualitative risk analysis provides relative rankings of risks to evaluate and manage risks.

Though both quantitative and qualitative risk analyses are beneficial in the overall comprehension of risk and can be performed simultaneously, qualitative risk analysis will not be described further in this study.

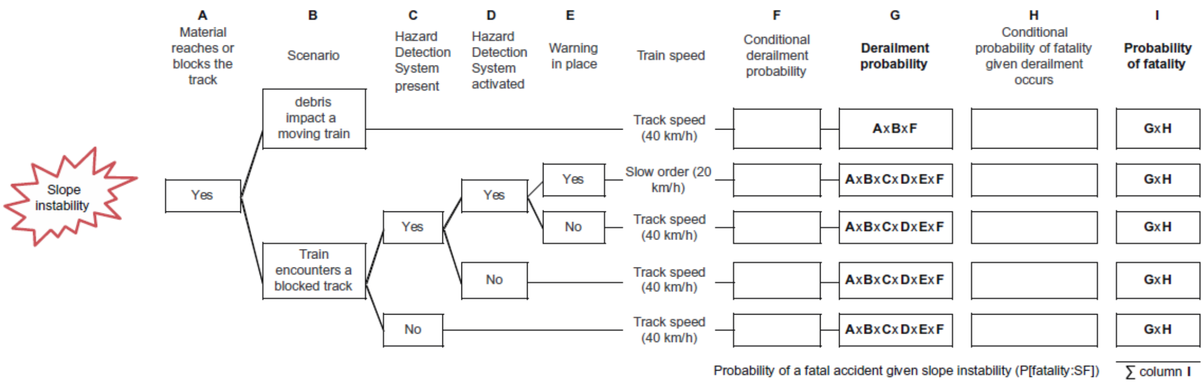


Figure 2-3. Event tree example of a quantitative risk analysis. Used to estimate the probability of a fatal accident given a rock slope instability (Macciotta et al., 2016).

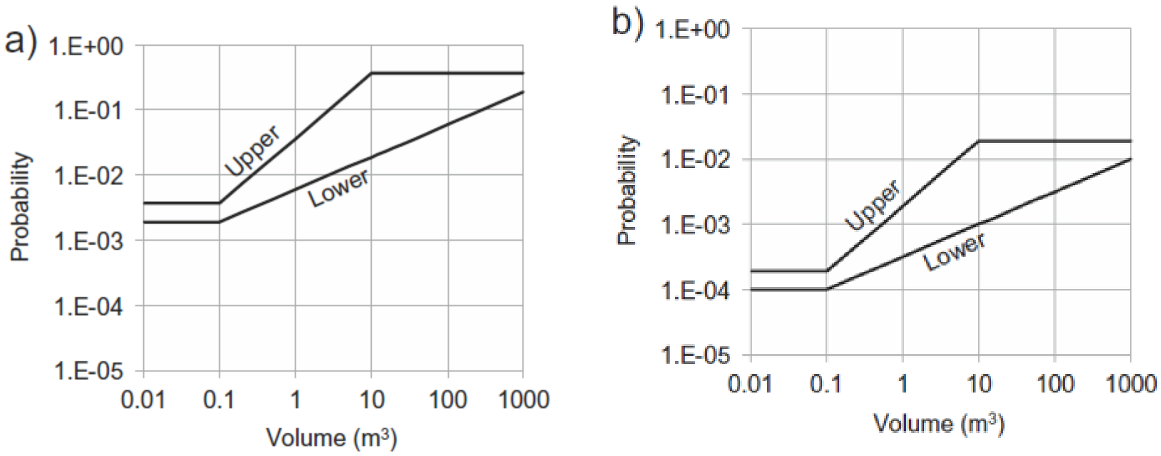


Figure 2-4. Sensitivity of track speed and probability ranges. Subjective probability that derailment occurs after a train reaches a blocked track at a track speed of a) 40 km/hr and b) at a slower order of 20 km/hr (Macciotta et al., 2016).

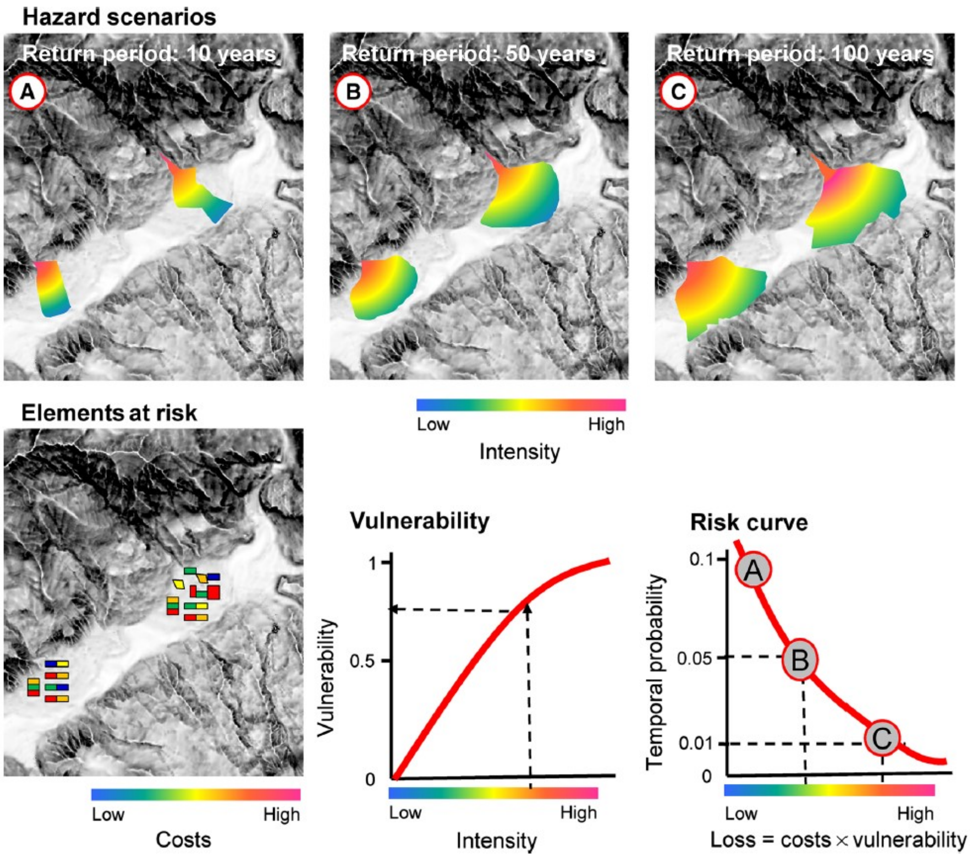


Figure 2-5. Risk scenarios in QRA (Corominas et al., 2014).

Corominas et al. (2014) explains Figure 2-5 further as an,

> Example of a risk curve plotting the temporal probabilities of different landslide scenarios with various return periods against loss. Each of the scenarios yields intensity maps (e.g. of impact pressure). Each element at risk (e.g. a building) is characterised by its type, location and replacement cost. The vulnerability of each exposed element at risk is determined using a vulnerability curve for that particular structural type and the intensity for the particular hazard scenario. The losses are determined by multiplying the vulnerabilities by the replacement costs for all exposed elements at risk. After defining a number of points, a risk curve can be drawn. The area under the risk curve presents the annualised losses.

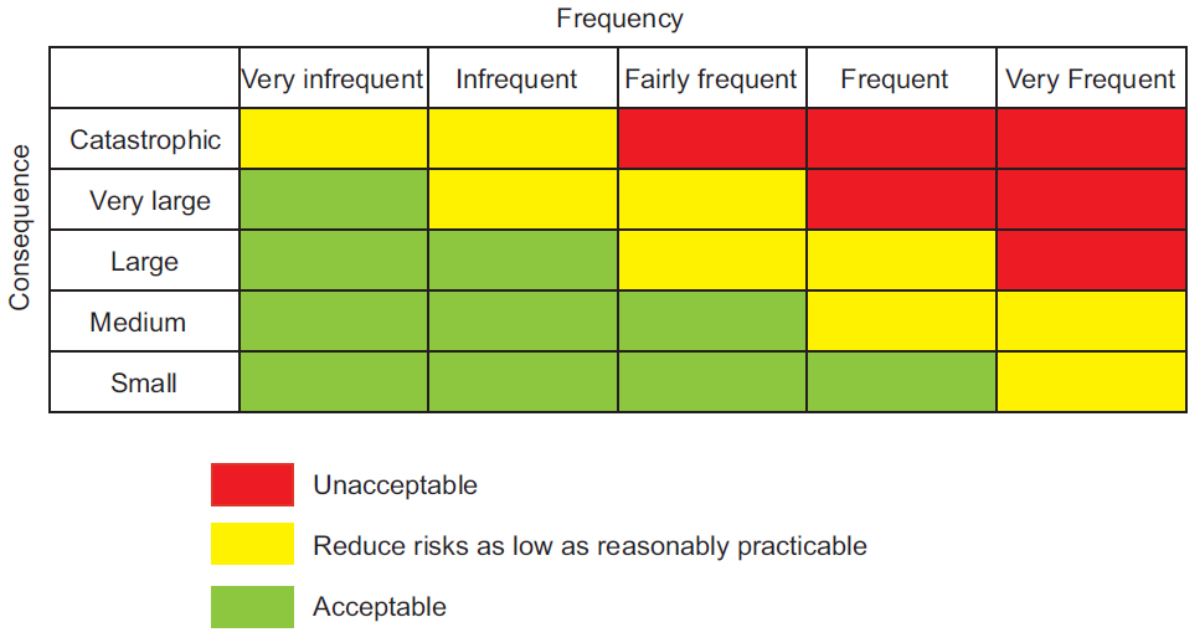


Figure 2-6. Simplified qualitative risk analysis matrix (Johansen, 2010).

QRA is important in managing risk because it grants the ability to evaluate risk in a way that is reproducible and objective. This allows for decision makers to have risk analyses that can be compared to one another from differing hazard locations and differing risk types (for example, the risk to a landslide hitting a car on the road versus the risk of a car crash in an unmarked intersection). Since the analysis is quantitative, cost-benefit analyses of mitigation options can also be performed, compared and prioritized.

In a QRA, the hazard, the exposure of the elements at risk and their vulnerability are essential components that must be considered in geohazard risk analysis. The hazard can be characterized using occurrence and intensity (Corominas et al., 2014) or magnitude and probability (Strouth and McDougall, 2022). Each are varying ways of assessing how large an event may be and how often it could happen. Classifying the geohazard needs high quality input data, including data sources such as geomorphology, soil and rock composition, climate and topographical data. Corominas et al. (2014) provides a comprehensive tabular overview of these classifying factors including descriptions of relevance, their importance to different types and scales of landslides, and whether the factor is a conditioning or triggering factor to the landslide.

Elements at risk include people, infrastructure, economics and services which are described further in the Terminology on Disaster Risk Reduction produced by the United Nations Office for Disaster Risk Reduction (UNDRR, 2009). Within QRA for geohazards, evaluation of the elements could include societal and individual risk and their criteria, cost-benefit analyses to objectify the risk analysis and the debated use of quantifying the value of a statistical life as an indicator of risk and risk reduction. The evaluation of the exposure of the elements of a QRA are described in more detail in Sections 2.5 and 2.6.

The exposure, and the vulnerability of the elements at risk, specify how the element interacts with the hazard. The exposure is the extent of the hazard which the elements at risk are exposed to.

The vulnerability is the specific conditions (physical, social, economic, environmental) which make an element susceptible to being impacted by a particular hazard or set of hazards. Another way of viewing the conditions of vulnerability are the social aspects of vulnerability described as the "capacity of a society to cope with hazardous events" and the physical as "the degree of expected loss in a system from a specific threat" (Lacasse et al., 2012). The exposure and vulnerability can both be classified as the degree or probability of the interaction (Corominas et al., 2014), and are often related to the consequences of the hazard (Anderson and Holcombe, 2013). The interaction and qualities of the hazard, along with the exposure and vulnerability of the elements, set the basis for risk evaluation.

2.5 Parameters for risk evaluation

Societal and individual risk evaluation are common parameters for quantifying risk. Societal risk analyzes the risk to a certain group of people, whereas individual risk evaluates which hazards a particular person could be exposed to. Figure 2-7 is a visual explanation. Societal risk quantifies the potential societal losses as a whole during a geohazard event (or events, in multi-hazard analyses). And individual risk quantifies the risk to an individual for an existing or proposed infrastructure or development (Porter and Morgenstern, 2013). Both types of analyses are used for geohazard risk analysis, however societal risk analysis is more common for high frequency low magnitude events and individual for the opposite. The following sections will review the background theory of societal and individual risk parameters.

A common indicator within risk evaluation and reduction is the concept of reducing risk to as low as reasonably practicable (ALARP). Using the concept of ALARP introduces acceptable, unacceptable and tolerable risk thresholds. Reducing risk to ALARP is often cited within engineering reports and guidance documents, however is frequently interpreted differently. Section 2.5.3 studies the initial meaning of ALARP as well as the different interpretations and uses of the indicator.

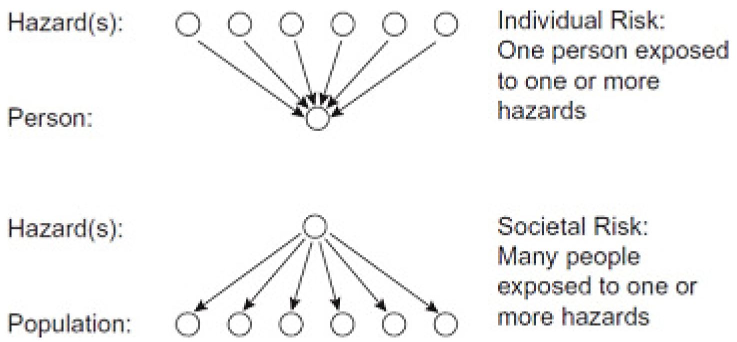


Figure 2-7. Individual and societal risk difference (Crowl and Louvar, 2019).

2.5.1 Societal risk

Societal risk, or a risk to a group of people, is often a concept which considers hazards that could have consequences that initiate sociopolitical responses (HSE, 2001). However, when analyzing geohazards, this is more simply distilled to the relationship between the probability and number of people killed during an event (Strouth and McDougall, 2020).

Frequently in literature societal risk is evaluated using the FN diagram (Figure 2-9), the fN diagram (Figure 2-8) or probable life loss (PLL) (Figure 2-8). This section describes the overview of each technique and gives reference to literature which reviews them in more detail. The Canadian case study in Section 4.2 demonstrates how these evaluation techniques are used together.

The fN diagram plots the probability of a geohazard event (f) against the number of fatalities for that particular geohazard event (N). The scenarios are relative to each other, so even when data is missing or incomplete, or the type of geohazard is different, for example a debris flow versus a rock fall, the fN diagram can still be used for comparing events making it a useful tool for decision makers. From the fN diagram, conclusions can be made on which hazards contribute to the most risk and how much risk reduction can be achieved from mitigation measures.

The probable life loss (PLL) is derived from the result of the fN scenarios. The PPL expresses how many fatalities are expected over a period of time. The PLL for individual scenarios can be summed for total PPL, which is particularly useful for multi-hazard sites where there are compounding hazards or multiple hazards which could affect the same area.

