CLIMATE RISK AND ADAPTATION MANAGEMENT IN MINE CLOSURE PLANNING IN MOUNTAINOUS WATERSHEDS

by

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, the dissertation entitled:

Climate risk and adaptation management in mine closure planning in mountainous watersheds

submitted by **Gabriel Alfredo Castillo Devoto** in partial fulfilment of the requirements for the degree of **Doctor of Philosophy** in **Mining Engineering**

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Abstract

The mining industry has the potential to play a leading role in contributing to sustainable development in societies. This is particularly important in mountainous regions because the livelihoods of many rural communities rely on ecosystem services from watersheds surrounding mining operations. It is therefore critical that mine closure planning adopts a social-ecological approach. Climate variability exacerbates the importance of this issue because it increases the risks of extreme events and may result in potentially large environmental impacts. Reassessment of mine closure strategies and management of associated ecosystem services may be required. Although the mining industry has improved energy efficiency to reduce greenhouse gas emissions, there is currently a lack of effective tools to quantify the extent of climate-related risks during mine closure design.

The purpose of this research is to improve fundamental knowledge in this field and identify practical strategies for proactively managing climate-related risks during mine closure planning. A new framework for climate risk assessment is proposed that can assist companies in considering hazards, vulnerabilities, and exposures within a social-ecological system to integrate human and ecosystem components during mine closure planning. The research adopted a multi-method approach. A systematic review was conducted of publicly available data and self-reported information from the global top ten mining companies by market capitalization. The assessment used a benchmarking methodology to analyse industry’s current approach to climate risk management. Secondly, to understand the practices that could facilitate adaptation to climate risks during mine closure, a group of experts was assembled to reach consensus on this topic through a Delphi survey. Following a review of climate risk assessment protocols in other areas, including public infrastructure, cities, and rural development, a novel framework was developed to support climate risk assessment during mine closure planning. This framework was tested through a qualitative case study focused on the Mine Closure Plan for Teck's Elkview Operations in British Columbia. The research illustrates the importance of adopting an ecosystem-based adaptation approach to inform sustainable mine closure planning and produces a novel framework to support improved decision making.

Lay Summary

The purpose of this research was to investigate potential impacts of climate change on the mining industry and surrounding ecosystems in mountainous watersheds and evaluate potential adaptation strategies. A novel framework, termed the Climate Risk Assessment and Adaptation Framework, is proposed to assess climate risk during mine closure. Potential adaptation strategies are proposed through an ecosystem-based approach. Unlike current mining protocols, this approach provides a holistic watershed perspective, which considers the social-ecological system as the area of study.

Climate risk information based on various scenarios of potential future climate extreme impacts would be available for decision-makers in the mining industry. Overall, the framework shows promise for improving a holistic understanding of climate hazards, vulnerabilities, and exposures in watersheds surrounding mining operations. This could in turn support land restoration planning using ecosystem-based adaptation strategies for coping with climate change and promoting sustainable development.

Preface

This dissertation is an original work and intellectual property of the author, Gabriel A. Castillo Devoto, except where acknowledgements and references have been made to previous work. I was responsible for designing the research, conducting the study, analysing the data, and reporting the results. Partial results from this research were presented at conferences.

Validation of the Climate Risk Assessment and Adaptation Framework on mine closure and the survey presented in Chapter 8 and referenced elsewhere in the dissertation were conducted under UBC Behavioural Research Ethics Board certificate of approval number H18-03514.

Delphi survey analysis and the round of questions with panel of experts reported on in Chapter 5 and referenced elsewhere in the dissertation were conducted under UBC Behavioural Research Ethics Board certificate of approval number H18-01644.

A version of Chapter 4 was published in 2018 [Castillo Devoto, G. Planning climate change adaptation practices in watershed ecosystems: What is the mining sector developing? *Proceedings of the Third Mine Water Solutions Conference*, Vancouver, Canada. June 2018, Pages 545–565]. I was the lead researcher responsible for the literature review, data collection, data analysis, and manuscript composition.

A version of Chapter 5 was published in 2019 [Castillo Devoto, G., Kunz, N. Strategies for climate change adaptation during land restoration and mine closure. *Proceedings of Tailings and Mine Waste*, Vancouver, Canada. November 2019, Pages 931–941]. I was the lead researcher responsible for the literature review, data collection, data analysis, and manuscript composition. All authors contributed with manuscript edits and content.

Partial results from Chapter 6 were presented at four conferences. In all cases, I was the lead researcher responsible for the literature review, data collection, data analysis, manuscript composition (if relevant), and presentation. 1) Castillo Devoto, G. Geospatial data analysis as a tool to manage and communicate vulnerabilities and risks in the watersheds surrounding mining operations. *Resources for Future Generations*, Vancouver, Canada. June 2018. 2) Castillo Devoto, G., Mehrjoo, M. Application of telemetric sensors in mining to holistically manage vulnerability and risk in watersheds. *CIM Convention*, Montreal, Canada. April 2019. Dr. Mehrjoo contributed to the literature review and manuscript edits. 3) Castillo Devoto, G. Climate risk management in the mining sector. *Water in Mining Conference*. April 2020.

I declare that the PIEVC Engineering Protocol and associated documentation were reviewed with authorisation of the author, Engineers Canada, and facilitated development of Section 6.2.3.

I also declare that I used established and authorised software programs (Qualtrics and Zoom) licensed to UBC to collect and analyse data for Chapters 5, 7, and 8.

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Acknowledgements

Some initial doubts surrounded my decision to step away from years working in the mining industry to pursue this doctoral research. Nonetheless, my aspiration to investigate climate risk and adaptation strategies to enhance mine closure and land restoration processes encouraged my resolution to look for answers. Today, these themes are even more critical for the mining industry and society: I am pleased that this dissertation