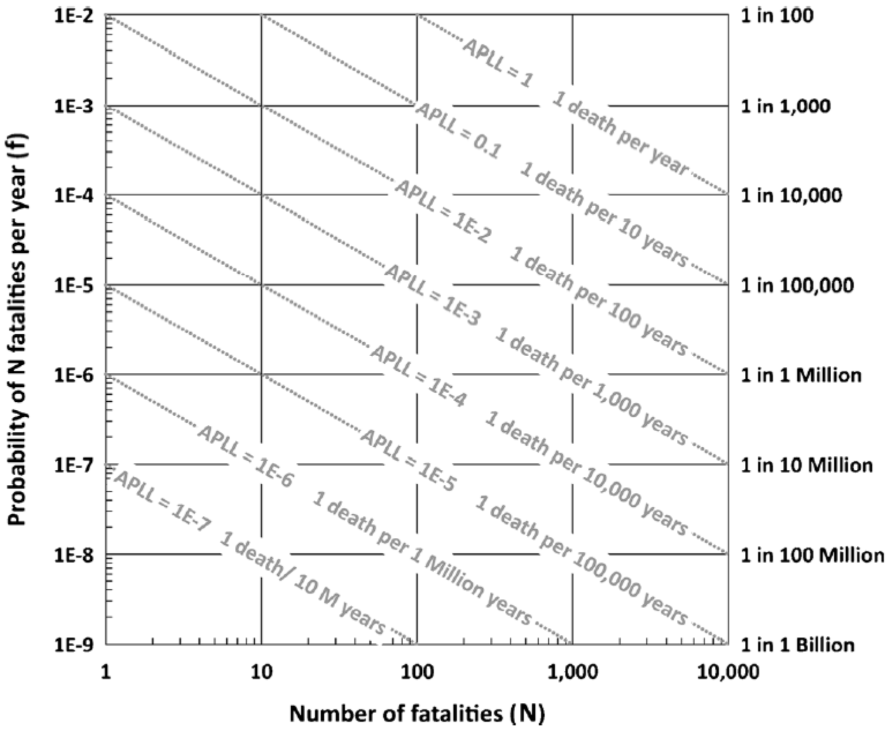


Figure 2-8. An example of an fN diagram with annual probable life loss (APLL) contours (Strouth and McDougall, 2020).

The FN diagram is one of the most used and highly debated risk evaluation techniques in risk evaluation literature and reporting (ERM-Hong Kong, 1998, Lacasse et al., 2012, Anderson and Holcombe, 2013, Strouth and McDougall, 2020). This is much due to the 'ALARP' zone, which is discussed in more detail Section 2.5.3. For now, the general concept of the FN diagram is shared.

The FN diagram relates the probability (F) of causing N or more fatalities. The risk scenarios developed for a hazard can each be plotted on the diagram to create an FN curve. It is noted that the N term can also be interchanged with other measures of consequence such as monetary cost (Lacasse et al., 2012). The FN curve is then used to compare the safety of specified events. The scenarios may be chosen by policy requirements, technical guidelines or site-specific concerns.

In the FN diagram, there are generally four zones with varying thresholds. Unacceptable risk, ALARP, broadly acceptable and the intense scrutiny zone. Many of the thresholds used today have been adopted from ERM-Hong Kong (1998) who were among the first to use the FN diagram for geohazard scenarios. The principles of this diagram are as follows:

1. If a risk plots within the unacceptable zone, they need to be reduced regardless of the cost.
2. If a risk plots within the broadly acceptable zone, no further risk reduction is required.
3. If a risk plots within the ALARP zone, the risk must be reduced As Low as Reasonably Practicable (more on this definition to come in Section 2.5.3) before it is considered tolerable.
4. If a risk plots within the intense scrutiny zone, meaning there is a low probability of the event but high consequence, a detailed study is required and the ALARP principle should be followed.

The FN diagram can accommodate all three risk evaluation criteria: Equity-based, utility-based and technology-based. These are discussed in more detail in Section 2.6. Examples of FN curves and diagrams produced for varying geohazard, industrial and societal risks can be reviewed in Lacasse et al. (2012), Anderson and Holcombe (2013) and Baecher et al. (2015).

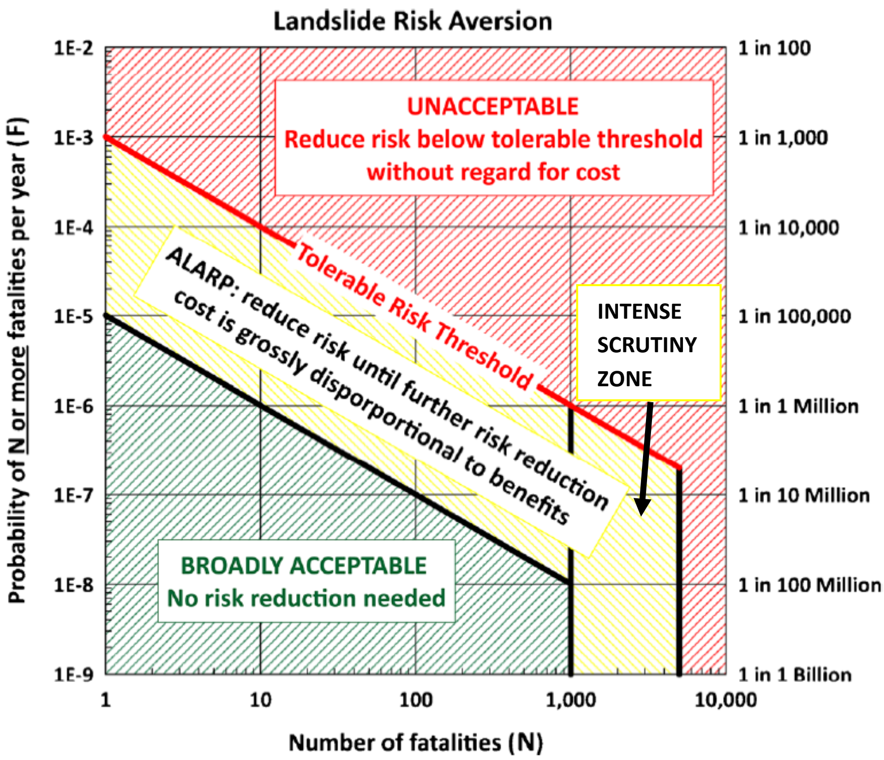


Figure 2-9. FN diagram example with comments for the unacceptable, ALARP and broadly acceptable regions from Strouth and McDougall (2020) with the addition of the clarification of the 'intense scrutiny zone'.

The outcomes of the fN diagram appear similar to the FN, but an important difference is the fN diagram only includes N fatalities per year per scenario, whereas the FN diagram includes N *or more* fatalities and is for a single scenario. Therefore, the data from the fN diagram plots as points, whereas in the FN diagram plot as a curve. A hypothetical example of this from Strouth and McDougall (2020) is in Figure 2-10.

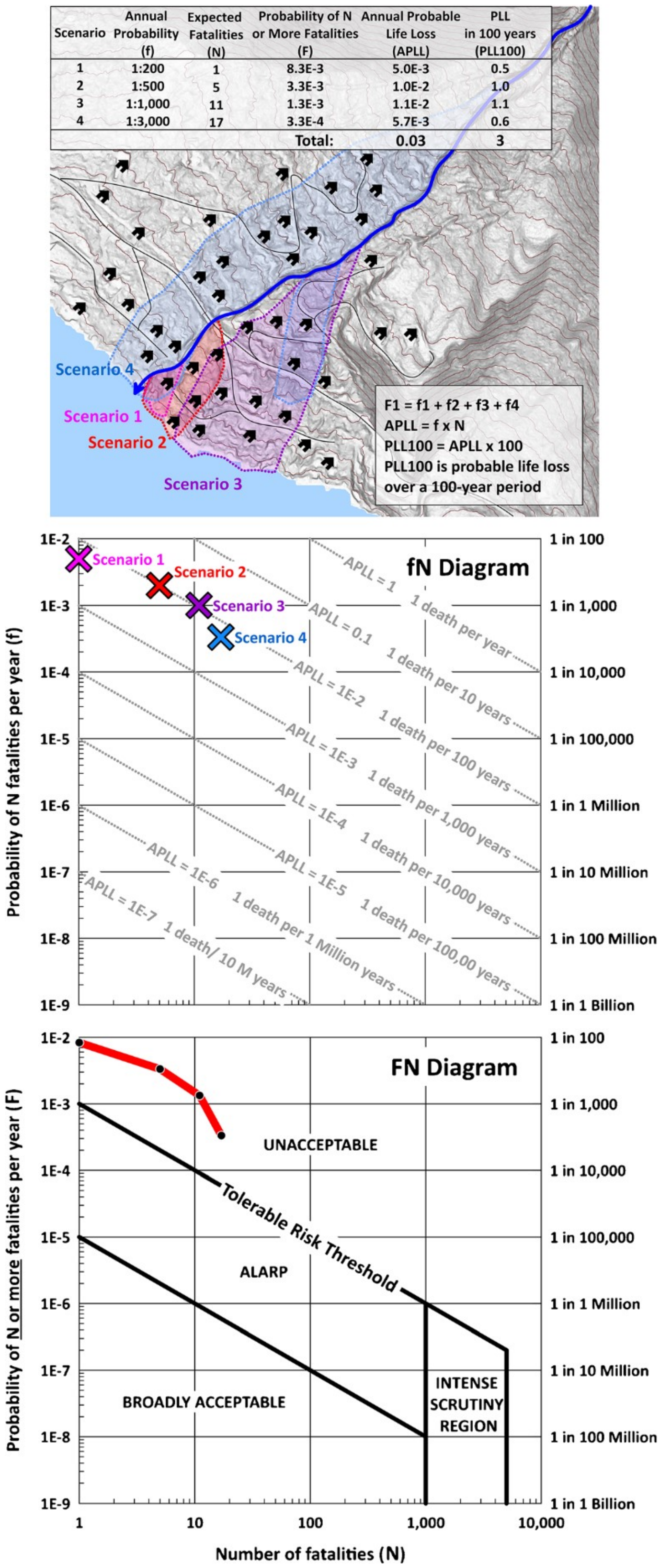


Figure 2-10. Hypothetical example of debris flow risk scenarios plotting in the unacceptable region in the FN diagram (Strouth and McDougall, 2020).

Societal risk evaluations are most appropriately used for scenarios with the potential of causing multiple fatalities. Special care should be given in scenarios of low-probability and high-fatality events as they are harder to quantify and predict. High-probability low-fatality events may be better suited towards individual risk assessments, which is described in the following section.

Further readings for the understanding, application and method of using societal risk evaluation, including suggestions for improving the methods, are available in ERM-Hong Kong (1998), Lacasse et al. (2012), Baecher et al. (2015) and Strouth and McDougall (2020).

2.5.2 Individual risk

While societal risk addresses the potential losses for society from a hazard or multi-hazard event, individual risk addresses the safety of the individuals which are most at risk for either an existing or proposed development (Porter and Morgenstern, 2013).

Individual risk is quantified by considering the exposure of an individual to a hazard. The method of using individual risk evaluation has been frequently explained in literature. This section summarizes the foundational equation and parameters used for individual risk evaluation. Notable papers from Fell et al. (2005), Porter and Morgenstern (2013) and Strouth and McDougall (2022) are recommended for further readings and explanations. The explanation of parameters in the individual risk equation herein are derived from these three sources.

Equation (2-1 is representative for assessing individual risk, from (BGC Engineering Inc., 2021):

$$PDI = \sum_{i=1}^{n} P(H_i) * P(S|H_i) * P(T|S) * V_i \qquad \textbf{(2-1)}$$

where:

- PDI is the risk. More specifically in this case it is the annual probability of death to an individual;
- $P(H_i)$ is the annual incremental probability of a geohazard scenario occurring summed for *n* landslide scenario;
- $P(S|H_i)$ is the spatial probability that the geohazard scenario will reach the facility or area typically occupied by the individual;
- $P(T|S)$ is the temporal probability that the individual will be present in the facility or area when the geohazard event occurs; and
- V_i is the vulnerability, or life-loss potential, if an individual is present when the event occurs.

Both *H* and *S* are parameters of the hazard since they are connected to the geohazard process type, the topography and the geohazard mechanics. *T* and *V* are consequence parameters since they relate to the person at risk and their area or facility they are within. Since individual risk is quantified for the person most at risk, this typically means the person who is the most frequent in the building or the most vulnerable if impacted (for example, a maintenance worker, children or the elderly) (Strouth and McDougall, 2022). For geohazard scenarios that could occur multiple times within a one-year increment, annual frequency replaces annual probability for *H*. An illustration of this equation is in Figure 2-11.

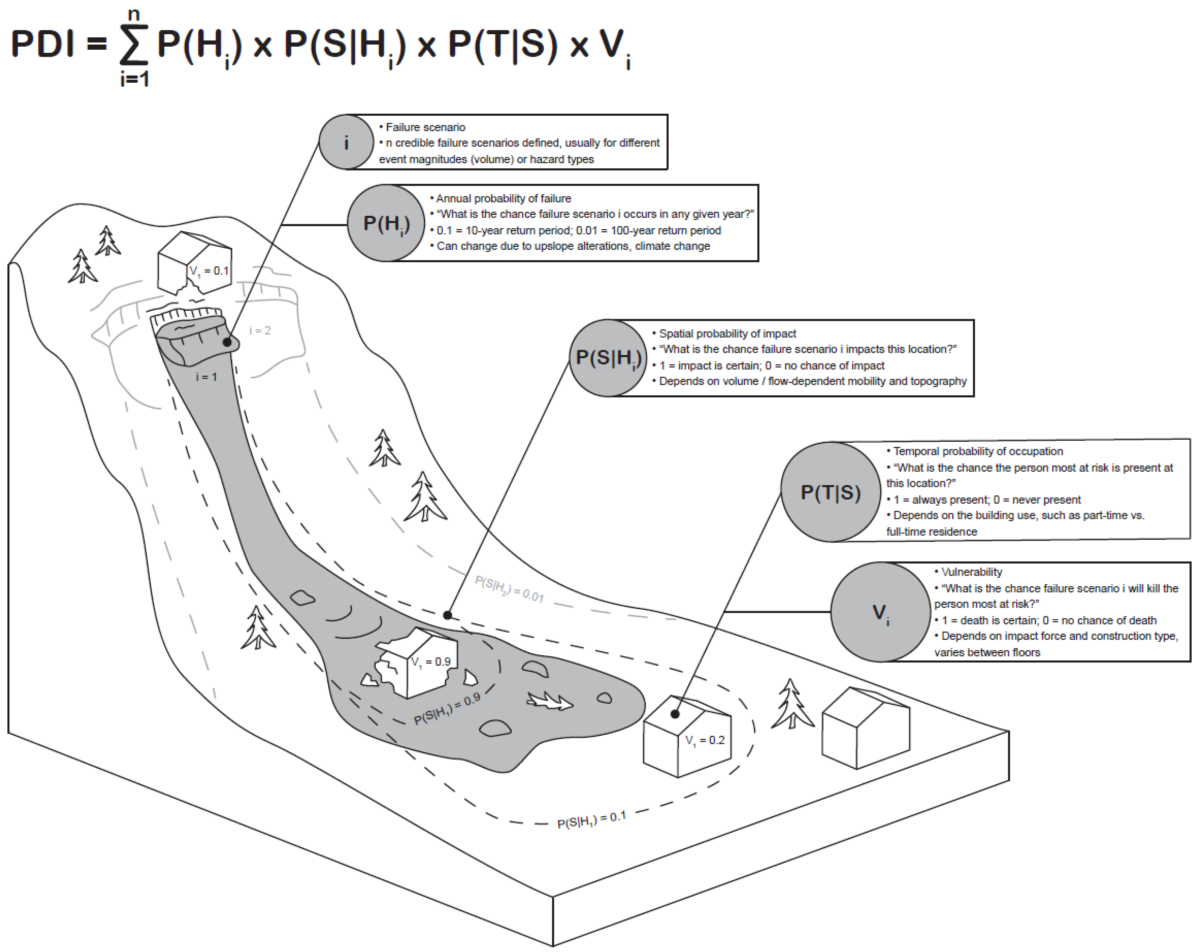


Figure 2-11. Sketch to illustrate the terms of the PDI risk equation (BGC Engineering Inc., 2021).

A complexity is introduced when decision makers must choose individual risk thresholds and guidelines, particularly in relation to other risks society faces (such as car accidents or health conditions) and especially across societies with differing risk levels within their communities. Porter and Morgenstern (2013) and Strouth and McDougall (2022) are great resources for further guidance on how to select individual risk thresholds and how to use them, respectively.

2.5.3 ALARP

Reducing risk to As Low As Reasonably Practicable, or ALARP, was introduced in this paper in the Societal risk section as a parameter for risk evaluation. This parameter was illustrated in Figure 2-9 as a sort of 'grey zone' between broadly acceptable and unacceptable risk. This section will explore the history and meaning of ALARP, how it is applied in geohazard risk management and misconceptions of the term.

The concept of ALARP was first introduced during a case by Edwards v. National Coal Board in 1949 in the British Court of Appeal. The purpose was to assess if the owner of a facility was ensuring the safety of the workers. The result was a ruling stating the risks to workers on industrial sites must be reduced to where the risk is insignificant in relation to the measures (money, resources) needed to reduce the risk further. In other words, ALARP is adopting all measures to reduce risk to the workers except when grossly disproportionate to the level of risk reduced. It is not about weighing the cost and benefits of reducing the risk (HSE, 2001).

This notion of ALARP became state-of-practice when it was integrated into the Health and Safety Work Act in 1974 for the nuclear, chemical and offshore oil and gas industries, then again in 1994 within Railway Regulations (ERM-Hong Kong, 1998). It has been adopted into guidelines on dam safety management (ANCOLD, 2003) and it continues to be applied for the safety of workers within the Health and Safety Executive (HSE) guidelines in the UK (HSE, 2022c).

ALARP was recommended as a suitable means for evaluating and managing landslide risk to areas of new building development in Hong Kong in the 1990s which began it's use in geohazard analyses (ERM-Hong Kong, 1998). The concept was first described in these recommendations where if a landslide risk evaluation fell within a grey zone between broadly acceptable risk and unacceptable risk, then the risk should be reduced until it becomes an "extremely inefficient use of resources" (ERM-Hong Kong, 1998).

Further in these guidelines, the act of applying ALARP is described as reducing risk to what is reasonably practicable implies the costs and benefits should be equal, or the mitigation measure should be rejected (ERM-Hong Kong, 1998). Using ALARP defined as 'cost-effective' has since been used in geohazard management when justifying the risk reduction measures (Macciotta et al., 2016), though Leroi et al. (2005) cautions that evaluating if ALARP has been met should not stray into synonyms for cost effective and tolerable.

In an attempt to correct the misconception on ALARP, HSE published a more detailed guideline on the specifics of how to determine if risk has been reduced to ALARP, including a sensitivity analysis, along with rules of thumb for assessing if the costs significantly outweigh the benefits (HSE, 2022c).

Cost-effective analyses are justifiable, reasonable and necessary in many circumstances for geohazard risk management, but should not used as an indicator of reducing risk to ALARP, based on the intended purpose (HSE, 2022b).

HSE has developed great resources and guidelines for understanding and applying the concept of reducing risk to ALARP, the reader is encouraged to read through these resources and use the interactive webpage of HSE (HSE, 2001, HSE, 2022b, HSE, 2022c). The criteria for establishing the current risk and future risk, when the hazard is mitigated, are reviewed in the following chapter.

To conclude this section, and for clarity for the remainder of the report, here are explanations of acceptable, tolerable and ALARP risk as understood by the author, referenced from literature:

Acceptable risk is "the level of risk loss a society or community considers acceptable given existing social, economic, political, cultural, technical, and environmental conditions" (Anderson and Holcombe, 2013).

Tolerable risk is "a risk that society is willing to live with so as to secure certain benefits in the confidence that it is being properly controlled, kept under review, and further reduced as and when possible" (Anderson and Holcombe, 2013).

The notion of *ALARP* is "about weighing the risk against the sacrifice needed to further reduce it. …the duty-holder must be able to show that it would be grossly disproportionate to the benefits of risk reduction that would be achieved. Thus, the process is not one of balancing the costs and benefits of measures but, rather, of adopting measures except where they are ruled out because they involve grossly disproportionate sacrifices" (HSE, 2022a).

2.6 Risk evaluation criteria

Risk evaluation is defined by Strouth and McDougall (2020) as, "the comparison of estimated landslide risks with available resources and perceptions of tolerable risks to decide what actions, if any, are needed". Risk evaluation criteria are a set of criteria with the purpose of comparing different types of risks with the same measures. They can include risk to society or risk to individuals, and can be economic, environmental, cultural or process risks. More about societal and individual risk evaluation parameters is in Section 2.5.

This section focuses on three common criteria for evaluating risk, as outlined in the book titled *Reducing risks, protecting people* by HSE (2001). These are equity-based, utility-based and technology-based evaluations, illustrated in Figure 2-12. These criteria each function as stand-alone evaluations, however using them in combination gives a more holistic view of risk and risk reduction. This section will review the concept of each criterion and how it applies to geohazard risk management.

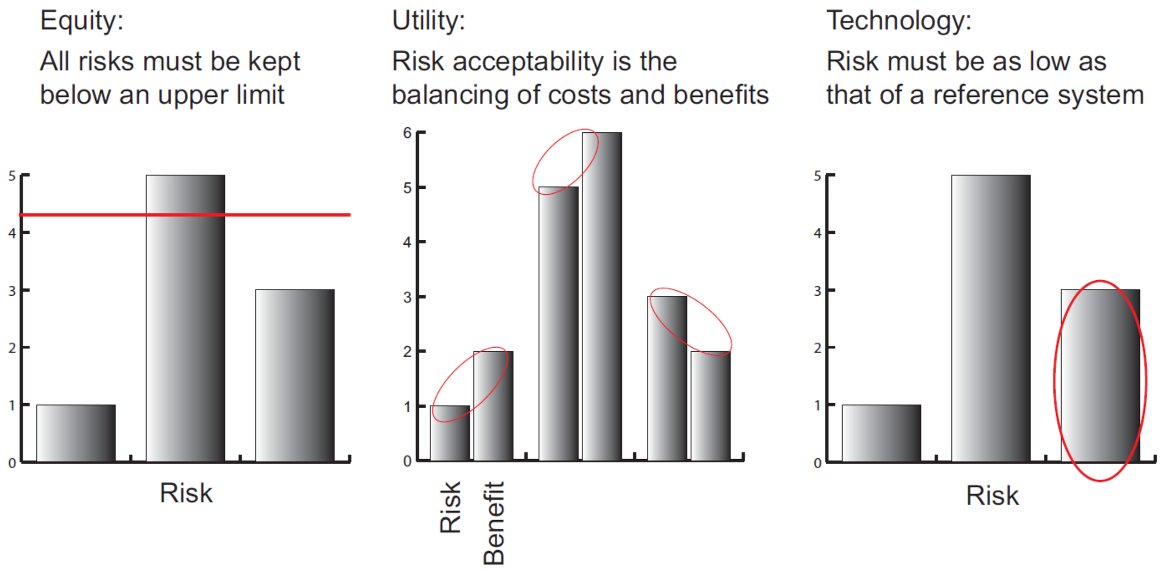


Figure 2-12. Equity, utility and technology criteria, visually explained (Johansen, 2010).

2.6.1 Equity based

The foundation of equity-based criteria is all individuals have the unconditional right to a level of safety. This certain level influences thresholds within policies, and is often considered the upper limit tolerability criteria (HSE, 2001). Risks that exceed this level of risk are intolerable and need to be reduced regardless of the cost.

Equity-based thresholds for geohazards may be established following a review of acceptable hazards for that community, country or hazard type. A disadvantage to using an equity-based criterion on its own is that often this would require decisions to be made on overestimated, worst-case scenarios potentially with little resemblance of the scenario in the real world. Care should be taken to use thoroughly researched and evaluated equity-based techniques for thresholds for broadly acceptable and unacceptable risk zones.

2.6.2 Utility based

Utility-based criteria, simply put, weighs the benefits against the costs. The criteria indicates if, or how much, risk reduction measures are needed based on if the benefits of the risk reduction outweigh the costs of the measures. Costs and benefits are transformed to monetary terms to be compared. This can be evaluated as statistical lives saved or damages avoided. The utility-based method is commonly used for displaying the reduction of risk following a proposed mitigation.

Though this criterion typically focuses on demonstrating the benefits being greater than – or equal to – the costs, as noted by Strouth and McDougall (2020), the balance can be skewed intentionally if using an ALARP approach and to specify gross disproportionality has been achieved.

The utility-based criterion, when used exclusively, ignores the ethical component of risk management decisions and transforms risk reduction into a monetary cost-benefit to achieve. This can be both a strength of this method, where biases are reduced, and also a challenge when ethics are ignored and replaced by performance metrics.

2.6.3 Technology based

Technology-based criteria uses state of practice as a benchmark for risk management, where state-of-practice risk reduction measures are seen as tolerable. Technology-based criteria is often the criteria used for design standards. For geohazards, this could include minimum factor of safety or an event return period (Strouth and McDougall, 2020).

Using the technology-based criterion is a delicate balance between using state-of-practice risk reduction as tolerable and demanding state-of-art management techniques to be implemented. Judgement is introduced when deciding what is state-of-practice and when it advances.

Using any of these criteria in isolation can magnify their challenges and limitations, however using them in cooperation helps build a more thorough understanding of the risk and its characteristics to improve management of the risk.

2.7 Other parameters and criteria

The author acknowledges there are many other concepts and nuances to risk assessment not detailed here. These include human interaction with risk and additional risk parameters and criteria. The purpose of providing background theory was to get an overall understanding of geohazard risk evaluation and its complexities, however not muddle the reader's grasp of these concepts. The parameters and criteria excluded from this study were also done so partly because they are not a main parameter or criteria used in the case studies further along in the paper. There are great papers and resources which focus on these topics and are provided for further study if the reader is compelled to know more about any particular concept.

The perception of risk from society along with acceptance factors of risk are detailed in Wachinger et al. (2010). This notion of voluntary versus involuntary risk which contributes to the acceptance of risk is studied in Porter and Morgenstern (2013) and Baecher et al. (2015). Along the track of risk perception, Slovic et al. (2004) details revealed versus stated preferences of risk.

Progressing from human perception to the quantification of geohazard risk, LaPorte (2018) reviews the importance of background risk. Porter and Morgenstern (2013) calculate and explain partial risk, also known as encounter probability.

In the Societal risk section, the FN diagram was presented with lines of tolerable and acceptable risk. The details of tolerable and acceptable risk and the view on these for society, as well as the development of thresholds can be studied further in VanDine (2012) and Lacasse and Nadim (2011). Detailed analyses and additional factors for risk evaluation and mitigation analyses are factors such as aversion factors (HSE, 2001) and discounting (HSE, 2022b).

If the risk is deemed necessary to be reduced or eliminated once the risk has been evaluated, analyzed and compared against other hazards, risk mitigation strategies need to be implemented. The following section will introduce risk management and review the possible components.

2.8 Risk mitigation strategies

Without risk mitigation, geohazard risk management would have little purpose. Once the risk has been identified, scenarios have been quantified and potential consequences have been acknowledged, risk mitigation strategies need to be implemented. Risk mitigation strategies are classified into six categories, as described by (Lacasse and Nadim, 2011). The six categories are as follows: land use plans, building codes and sound construction practices, early warning systems, community preparedness including campaigns for public awareness, pooling and transferring of risk and physical mitigation measures and engineering works.

The first four mitigation strategies are the focus for Section 3, reviewing the geohazard management strategies for Norway, Canada and Guatemala. The fifth, pooling and transferring of risk, will not be reviewed further in this study, though it is recommended future studies to review the insurance schemes and financial transfer of risk for communities and countries.

There are many competing constraints to risk management and mitigation visually represented by Leroi et al. (2005) in Figure 2-13. These constraints on the decision makers include the regulations placed by governments or institutions, financial resources, the demands from society and political aspirations. These constraints are critical for the success of implementing risk mitigation strategies. Constraints for risk mitigation are highlighted in Section 4 where case studies are presented.

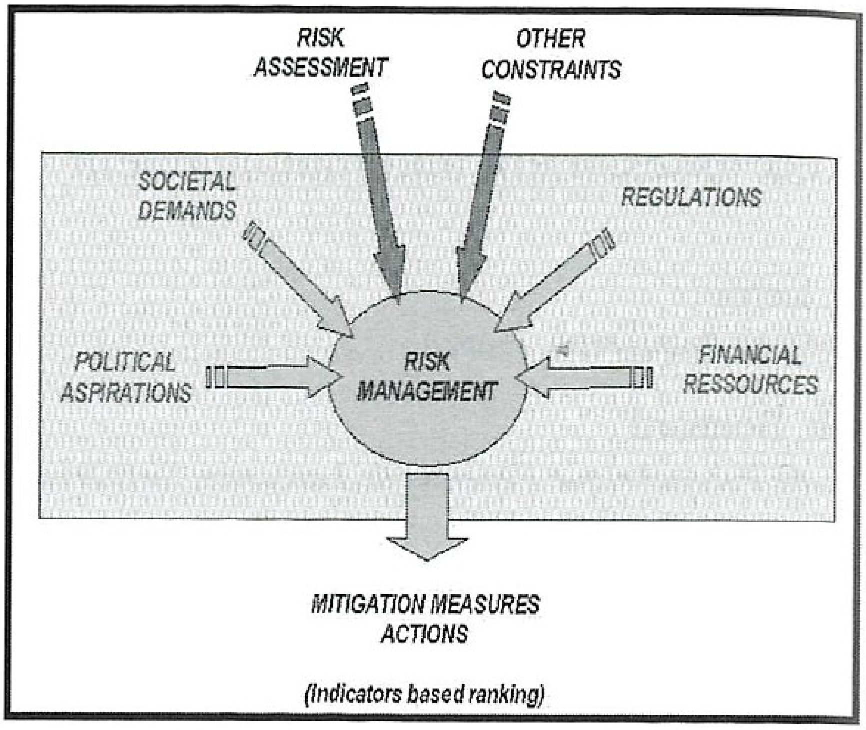


Figure 2-13. The constraints to be taken into account in Landslide Risk Management (Leroi et al., 2005).

These mitigation measures are essential to reduce the economic and societal impact of geohazards as well as turn away from disaster response towards prevention and preparedness. The United Nations and The World Bank (2010) published a book on the economics of effective disaster prevention. In this book the study found disaster mitigation is often possible and cost-effective, though not always obvious. It stresses the point where private and public authorities must work together to accomplish effective disaster prevention. The book concluded with a positive outlook, where though exposure to geohazards will rise as population and hazard frequency rises, this does not have to mean an increase in vulnerability and risk if the risk is mitigated appropriately.

Though this study will review three countries' risk management strategies in detail, the reader is encouraged to read the book on global risk preparedness, edited by Sassa et al. (2013), for examples and inspiration of mitigation strategies from Mexico, Indonesia, Canada, India, West Africa, Croatia, Ukraine, China, Kyrgyzstan, Peru, Japan and Columbia.

3 Geohazard management state-of-practice exposition

The report thus far has introduced geohazard management and studied key concepts relating to the background theory of risk evaluation and mitigation. The origin and development of geohazard risk management was narrated, common elements in risk management frameworks and analysis methods were studied, and the types of risk management strategies were presented. Until now, the paper has been theoretical, and it is time to study it in practice.

This chapter reviews geohazard risk management techniques of Norway, Canada and Guatemala. It discusses the history and state-of-practice of the policies, guidelines, initiatives and major disaster events that have shaped the risk management of each nation. It examines which mitigation strategies outlined in Section 2.8 are practiced, including risk policies, hazard prevention, early warning systems and land use planning.

The author recognizes these three countries could seem quite random and explanation is granted. The countries were chosen partly since the author has connection to and familiarity with them, but also since all of them face many compounding geohazards that have caused significant economic and life losses, which are also predicted to increase with climate change and the increase in extreme weather events.

Another benefit of highlighting these three countries is that each has something unique to offer and challenges they face. Norway is relatively small in population with floods, snow and rock avalanches and quick clay landslides being the main focus in geohazard management (DSB, 2019). Canada is the second largest country in land mass in the world with earthquakes, floods and debris flows among the top contributors of loses (Sassa et al., 2013). And Guatemala is a relatively densely populated, developing nation where hurricanes, earthquakes, tropical storms and secondary landslides are the biggest disasters (Faber, 2016).

All three countries have different compositions of population density, land mass, climate, development and culture that contribute to the knowledge and actions taken to address geohazard risk. A reminder that this isn't a comparison where it would be desired for these countries to have similarities to be able to draw direct comparisons, but instead is an exposition where the purpose is to learn from the experiences and perspectives of each country by studying their risk management strategies side by each.

This chapter tells the narrative of how these countries have responded to and prepared for geohazards through the history and disasters that have driven their geohazard risk management efforts from the 1960s to present day.

The chapter is structured in such a way where the geohazard management strategies of each country are summarized. Then, the sequence of geohazard events and the history and state-of-practice of the policies, guidelines and initiatives of each country are unfolded in timelines and tables.

Further examination of the strengths and gaps of the risk management techniques of each country are in Chapter 5, where a discussion on the analysis is presented and areas for improvement are suggested.

3.1 Geohazard management in Norway

Geohazard management in Norway has been consistently led by governmental organizations and policies. The dominant organizations are the Norwegian Water Resources and Energy Directorate (NVE) who have the operative authority for landslides in Norway (Chiu and Eidsvig, 2016) and the Norwegian Public Roads Administration (NPRA) who has responsibility for the management of geohazards along Norwegian Roads. In addition, the Norwegian Directorate for Civil Protection (DSB) conducts risk assessments for the nation on a yearly basis (DSB, 2019).

The timeline of geohazard risk management in Norway is illustrated in Figure 3-1. Geohazard risk management has been driven by key national building policies with community engagement initiatives and national guidelines scattered throughout. Select geohazard events are added to the timeline and listed in Table 3-1. Corresponding tables associated with the numbering system within the timeline for the policies, guidelines and initiatives are in the following subsections.

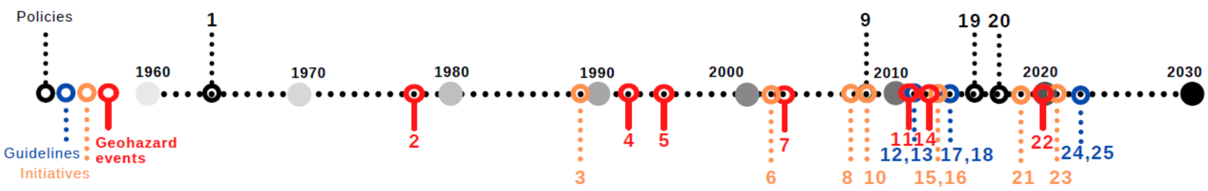


Figure 3-1. Geohazard disasters and the evolution of geohazard risk management in Norway through time.

Table 3-1. Historic geohazard disasters in Norway associated with Figure 3-1.

Timeline #	Year(s)	Name/Type	Source
2	1978	Rissa quick clay landslide	L'Heureux et al. (2012)
4	1992	New Year Hurricane	Eide (2015)
5	1995	Massive flood eastern Norway	Eide (2015)
7	2003	Multiple debris flow events during an extreme weather event	Eide (2015)
11	2011	Flooding in east Norway rivers	Eide (2015)
14	2013	Eastern Norway rivers flooding	Eide (2015)
22	2020	Gjerdrum quick clay landslide	Kalsnes et al. (2022)

3.1.1 Policies

The policy development for geohazards in Norway began with the building act of 1965 which required safety measures to be implemented against natural hazards for buildings and construction works. That policy was followed until 2008 where it was updated to add security classes and thresholds for geohazard events (Norwegian Building Authority, 2017). In 2015, the Directorate for Building Quality restricted development in areas subject to landslides and landslide induced waves (Hungr et al., 2016).

In 2017 technical requirements for geohazard evaluations were introduced for construction and building works (Norwegian Building Authority, 2017). These policies were all implemented at a national level and are consistently used by county and local authorities. A key component of these policies is they only include policies for new developments. There has not yet been a policy surrounding existing developments, unless they are to be altered. The policies corresponding with the timeline are in Table 3-2.

Table 3-2. Key policies for geohazard risk management through time in Norway associated with Figure 3-1.

Timeline #	Year(s)	Name	Contribution	Source
1	1965-2017	Building Act	Require safety measures against natural hazards	Chiu and Eidsvig (2016)
9	2008	Building Act update	Adds security class thresholds for geohazard events	Norwegian Building Authority (2017)
19	2015	DBQ restricted development	in areas subject to landslides and landslide induced waves	Hungr et al. (2016)
20	2017	TEK17	Regulations on technical requirements for construction includes geohazard evaluation	Norwegian Building Authority (2017)

3.1.2 Guidelines

Guidelines in Norway have focused on creating tools to help everyone from county officials to local contractors with implementing the policies. This is done through thematic guides, interactive checklists and guidebooks and have been introduced following geohazard events and as the policies evolved, adding impact assessments, chapters on climate change and guidelines for building on sensitive clay. The details of the guidelines corresponding with the timeline are in Table 3-3.

Table 3-3. Guidelines for geohazard risk assessment and management for Norway associated with Figure 3-1.

Timeline #	Year(s)	Name	Contribution	Source
12	2011	Assessment guidelines	Flood risk and Impact assessment by NRPA	Colleuille and Humstad (2016)
13	2011	Area plans guide	Includes danger for geohazards by NVE	Colleuille and Humstad (2016)
17	2014	Guidelines for risk acceptance criteria	For landslides on the road by NPRA	NPRA (2014)
18	2014-present	Management manuals	For Geohazards by NPRA	Humstad (2020)
24	2022	Guide for geohazard assessment	Revised to include chapter on climate change	DBQ (2022)
25	2022-in progress	Guideline for buildings	On sensitive clays	NGI (2022)

3.1.3 Initatives

Norway has focused efforts on early warning systems, international collaboration and civilian knowledge and empowerment (Table 3-4). Warning systems by NVE have been developed since 1989 including flood warnings and avalanche and danger rankings.

NPRA has created a program called ELRAPP where contractors are trained on geohazard risk and given a tool for registering that risk. A similar system has been developed by NVE called RegObs through xgeo.no, which is an online platform where civilians are guided through the process of registering geohazard events with an online form. This responsibility of recording of events heightens awareness for civilians and creates a wealth of data useable by engineers and risk analyzers.

Table 3-4. Initiatives surrounding geohazard risk management and mitigation for Norway, associated with Figure 3-1.

Timeline #	Year(s)	Name	Contribution	Source
3	1989	Flood warning system by NVE	To better predict and respond to floods	Colleuille and Humstad (2016)
6	2002-2012	International Center for Geohazards	For international collaboration on researching geohazards	VanDine (2012)
8	2007-present	ELRAPP	Geohazard identification, registration, communication and training by NPRA	Colleuille and Humstad (2016)
10	2008	Safeland Europe	To reduce risk from geohazards	Lacasse and Nadim (2011)
15	2013	VARSOM	National avalanche, landslide danger ranking and warning system established	Chiu and Eidsvig (2016)
16	2013	xgeo.no & RegObs	Geohazard observation recording for civilians and NVE natural hazards atlas launch	Colleuille and Humstad (2016)
21	2019	Open-source natural hazard & susceptibility map	Step-by-step geohazard assessment procedure through NVE Atlas	Devoli (2020)
23	2021	International Quick Clay Center	Collaborative project to advance sensitive clay research	NGI (2022)

3.2 Geohazard management in Canada

Geohazard management in Canada has been consistently evolving through the years. Many policies, guidelines and initiatives have been implemented to reduce the risk of geohazards Figure 3-2. However, the majority of these management strategies have been implemented on a regional or municipal basis, and though municipalities are learning from each other, there lacks management requirements at a national scale.

Much of Canada's geohazard management guidelines and initiatives have been driven by consultants and researchers working with communities, governmental organizations and the resource sector.

Corresponding tables associated with the numbering system within the timeline for the policies, guidelines and initiatives are in the following subsections.

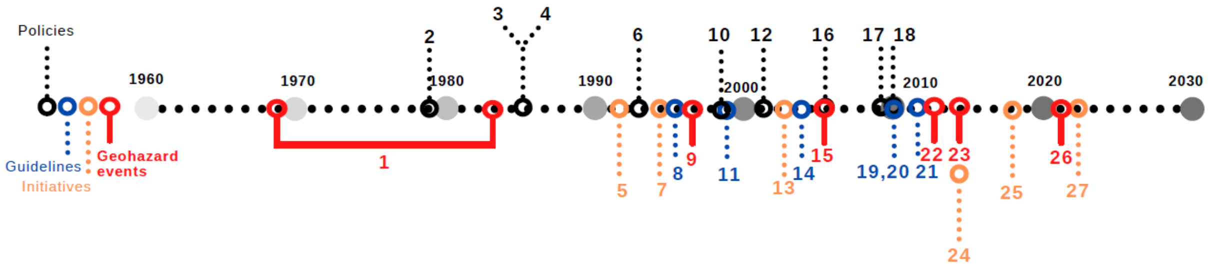


Figure 3-2. Geohazard disasters and the evolution of geohazard risk management in Canada through time.

Geohazard disasters which have encouraged and shaped the risk management in Canada are added to the timeline in Figure 3-2 and presented in tabular form in Table 3-5.

Table 3-5. Geohazard disasters through the years in Canada associated with Figure 3-2.

Timeline #	Year(s)	Name/Type	Source
1	1969-1983	Debris flows along highways in BC	VanDine (2018)
9	1996	Saguenay Region Flooding, QC	VanDine (2018)
15	2005	Extreme rainfall causing flow slide in DNV, BC	VanDine (2018)
22	2013	Extreme rainfall, flooding and debris flows, AB	VanDine (2018)
23	2014	Mount Polley tailings dam failure, BC	Government of BC (2014)
26	2021 – evacuation orders remain ongoing	Prolonged extreme weather causing flooding and debris flows, BC	Clague (2021)

3.2.1 Policies

Building code, land use planning acts, landslide thresholds and policies mandating geohazard risk evaluations have all been implemented in Canada (Table 3-6). However, these are typically at the municipal or provincial levels, driven by disaster events in particular regions. Though the advancements in geohazard management have been state-of-art in Canada, the fragmented policy creation has created an inconsistent way of managing and mitigating geohazards in.

Table 3-6. Policies implemented across Canada for, or including sections on, geohazard risk management associated with Figure 3-2.

Timeline #	Year(s)	Name	Contribution	Source
2	1979	BC Land Titles Act	First Act used as a reference to restrict development in a landslide-prone area	VanDine (2018)
3	1985	National Building Code of Canada	Includes annual probability recommendations for earthquakes and landslides	VanDine (2018)
4	1985	BC Municipal Act	Requires geotechnical investigations for new developments	VanDine (2018)
6	1992	BC MOTI	Establishes acceptable risk criteria	VanDine (2018)
10	1998	Movements of Terrain within Ministry of Transportation, QC	New law to address landslide hazard assessment	VanDine (2018)
12	2001	Ministry of Natural Resources Natural Hazards Policy	Established in Ontario	Porter and Morgenstern (2013)
16	2005	National Building Code of Canada	Includes statement for sloping ground evaluation	Porter and Morgenstern (2013)
17	2009	Landslide risk tolerance criteria	Established for individual risk in District of North Vancouver	Porter and Morgenstern (2013)
18	2010	Landslide Assessments	Legislated for developments in BC	Hungr et al. (2016)

3.2.2 Guidelines

The guidelines follow a similar theme to the policies in Canada (Table 3-7). There are great resources available, but most are for certain industries or regions. This was realized by the technical experts within geohazard management in Canada, and the National Technical Guidelines and Best Practices on Landslides was developed from 2010-2016 in response (VanDine, 2018). These guidelines offer resources, processes and thresholds for geohazard risk reduction in Canada. The guidelines are typically used by consultants contracted by municipalities to manage their geohazard risk.

Table 3-7. Guidelines established to enhance the quality of geohazard risk management in Canada, associated with Figure 3-2.

Timeline #	Year(s)	Name	Contribution	Source
8	1995	BC Ministry of Forests Mapping and Assessing Terrain	Slope stability guidebook	VanDine (2018)
11	1997	Canadian Standards Association Risk Management Guideline	Established risk standards for decision makers	VanDine (2018)
14	2004	City of Ottawa Slope Stability Guidelines	Established for development applications in Ottawa	Porter and Morgenstern (2013)
19	2010	EGBC guidelines	Includes seismic slope stability	VanDine (2018)
20	2010-2016	National Technical Guidelines and Best Practices on Landslides developed	First national guidelines for geohazards	VanDine (2018)
21	2012	EGBC Professional Practice Guidelines	For legislated flood assessments in a changing climate	VanDine (2018)

3.2.3 Intiatives

In the earlier years, the initiatives in Canada had focused efforts on international collaboration and initiatives within resource sectors (Table 3-8). In 2014, following the major flooding in Alberta, the shift focused towards engaging community members to better prepare for, prevent and respond to disasters (VanDine, 2018). The Canadian Hazards Emergency Response and Preparedness Research Initiative has developed out of the University of British Columbia (UBC) and is in its pilot phases. This project, and projects like these, will be instrumental in helping citizens be aware of and take action on geohazard management.

Table 3-8. Initiatives across Canada to increase awareness and management of geohazards, associated with Figure 3-2.

Timeline #	Year(s)	Name	Contribution	Source
5	1991	Geological Hazards in British Columbia	Workshop to educate about and collaborate on geohazards	Porter and Morgenstern (2013)
7	1994	Terrain stability classes	Established for BC Ministry of Forests	VanDine (2018)
13	2003-2018	Railway Ground Hazard Research Program	To advance management and mitigations of geohazards on railways	VanDine (2018)
24	2014	Canmore focus group	For affected and non-affected residents post floods	VanDine (2018)
25	2018-2023	Disaster Mitigation and Adaptation Fund	Established by the federal government	Infrastructure Canada (2021)
27	2022	The Canadian Hazards Emergency Response and Preparedness	Research initiative for community awareness and response to geohazards	Reynolds (2022)

3.3 Geohazard management in Guatemala

Geohazard management in Guatemala has been mainly driven by disaster events, as illustrated in Figure 3-3. Geohazard management began as a reactive response but is slowly evolving to proactive initiatives to reduce the risk to individuals and society within Guatemala. The lack of policy development is evident within the timeline, which could be attributed to the high corruption index and low government effectiveness in implementing policies (European Commission, 2022). However, decentralized institutions have taken leadership in managing geohazard risks and community members are contributing to the reduction of geohazard risk in Guatemala (LaPorte, 2018).

Corresponding tables associated with the numbering system within the timeline for the policies, guidelines and initiatives are in the following subsections.

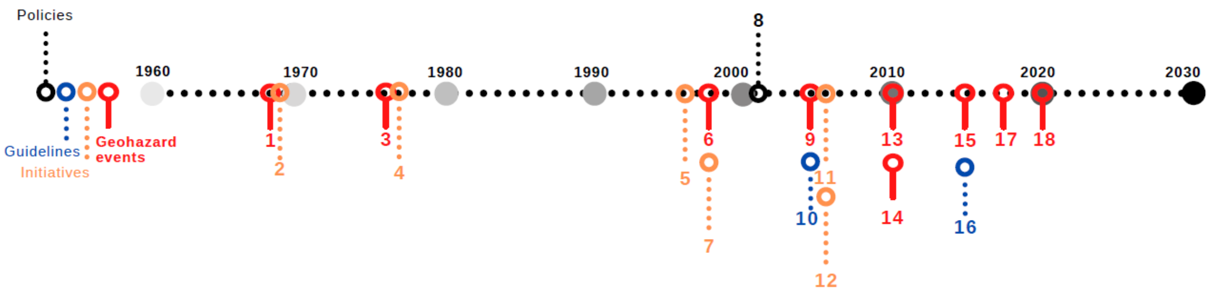


Figure 3-3. Geohazard disasters and the evolution of geohazard risk management in Guatemala through time.

Table 3-9 outlines the major disaster events in Guatemala that have driven geohazard management in the country.

Table 3-9. Disaster events in Guatemala from the 1960s to 2020s, associated with Figure 3-3.

Timeline #	Year(s)	Name/Type	Source
1	1969	Hurricane Francelia	OCHA (2022)
3	1976	Earthquake	OCHA (2022)
6	1998	Hurricane Mitch	OCHA (2022)
9	2005	Tropical Storm Stan	OCHA (2022)
13	2010	Tropical Storm Agatha	OCHA (2022)
14	2010	Pacaya volcano eruption	OCHA (2022)
15	2015	Cambray landslide	LaPorte (2018)
17	2018	Fuego volcano eruption	OCHA (2022)
18	2020	Tropical Storm Eta/Lota	OCHA (2022)

3.3.1 Policies

There has been one policy developed in Guatemala for geohazard risk management, and that is the ban of developing infrastructure within 100 metres of a river within a ravine (Table 3-10). Unfortunately, this is often the only land available for low-income families and thus is often inhabited anyway (Strouth et al., 2017).

Table 3-10. Policy developed by the Guatemalan government to reduce the risk of geohazards, associated with Figure 3-3.

Timeline #	Year(s)	Name	Contribution	Source
8	2001	Declaration 197	Ban of development within 100 m of river in a ravine	LaPorte (2018)

3.3.2 Guidelines

The frameworks created by the United Nations office of Disaster Risk Reduction have influenced the national risk management and helped improved the risk governance and disaster response (Table 3-11).

Table 3-11. Guidelines adopted for geohazard risk management in Guatemala, associated with Figure 3-3.

Timeline #	Year(s)	Name	Contribution	Source
10	2005-2015	International Strategy for DRR and Hyogo Framework	Influenced national risk management improvements	OCHA (2022)
16	2015-2030	Sendai Framework	Better guidelines to improve risk governance and disaster response	OCHA (2022)

3.3.3 Intiatives

Committees and initiatives have been formed and adapted in Guatemala (Table 3-12). There is a shift from the early days in the 1970s focusing on effective emergency response, to proactive risk analysis and management, early warning systems and decentralized Coordination of National Reduction of Disasters (CONRED) which has increased the national networking and knowledge transfer.

Table 3-12. Initiatives created to reduce the risk of disasters, as well as prepare for and respond to disasters in Guatemala, associated with Figure 3-3.

Timeline #	Year(s)	Name	Contribution	Source
2	1970	National Emergency Committee (NEC) created	For effective disaster response	OCHA (2022)
4	1977	INSIVUMEH and National Reconstruction Committee created	To evaluate hazards and build back better	OCHA (2022)
5	1996	CONRED established, NEC abolished	Shift focus to reducing disasters	LaPorte (2018)
7	1998	Beginning of risk analysis in the country	Initiation of risk analysis in geohazard management	LaPorte (2018)
11	2006	Community-based alert and alarm system for rainfall induced landslides	Informs and prepares residents	LaPorte (2018)
12	2006	Decentralization of CONRED	Created opportunity for local responsibility with a national network	OCHA (2022)

4 Case Studies

The case studies presented in this chapter reflect the geohazard risk management techniques and strategies examined in Chapters 2 and 3. Each case study focuses on a unique aspect of geohazard risk management and provides applied examples of risk management in practice.

The Norwegian case study site was evaluated by the Norwegian Public Roads Administration and focused on using the policies and guidelines set by the government institutions for the analysis. The Canadian case study was evaluated by a consulting company which used evaluation techniques reflective of those set in the national guidelines. Reference thresholds were used from nearby jurisdictions since there is no national policy for geohazard risk thresholds. And lastly the Guatemalan case study site was evaluated by an external organization in cooperation with government institutions resulting in education of community members to perform risk evaluations and implement simple, cost-effective mitigation strategies.

The case studies are structured so the reader gains background information about the site, gets an overview on the geohazard risk assessment, then learns about the mitigation recommendations, actions, and follow-up.

4.1 Trollstigen, a national treasure tourist road in Norway

The Norwegian case study is a site that is examined by technical experts within the national governmental organization responsible for the road systems in Norway, NPRA. However, the decisions are made by the local county, Møre og Romsdal. This is typical for the road systems in Norway.

The hazard and risk evaluation focuses on following the Guidelines for risk acceptance criteria for landslides on the road (NPRA, 2014) with input from ELRAPP and RegObs entries as mentioned in Section 3.1.3. This section will introduce the case study site, give an overview of the geohazard risk analysis and explore the mitigation recommendations, actions and follow-up.

4.1.1 Background

The Trollstigen road in Norway, literally translating to "the Troll's ladder" in English, is appropriately given the name due to its scenic hairpin turns winding up nine hundred meters of vertical elevation. While driving up the mountain pass road, the surrounding mountains, towering up to 1700 meters, are barely visible. The Trollstigen road was constructed in 1936 and has been a functioning road for commuters and tourists ever since. The road is closed every winter season, due to snow accumulation and high avalanche and icefall danger and reopens in spring.

Previous geohazard analyses have indicated the most traditional solution for mitigating geohazards for this road is to build a tunnel through the mountain, though due to the breath-taking scenery (Figure 4-1), historic construction and tourism attraction, the National Public Roads Administration (NPRA) has committed to keeping this national treasure open and safe.

Figure 4-1. The Trollstigen road from above, looking north along the valley. Photograph taken by the author.

Trollstigen is located at the head of the Isterdalen valley in the Møre and Romsdal county in Norway. Geographical location references are in Figure 4-2 and Figure 4-3. During the few months the road is open for traffic the main hazards are rockfalls, but debris slides, debris flows and floods are also notable hazards in the valley that could, and have, impact the road. Hazard zones are mapped in Figure 4-4.

Figure 4-2. Overview of Norway and location of Trollstigen (Google Earth Pro, 2022).

Figure 4-3. A view of Trollstigen in 2.5 dimensions (Google Earth Pro, 2022).

Local residents and economy depend on the consistency of this road to stay open in the spring through to the autumn, and over one million visitors each year travel to see this wondrous road. Properly understanding, monitoring and mitigating the natural hazards at Trollstigen directly relates to the safety and satisfaction of all those who travel the road, and not only the initiation of necessary road closures but also the avoidance of unnecessary closures.

The Trollstigen slope is the location of a pilot project for the Climate 2050 Center for Research-Based Innovation. Climate 2050 has the goal to reduce the societal risks associated with climate changes. The Norwegian Geotechnical Institute (NGI) is a participant of this pilot project and the NPRA is the owner. Though the NPRA is the owner of this pilot project, the structure of the maintenance and management of the roads in Norway has shifted in recent years. Now the local counties are responsible for the maintenance and safety of the roads with technical guidance from NPRA.

The information in this case study is summarized from the Natural Hazard assessment report of Trollstigen by Dahle and Humstad (2018) from the NPRA with contribution from the summary and follow-up report from the Møre og Romsdal county Transport Committee (2019).

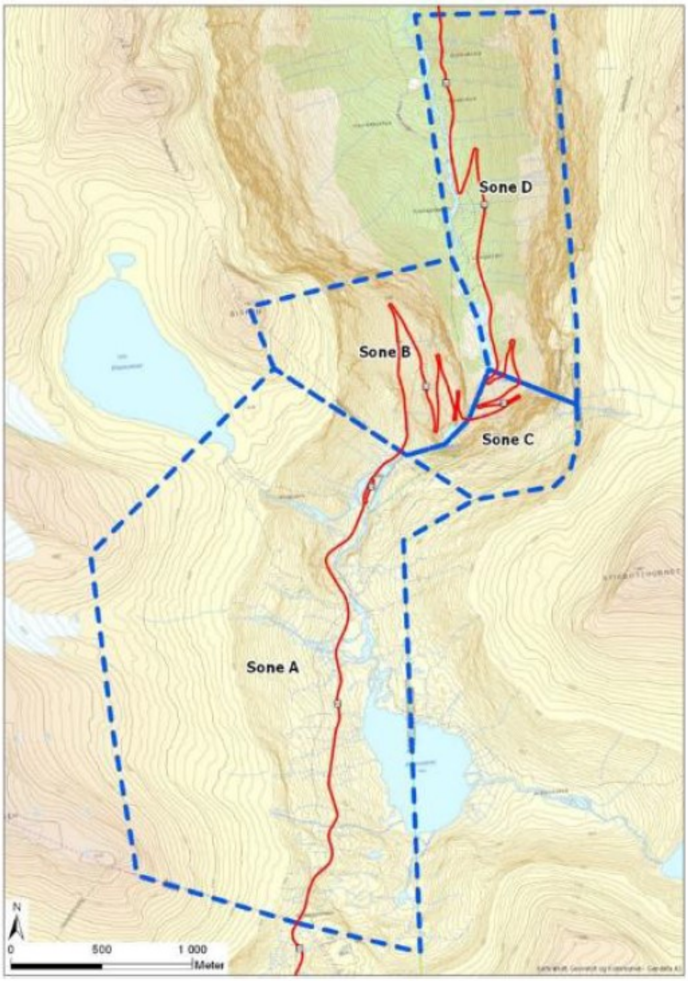


Figure 4-4. Zoning used in the risk assessment for natural hazards at Trollstigen (Dahle and Humstad, 2018).

4.1.2 Geohazard risk assessment

The Guidelines for risk acceptance criteria for landslides on the road (NPRA, 2014) and the Regulations on technical requirements for construction works (Norwegian Building Authority, 2017) were used as a guide for this assessment, even though these regulations and guidelines only include risk evaluation and acceptance criteria for new developments.

The objective of the work done by NPRA was to update the need for landslide protection at Trollstigen. The assessment included traffic volume, avalanche and landslide frequency and extent (including landslides in the surrounding area), detour time, the past frequency of closing the road and preventative closing.

The high number of tourists, traffic jams, type of vehicles (a large proportion are busses), pedestrians and cyclists are notable factors that weren't included in the assessment. It is also noted that secondary consequences such as loss of reputation as a tourist destination, a decrease in visitor numbers or devastation if a facility or vehicle is hit are not included either. This assessment was only intended to assess the avalanche and landslide risk given the empirical data from the area.

The maintenance crews had been trained in the ELRAPP reporting system (Humstad, 2020) so avalanches and landslides were recorded on a regular basis Figure 4-5. The data collected for these events were from the ELRAPP reporting system, the road logs, and WELD and MIME archives. The report notes this only includes events where people were present, so events in the winter when the road is closed or where it does not impact the report may not be recorded. This under recording was not adjusted for in the analysis.

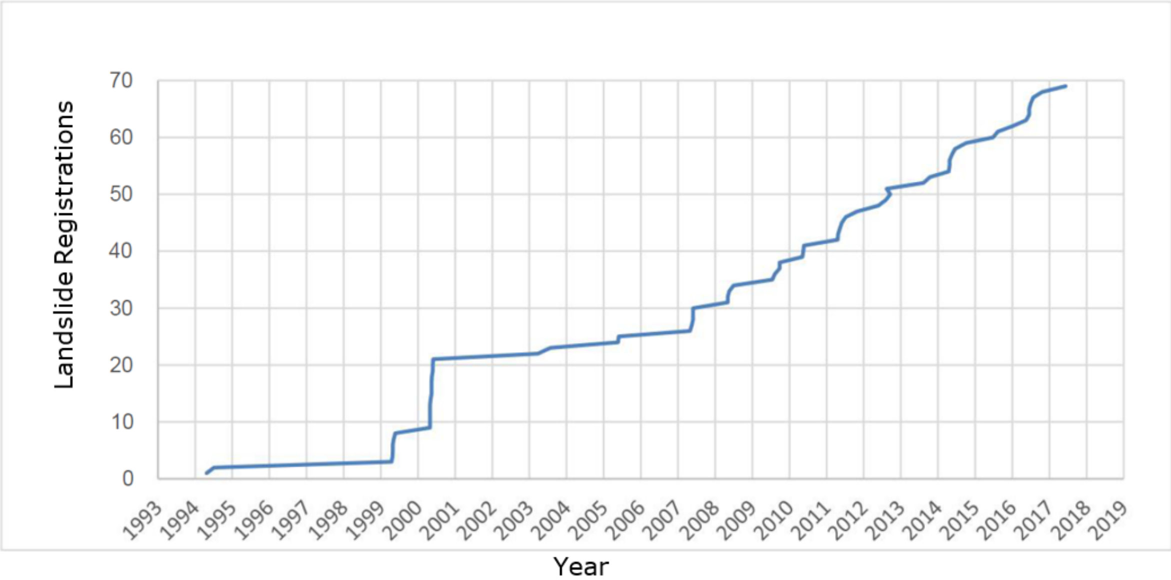


Figure 4-5. Accumulated landslide registrations used for the analysis (Dahle and Humstad, 2018).

Monthly traffic data was compiled and plotted against the registered landslide events per year (Figure 4-6). This was used to gain a more wholistic view of when the landslides are occurring with respect to traffic volumes for mitigation options. The monthly traffic data was also used to categorize the risk levels of the zones with respect to the annual nominal landslide frequency per kilometer. This evaluation (Table 4-1) uses the individual risk criteria explained in Section 2.5.2.

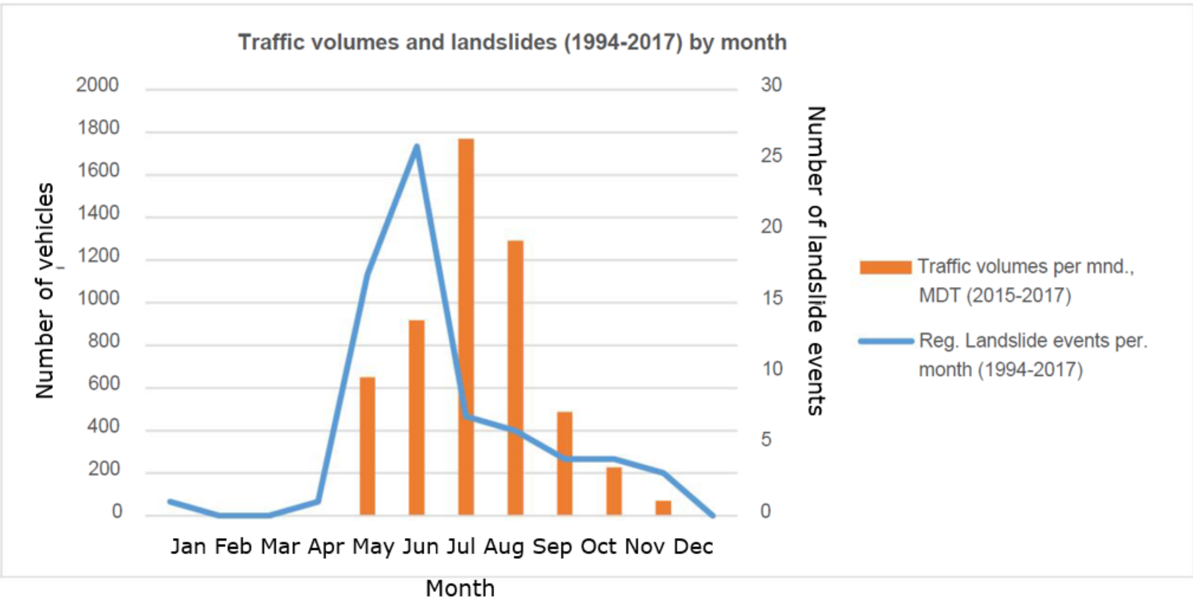
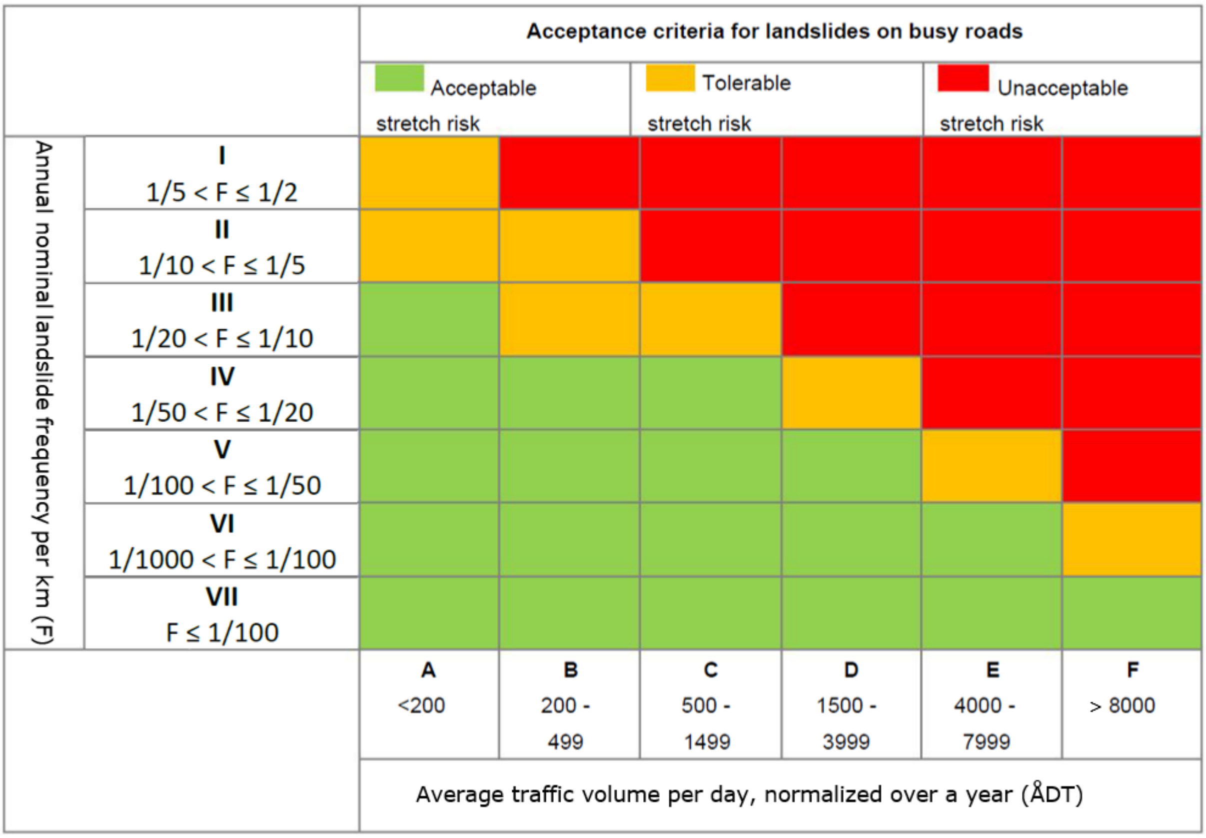


Figure 4-6. Monthly traffic and landslide events per month, normalized to amount of days open. Adapted from (Dahle and Humstad, 2018).D

The evaluation takes the monthly traffic volume category, number of registered landside events per zone and number of kilometers per zone to obtain a registered landslide frequency per kilometer per year. The outcome of these calculations are the frequency categories in Table 4-1.

Table 4-1. Acceptance criteria for landslides on roads, adapted from (NPRA, 2014).



The outcome of the evaluation is Table 4-2, which displays the risk classes of each zone in relation to the month. It is important to note that these evaluations were completed for present-day, recorded conditions and do not take into account the underreporting of the avalanches and landslides nor the projected increase in traffic volume.

Table 4-2. Comparison of registered landslide frequency (1994-2017) with estimated traffic volume (2014-2017) with relation to the risk classes (Dahle and Humstad, 2018).

Month	Zone A Alnesreset - Stigrøra	Zone B Stigrøra - Stigfoss Bridge	Zone C Stigfoss Bridge - Tverrelva	Zone D Tverrelva - Byteskredbrua
January-April	-			
May	I / C	I / C	I / C	II / C
June	I / C	I / C	I / C	II / C
July	III / D	I / D	I / D	II / D
August	III / C	I / C	I / C	II / C
September	III / B	I / B	I / B	II / B
October	III / B	I / B	I / B	II / B
November	III / A	I / O	I / O	II / A
December	-			

4.1.3 Mitigation recommendations, actions and follow-up

The recommended risk reduction measures presented in the assessment report included many of the mitigation strategies presented in Section 2.8. The suggestions ranged from the highest priority, corresponding to the unacceptable hazard classifications in Table 4-2, and most cost effective to implement within 1 to 2 years. These included remote sensing measurement campaigns and maintenance of previous structural mitigation measures. The list continued to priority levels 2 and 3 which includes collaboration with contractors on engineered mitigation designs, establishing near real-time monitoring for the site, and routine inspections and reevaluations (Dahle and Humstad, 2018).

Unfortunately, Trollstigen was deemed not a priority for mitigation the Møre og Romsdal county in 2019, nor in the 2022-2033 national transport plan, given the other developments and mitigation measures in the county coupled with the limited funds (Transport Committee, 2019, Det Kongelige Samferdselsdepartement, 2021). This meant regular maintenance was able to be performed, but no additional mitigation measures were implemented.

Following this evaluation, Trollstigen experienced a rockfall, which hit a car, in May 2021 (Figure 4-7) and an avalanche which significantly damaged the visitor center, prior to the road opening for traffic, in April 2022 (Figure 4-8).

Figure 4-7. Aftermath of the rock hitting the hood of the car in a rockfall event at Trollstigen, May 2021. Photo taken by John Dokken / NAF (Hellem-Hansen, 2021).

Figure 4-8. Broken windows and snow filling the visitors center, April 2022. Photo taken by Dag Christian Ugseth (Bjerknes and Sørensen, 2022).

4.2 Cold Spring Creek Fan Debris-Flow in Canada

The Cold Spring Creek risk assessment has been performed by a consultant, BGC Engineering, sub-consultant contracted with McElhanney Ltd. And contracted by the Regional District of East Kootenay (RDEK). This is a typical format for Canadian risk analyses and hazard management. The government officials contract out the assessments and recommendations to consultants since they typically do not have the technical expertise within the governmental organizations.

The risk analysis follows national guidelines. These guidelines are most commonly used by consultants who have the technical expertise for proper evaluation. Neighbouring districts with risk thresholds are referred to for guidance and comparison, since there aren't national policies for geohazard risk thresholds.

This section will introduce Cold Spring Creek and review the geohazard risk assessment techniques used. Options for mitigation actions are presented and the follow-up from the district is revealed. The report produced by BGC Engineering Inc. (2021) (BGC) made available online by RDEK, is the source of the assessment.

4.2.1 Background

The Cold Spring Creek case study site is located in the community of Fairmont Hot Springs in southeastern Canada in the province of British Columbia (BC) (Figure 4-9). It is located in the Columbia valley where debris-flow hazards which create risks to the people and infrastructure within the Cold Spring Creek fan (Figure 4-10). A detailed hazard assessment had been previously performed in 2020 by BGC. This risk assessment in 2021 was completed to determine if the risk at Cold Spring Creek is tolerable, and if not, to propose mitigation options for RDEK at the Cold Spring Creek fan.

Though debris-flows have been rare in Cold Spring Creek, with no recorded event since Fairmont Hot Springs was built in the 1970s, a destructive debris flow occurred on Fairmont Creek, the adjacent creek, in 2012 (BGC Engineering Inc., 2021).

Figure 4-9. Overview of southern Canada and the Cold Spring Creek location (Google Earth Pro, 2022).

Figure 4-10. A 2.5D view of Cold Spring Creek (Google Earth Pro, 2022).

4.2.2 Geohazard risk assessment

The geohazard risk assessment estimates life-loss risk and economic risk at Cold Spring Creek from debris flows. Baseline and mitigated debris-flow risk was estimated and compared to individual and societal risk tolerance thresholds that are being used by other districts in BC, such as the District of North Vancouver, as reviewed in Section 3.2.

Three mitigation options, as well as the baseline case, were assessed. One mitigation option is a debris basin, another a debris net in the canyon, and another a combination of the debris basin and net.

An assessment and evaluation of the individual and societal life-loss risks from debris flows was performed. The life loss risk was calculated for each scenario by estimating the probability the scenario occurs, the spatial impact, the probability a person will be present and the vulnerability that it would result in loss of life. These estimates were summed and the individual risk probability of a fatality at each building was estimated, as well as the number of expected fatalities for the different scenarios, or societal risk probability. Then, the economic risk was estimated considering the impact to buildings and infrastructure. This assessment method follows the same theory presented in Sections 2.5 and 2.6. The debris-flow scenarios cover return period ranges from 100 years to greater than 1000 years, all corresponding to events with certain frequencies, volumes and discharges.

The individual risk assessment revealed the PDI risk values are over ten times higher than the risk threshold presented in the Canadian Technical Guidelines (Porter and Morgenstern, 2013). Also for the unmitigated scenario, the average return period for one life loss is 22 years (Table 4-3).

Table 4-3. Number of buildings exceeding the 10-3 and 10-4 risk tolerance threshold. The scenarios represent full occupancy for the unmitigated case (1b), the debris net (2b), the debris basin (3b) and the debris net and basin (4b) (BGC Engineering Inc., 2021).

Scenario	Debris Flow Scenario						Total Risk (All Scenarios Combined)	
	100 to 300		300 to 1000		>1000			
Thresholds	$>10^{-3}$	$>10^{-4}$	$>10^{-3}$	$>10^{-4}$	$>10^{-3}$	$>10^{-4}$	$>10^{-3}$	$>10^{-4}$
1b - FO	36	91	0	72	0	84	36	108
2b - FO	22	77	0	38	0	64	22	94
3b - FO	0	0	0	3	0	17	0	18
4b - FO	0	0	0	0	0	10	0	10

The societal risk assessment used the same scenarios for the individual risk assessments. The annual frequencies of N or more fatalities were plotted against the number of fatalities in an FN plot, explained in Section 2.5.1. Risk zones rather than lines were chosen for the FN plots to avoid the illusion of precision, since uncertainties are present in the analysis.

The baseline scenario and each mitigation option were plotted, as well as reference projects in the region of southern BC where quantitative risk assessments were also performed (Figure 4-11).

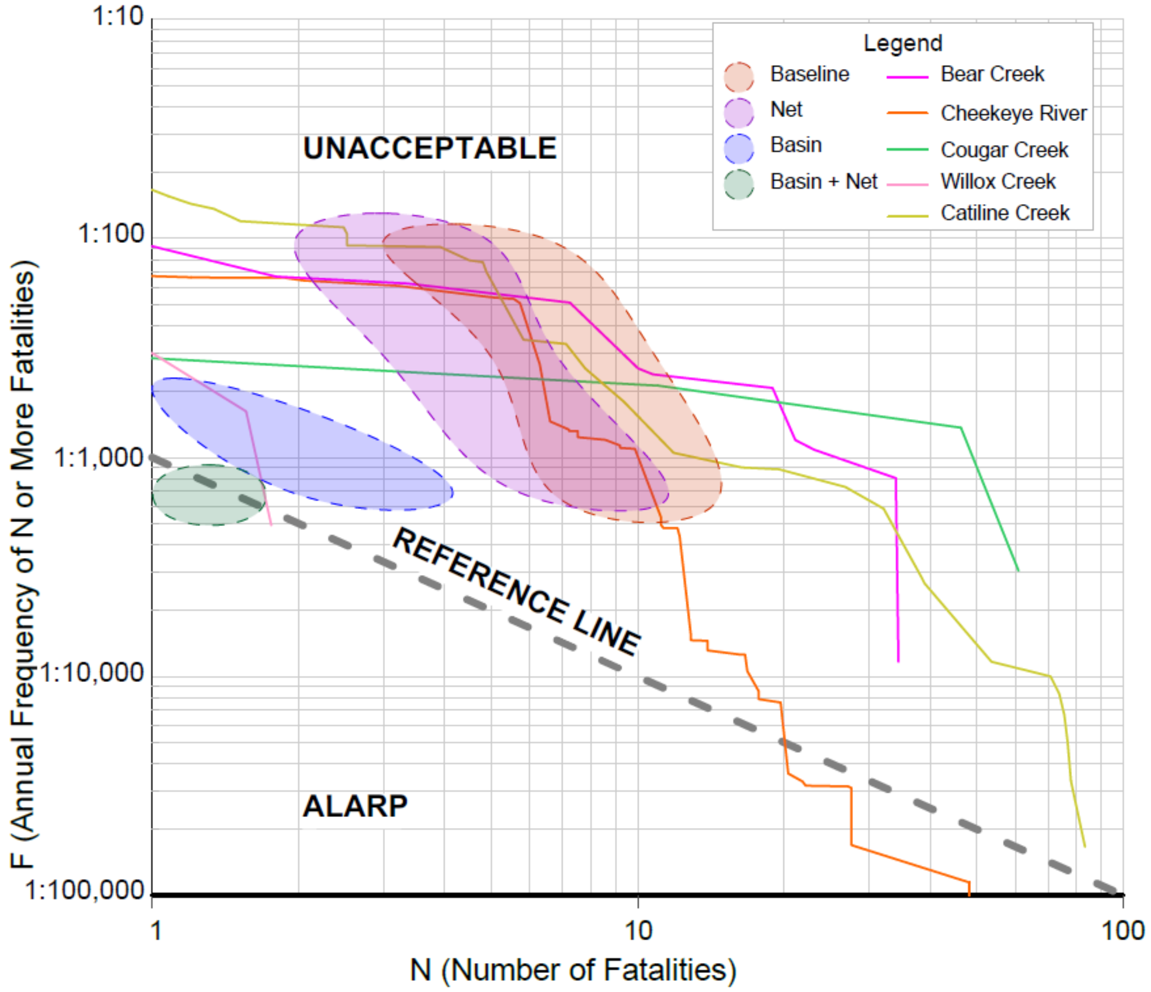


Figure 4-11. Results of the societal risk assessment for existing and proposed development, compared to group risk tolerance criteria used elsewhere in BC (BGC Engineering Inc., 2021).

The last assessment was a comparison of the potential economic losses with the debris-flow mitigation options, in terms of building damage (Figure 4-12).

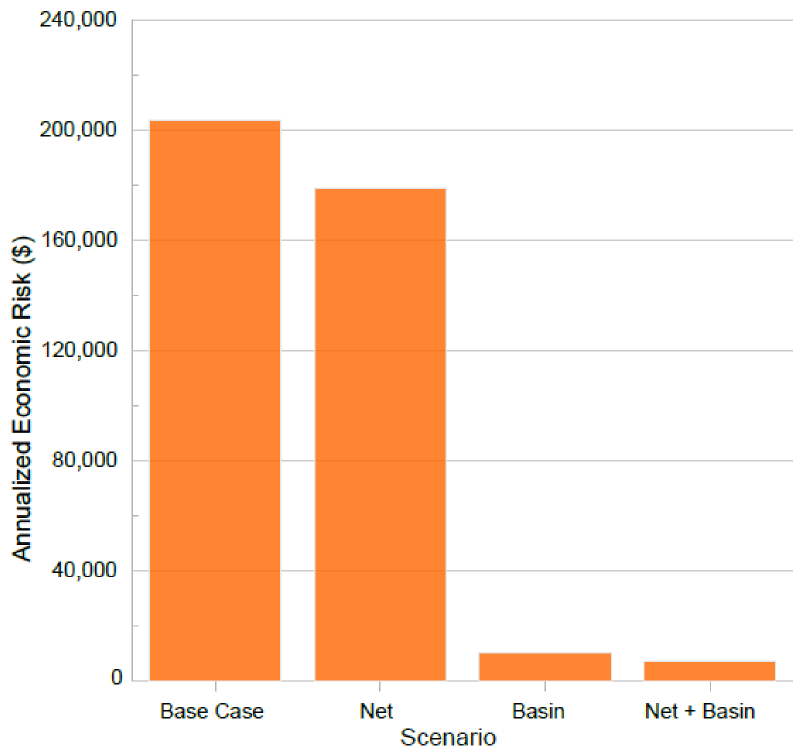


Figure 4-12. Plot comparing estimate of annualized economic risk for the four different scenarios (BGC Engineering Inc., 2021).

4.2.3 Mitigation recommendations, actions and follow-up

A comprehensive debris-flow risk management plan including structural mitigation and early warning systems was recommended by BGC. The conclusion was a debris net would reduce debris-flow life los and economic risk, but it is recommended to be coupled with a debris-flow basin to reduce risk to within tolerable levels.

Even with these measures, residual risk will be present. BGC recommends reducing this risk through property-specific measures, a nearly warning system and resident education in case of a debris-flow occurrence. These reflect the risk mitigation strategies presented in Section 2.8.

Following this report and these recommendations, RDEK shared the report with the community and also applied for a grant from the federal government. Geophysical investigations began in June 2021 with geotechnical investigations scheduled for July 2021, however no additional updates have been published by RDEK.

4.3 Landslide risk reduction of communities on the margins of Guatemala City

The case study in Guatemala City developed from a regional initiative for landslide risk reduction set in motion by the institutions of CONRED (translated as Coordination of National Reduction of Disasters) and INSIVUMEH (translated as National Institute of Seismology, Volcanology, Meteorology and Hydrology). The project was then carried further by research from a masters student at a university in the United States, the Colorado School of Mines (Faber, 2016). This is the common structure for geohazard risk reduction in Guatemala, where governmental institutions create the framework necessary to catalyze organizations, often external non-for-profit, for further development and implementation.

This case study will review the background information about the Guatemala City Metropolitan Area (GCMA), discuss the geohazard risk analysis techniques and lastly discuss the mitigation strategies implemented. The thesis from Faber (2016) and the subsequent conference paper by Strouth et al. (2017) provide the basis for this case study.

4.3.1 Background

Guatemala City is the capital city of Guatemala, located in southern Guatemala, about 75 kilometers from the coast (Figure 4-13). Characteristic, beautiful ravines can be seen throughout the city. These ravines have steeply dipping slopes made of weak deposits that are subject to periodic, landslides. These landslide risks are amplified by hurricanes, relentless wet seasons and earthquakes.

The people who reside on the margins of the city, in the GCMA, are often low-income families living in impoverished conditions. These are often families who have migrated from rural areas to GCMA for the economic opportunities in the urban settlements of Guatemala. This means the developments are poorly planned, made with sparce construction materials and are located within these dangerous ravines prone to landsliding (Figure 4-14).

Figure 4-13. Overview map indicating the geographical location of Guatemala City (Google Earth Pro, 2022).

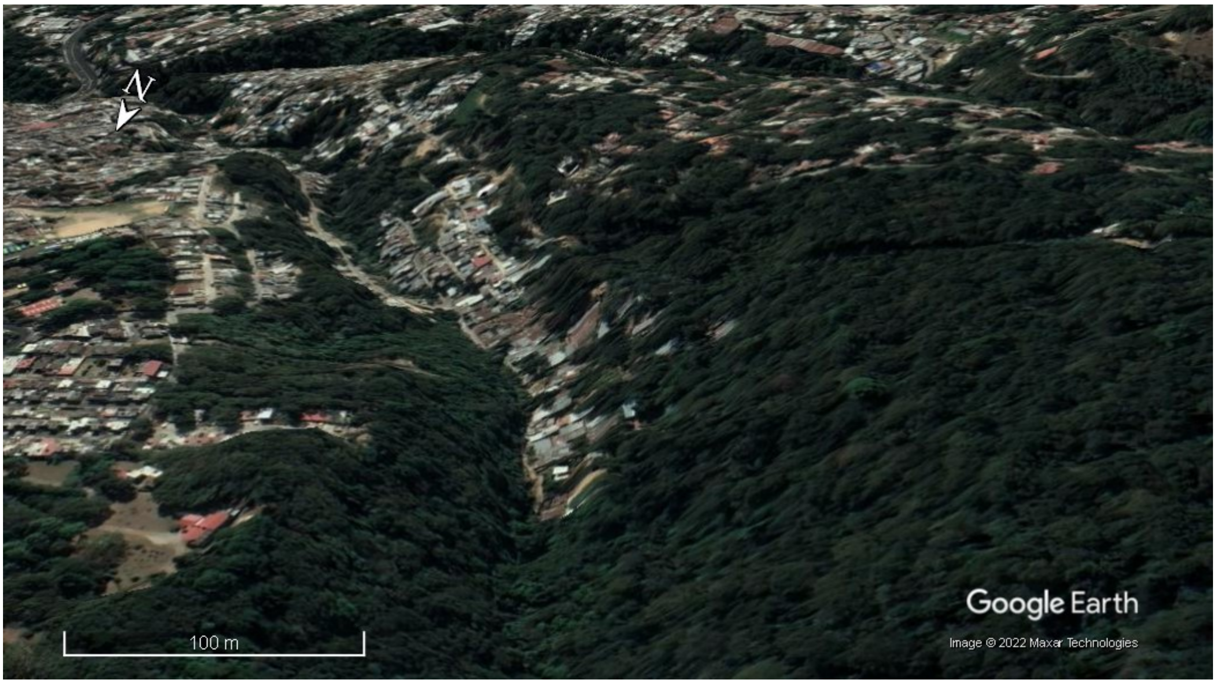


Figure 4-14. A 2.5D map view of dwellings along the ravines in the GCMA (Google Earth Pro, 2022).

4.3.2 Geohazard risk assessment

There is little landslide inventory and availability of historical data on landslides in Guatemala. The inventory that has been completed in the past century often has incomplete data, is lacking critical information and is missing many years of recording. This creates a challenging baseline for quantitative empirical risk assessments, which are assessments founded in historical data.

The project first took an inventory of landslides in Guatemala City through historical imagery and field observations. Landslide risk was then calculated using the PDI equation (2-1) as explained in Section 2.5.2. A landslide-risk-rating-system (LRRS) was developed in this project to quantify the risk of small-scale landslides (defined as the size of a house or smaller). This identified and evaluated hazard factors, consequence factors including landslide volume, spatial impact, vulnerability of the people, and robustness of construction material (Faber, 2016).

Forty slopes were then evaluated with this LRRS in four communities throughout GCMA to assess the condition of the risk and pilot the effectiveness of the LRRS. The LRRS plots the sites on the CERRPED small-landslide risk matrix with relative scorings for susceptibility and exposure to landslide hazards (Figure 4-15).

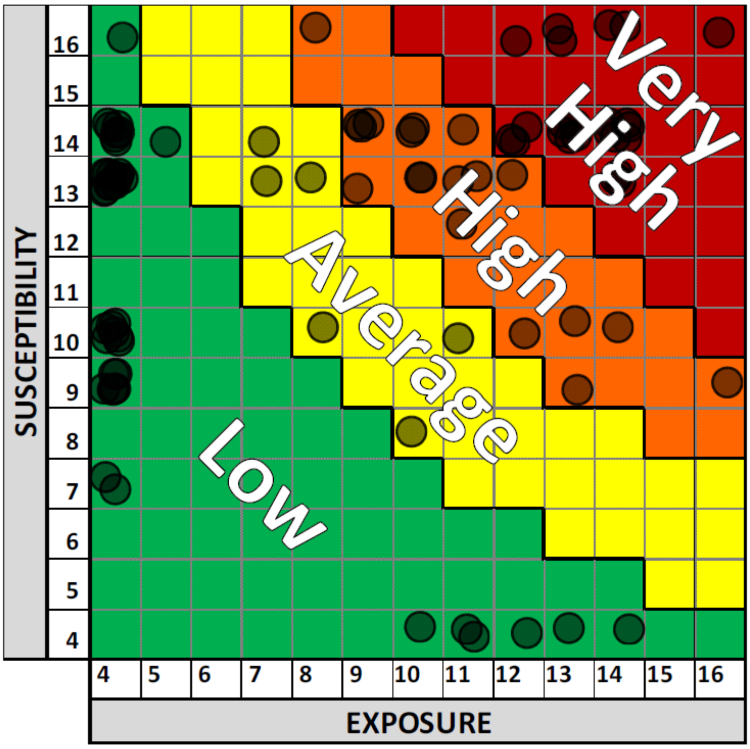


Figure 4-15. CERRPED small-landslide risk matrix (Strouth et al., 2017).

The x and y axis scales are based on susceptibility and exposure values from the Small-Scale Landslide Risk Classification Tool (Strouth et al., 2017). Within this tool in Table 4-4, (above) refers to the Classification Tool for slopes above houses and (below) refers to the Classification Tool for slopes below houses.

Table 4-4. Small-Scale Landslide Risk Classification Tool summary of points assigned to landslide factors (Strouth et al., 2017).

Factor		1 Point Values	1 Point Notes	4 Points Values	4 Points Notes
Susceptibility	Slope Height (m)	3 – 4 (above) 4 – 5 (below)	Contributes to small volume landslide with small area of impact	7+ (above) 10+ (below)	Potential for large volume landslide and large area of impact
	Slope Angle (°)	15 – 45	Landslides uncommon, slopes typically stable	71 – 90	Landslides commonly occur, unstable in the long-term
	Slope Material	Rock	Slopes typically stable	Top soil, fill, weak material	Landslides commonly occur
Exposure	House-to-Slope Distance (m)	6+ (above) 4+ (below)	Most landslide deposits are unlikely to reach the house	0 – 2 (above) 0 – 1 (below)	A landslide or rock fall will almost certainly impact the house
	Number of People	1 – 4	A person might not be occupying the impacted portion of the house when the landslide occurs	9+	A person will very likely occupy the impacted portion of the house
	House (Construction) Material	Reinforced concrete	Able to resist some landslide and rock fall impacts without collapse	Corrugated metal	Provides no protection from small landslides will be destroyed by small impacts.

4.3.3 Mitigation recommendations, actions and follow-up

Following the risk evaluation, permanent relocation is stated as the only mitigation option which would eliminate the risk, as all other options would remain in the unacceptable zone of risk. Economic and social obstacles make relocation unfeasible for the residents living along these ravines. Therefore, a landslide risk reduction project focusing on educating the community members was recommended and implemented, called CERRPED (translated as Empowered Communities in Small Landslide Risk Reduction).

CERRPED focuses on educating community members through a training course which gives them the tools to identify, evaluate and mitigate the risk to small landslides and provides suggestions for affordable mitigation options. These affordable options include water management, build set back from dangerous slopes, rearrange the living area to reduce the spatial vulnerability to the landslide and control erosion along the ravine with rubble or rock. Examples are illustrated in Figure 4-16 The goal of this project is to reduce the risk and vulnerability to landsliding and shift from a reactive, costly approach to a proactive, cost-effective approach to landslide risk management in Guatemala.

A subsequent masters student at Colorado School of Mines has researched the effectiveness of the pilot project with promising outcomes (LaPorte, 2018). There is a plan for widespread implementation of this project with input from CONRED.

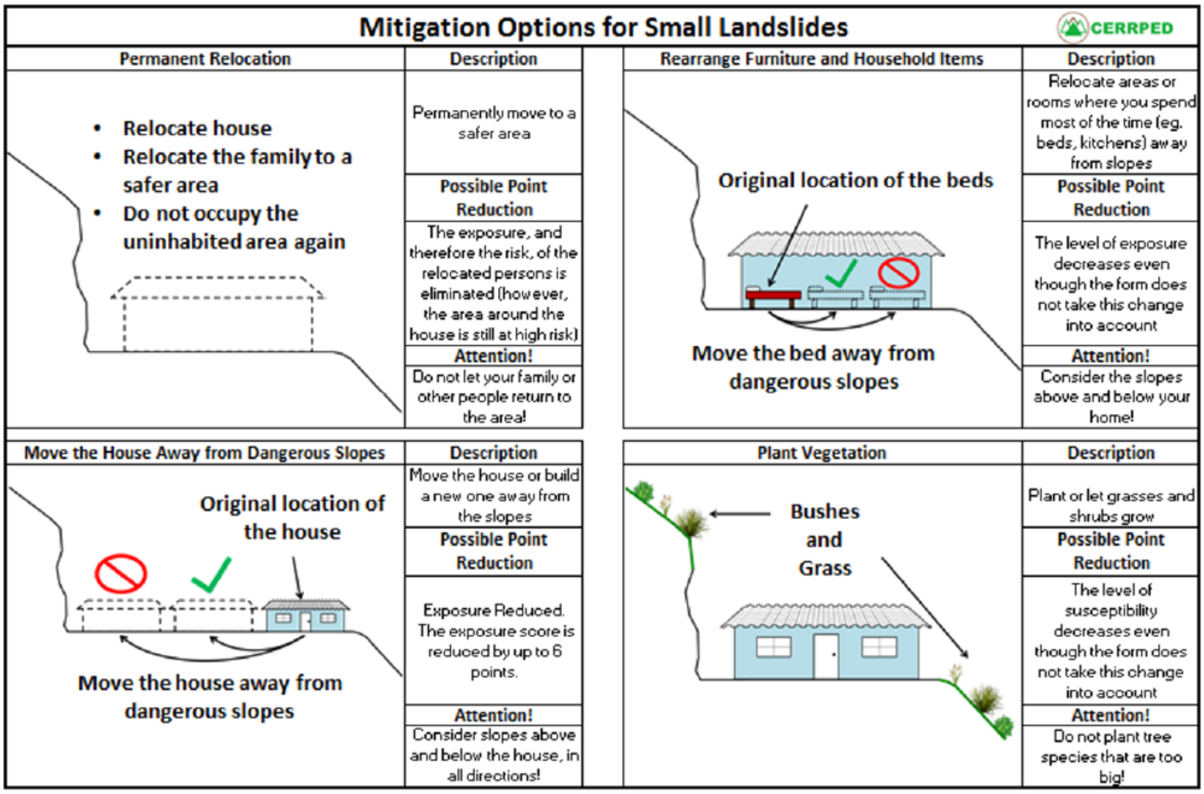


Figure 4-16. CERRPED mitigation options list for select mitigation examples (Strouth et al., 2017).

5 Discussion

Now that the evolution of geohazard risk management has been studied, geohazard risk management strategies have been categorized and case studies have been summarized, it is time to discuss the concepts and findings from the paper thus far.

This section begins by discussing the themes and trends revealed in the state-of-practice exposition. Then, the barriers and challenges surrounding geohazard risk management is debated. Based on this review, suggestions are made for areas of improvement in state-of-practice geohazard risk management.

5.1 Discussion of state-of-practice

The history and state-of-practice for geohazard risk management was presented for Norway, Canada and Guatemala in Section 3 and supporting case studies in Section 4. The strength of the geohazard management strategies can be extracted from each of these reviews.

In Norway, there is strong national governance of building codes and land use plans with supplementary guidelines to ensure each new development is being evaluated properly. Consistent, focused effort from governmental organizations like NVE and NPRA have enabled hazard maps, susceptibility maps and warning systems to be developed and openly accessible. Education and online tools have enabled a sense of ownership of hazard recording for civilians, resulting in a more thorough database and prepared communities.

Norway's funding allocation for geohazard risks is at a county level and is pooled with all other risks the county may face (Det Kongelige Samferdselsdepartement, 2021). The benefit to this is all risks are evaluated against each other. The drawback is efforts in assessing the hazards may result in more knowledge about the unacceptable risk, however without having the funds to mitigate the risk. This is seen in the case of Trollstigen in Section 4.1.

There is much effort in into geohazard risk management in Canada, however it is often isolated to certain municipalities or jurisdictions who set their own management strategies and risk thresholds based on the hazards they face and recommendations from consultants. This can be positive when the thresholds are suited to their unique circumstances. However not having a nation-wide policy on risk management in terms of land use plans, building codes or risk thresholds leaves much of the decisions up to interpretation and the municipalities with less resources are left without policy to lean on.

The awareness of the importance of knowledge transfer in risk reduction, not only from governmental organizations and consultants, but also to civilians, has gained traction in the 2000s in Canada. In recent years, programs have been initiated to set guidelines for practitioners and decision makers (Porter and Morgenstern, 2013) and engage locals in understanding what geohazards are present in the area they live (Reynolds, 2022).

Guatemala's risk management is lacking in terms of enforced land use plans and sound construction practices. However, significant effort has been made to reduce geohazard risk and create resilient communities through community engagement and thoughtful, impactful institutions. Education of community members has been a leading contributor to reducing the risk to geohazards (LaPorte, 2018). A decentralized management institution, CONRED, enables each municipality and jurisdiction to consult with and be educated by CONRED representatives, who then collaborate, share knowledge and resources among the committee (OCHA, 2022).

Each of these countries are working towards better geohazard risk management techniques within the limitations of their social and economic structure.

5.2 Analysis of barriers and challenges to geohazard risk management

In all the cases, when policies were reviewed, none of the countries had policy for what to do when communities or infrastructure is mapped within unacceptable risk zones. This could be because the risk has not been quantified in the area before, or new techniques for mapping have included existing infrastructure. Further guidance on action plans for these communities and infrastructure is needed.

A specific challenge brought to light in Canada and Norway is that with further coverage and refinement of the hazard maps and susceptibility maps, counties, communities and even neighbours are being divided between who is 'in' and who is 'out' in terms of risk thresholds. This creates a complexity for the county and municipality.

One scenario could be where only one or a couple individual homes are within a hazard zone, for example an expansion of a floodplain hazard due to the increase of large storm events due to climate change. To mitigate the entire area from flooding could be extremely expensive, unmanageable and a poor allocation of resources if only a couple of houses are involved.

Guidance from the government for municipalities could be given to address these situations would be valuable. Should the mitigation be the responsibility of the homeowner or the municipality? Further studies could include a literature review of how countries are addressing this challenge. Reviewing countries like Switzerland and France where the alps pose hazards to individual dwellings and mitigating an entire rockfall area or an entire avalanche zone is not feasible or practicable. What guidelines, policies or resources are in place for such homeowners?

Landslide risk management strategies that are developed with robust risk analysis are limited to effectiveness in developed countries (Hungr et al., 2016). For Guatemala, limited historical data is available and there are limited resources for lengthy risk analyses and mitigations (LaPorte, 2018).

A common theme among the countries and throughout the world is the lack of insurance, or risk transfer, for institution and individuals experiencing disasters. This was one of the six categories for mitigating risk described in Section 2.8. Less than half the worldwide disaster-related costs were insured in 2020, and these were disproportionately concentrated to more insurance in richer countries (UNDRR, 2022).

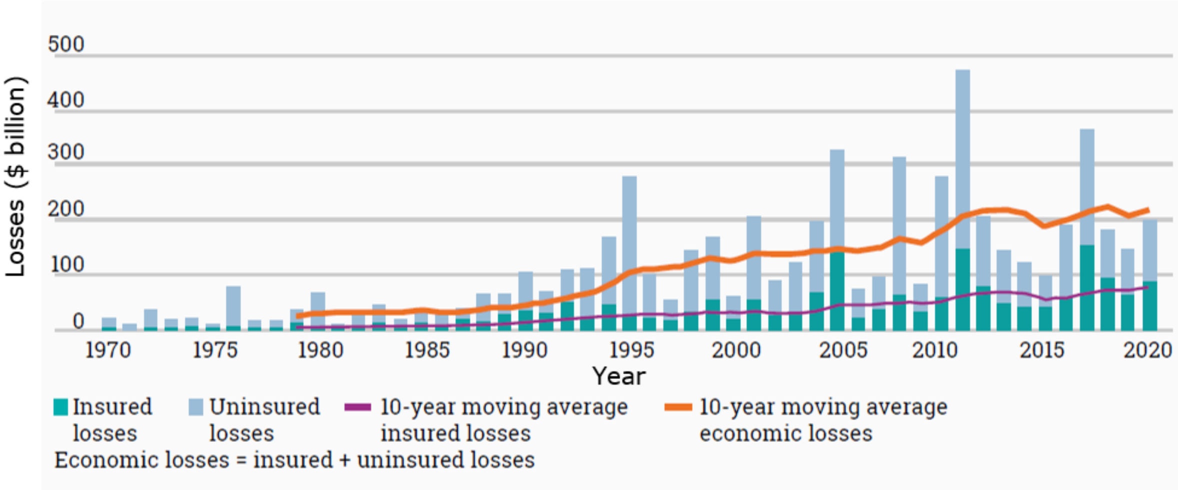


Figure 5-1. Insured and uninsured losses ($ billion at 2020 prices), 1970-2020 (UNDRR, 2019).

5.3 Areas for improvement on state-of-practice

A general threshold policy, for example like the one from Porter and Morgenstern (2013), either at a provincial level or a national level could be valuable for common ground on risk management in Canada. Then, each province or municipality can choose to adopt these thresholds or increase the thresholds based on the funding available, types of hazards and tolerance of the civilians. This would follow the model of what is currently in place for Occupational Health and Safety Regulations (Canada Labour Code, 2022).

Another area for improvement for Canada and Norway would be to have a plan or guideline for existing buildings and roads. The susceptibility and hazard maps are being refined and are having larger coverage across the country, however there is no plan in place for if someone's individual house is mapped into a hazard zone. Unless, of course, they would like to do an expansion or sell their house then there are implications to address the risk. There could be an additional chapter added to the building code that addresses previously built residences, buildings and infrastructure. It could start with communication of what it means to live in a hazard zone and develop into an action plan for municipalities or residents to apply for funding to make their house more tolerably safe, or funding to move their family to a safer location.

CONRED in Guatemala is a great example of an institution which is responsible for bringing knowledge, laws, and resources to communities that need it the most. They have representatives in the municipal, county and federal levels to bring training courses to the community members, teach about geohazards and help the community be prepared for disasters and bring the barriers and difficulties of the individual areas and communities to a larger stage where themes of challenges and gaps can be discussed and addressed.

Canada and Norway could learn from the model of CONRED. Having a decentralized institution or committee that regulates the policies and guidelines given by the federal government and assesses the practicality of these policies and the need to adapt or increase the strictness. They could also bring knowledge of new policies to the municipalities. It would create a bridge between the experts in the field and the municipal decision makers, getting guidance from the institution members responsible for their area.

Another benefit for Canada introducing a committee for disaster risk reduction would be the grants established at a federal level can be distributed equitably to the communities who need it the most, being the responsibility of the trained committee member to apply for grants for the communities in need, and a central discussion with the committee members to decide which communities are best suited to be supported by the federal grants. A regulator like Engineers Canada (2022) could be a good platform to support this.

In Norway, another benefit of the decentralized institution would be guidance on the amount of budget needed from the county to assess the geohazards in their area. Furthermore, Norway could benefit from a grant pool, as Canada has, where additional funding is made available from the federal government to supplement the municipal and county budgets for geohazard preparedness and risk mitigation that would go above and beyond a typical county budget intended for the maintenance and expansion of the county.

For Canada, dissemination of knowledge beyond experienced practitioners is slowly starting to develop, however bridging the gap and having more experience within the local government to address these hazards and make thoughtful decisions could be improved. The dissemination of knowledge from the decision makers and practitioners to the local civilians is typically an even larger gap. Creating country wide or province wide programs to teach people about geohazards so they can learn how to avoid creating risk situations, what to look for to identify hazards when, for example hiking or skiing and what to do in the event of a disaster (before, during and after).

A great initiative started by a PhD student at the University of British Columbia in Canada is the Canadian Hazards Emergency Response & Preparedness Research Initiative (CHERP). The ability to identify and learn about the hazards around where you live, or where you are going to visit, say for a holiday. It also has steps and a checklist to create an emergency plan in the event of a disaster (Reynolds, 2022).

One barrier for Guatemala is the coverage of hazard and susceptibility mapping, though it is beginning to be underway. Reviewing low-cost options for hazard mapping, such as change detection through satellite imagery could be a useful tool to explore. Though it is important to understand it's effectiveness for larger-scale landslides in sparsely vegetated areas, whereas small-scale landslides would not be captured.

Since Guatemala is more densely populated and many locals are knowledgeable of hazards, an interactive online database, such as RegObs in Norway (Colleuille and Humstad, 2016), could be piloted for community members to record geohazard events. This would allow for a better overall understanding of the frequency of events in Guatemala, where they are occurring and where funds could be most appropriately allocated. The population density would help capture a significant amount of geohazard events, and the previous knowledge of geohazards in the communities creates an environment where implementing this initiative would be a manageable step forward.

The recording of the geohazard events by community members could also help correlate rainfall intensities with things such as landslide events or flooding to create more refined thresholds for that particular area without having to conduct costly and thorough ground investigations to refine the thresholds.

These discussion points fall in line with the core pillars of GRAF, the Global Risk Assessment Framework. This framework was established by the UNDRR in conjunction with policy makers, local governments, and experienced practitioners from around the world. The core principles of GRAF are to promote collaboration between industries and countries to share learnings, and to enable all to have open access to resources necessary for evaluation and management of geohazard risk. The author encourages the reader to study the 2019 Global Assessment Report for further information on GRAF (UNDRR, 2019).

The Global Assessment Report (GAR) by (UNDRR, 2022) delves into global risk communication and what is and isn't effective worldwide. The report begins with exploring risk perceptions, risk and vulnerability, risk management approaches, communication advancement in risk reduction and ends with state-of-the-art approaches to assess and govern risk. Particularly chapter 5 is useful where there is a discussion of systemic risk and the necessary evolutions to better assess and manage risk.

One note made in the GAR report by UNDRR (2019) that will be emphasized again here is that it is essential for disaster risk mitigation institutions, governance systems, research institutions, the private sector and community members to all engage and work together to mitigate geohazard risks.

There needs to be a shift in the narrative from notions risk reduction is solely an expensive way to decrease a risk that may not happen. Investing in strengthening social safety nets, increasing collaboration and networking, increasing awareness of the risk, and creating community involvement and ownership need to be seen as valuable gains from proactive risk reduction.

5.4 Future studies

Future studies could extend this research to more countries, review the funding and insurance schemes for geohazards in each country and study the compatibility and feasibility of implementing the practices of the United Nations Global Risk Assessment Framework.

Additional studies could use the Risk Management Index method to better quantify gaps in the countries' geohazard risk management strategies (Chiu and Eidsvig, 2016).

Future studies could look at the outcomes from the risk management strategies of each country and address the following questions: Is the overall and site-specific risk being reduced short and long term? To what degree of effectiveness are the mitigation techniques? What cost benefit is being displayed? For each, is there an increase in expenditure for preparedness and mitigation and a decrease in disaster response?

A review of insurance and funds available would be beneficial at each level of government: federal, provincial (county), municipal and local. The allocation process flow of these funds and insurance schemes and areas for improvement would be valuable.

6 Conclusions

The research objectives at the start of this paper posed unanswered questions about geohazard risk management: how does risk assessment transform into an understanding of how much should be done to reduce the risk of the geohazard? Who is responsible for implementing risk management and setting thresholds? What involvement and education do civilians have? How do these answers and techniques differ across nations and regions in relation to policies, guidelines and initiatives? These questions were explored through three subsequent chapters.

In Chapter 2, a review of risk management evolution followed by risk evaluation parameters and criteria were studied to gain perspective on how using these techniques in a comparative manner can provide deeper understanding if a risk is acceptable, tolerable or unacceptable.

An exposition was presented in Chapter 3 to address the questions of who is responsible for implementing risk management and setting thresholds. The result was identifying each country, Norway, Canada and Guatemala, have different governance strategies for geohazard risk management. Norway has a national governance; Canada gives freedom to the municipalities for policy with national guidelines and Guatemala uses institutions and committees to address risk management.

The questions exploring involvement and education of civilians were surfaced in Chapter 3 reviewing the community initiatives implemented by each country. They were also explored in Chapter 4 where case studies were presented, highlighting the complexities of geohazard risk management strategies and revealing the strength of community involvement throughout the cases.

The discussion in Chapter 5 addressed the question about how the risk management strategies differ across nations. The state-of-practice was discussed, an analysis of barriers and challenges for the countries was presented and areas for improvement were suggested. Future studies were proposed to continue refining understanding to these questions and to new questions as they arose in the study.

The climate is changing and more disasters are being recorded every year (UNDRR, 2022). Developing state-of-art strategies and proactive risk reduction and adaptation need to be the focus for effective geohazard risk management.

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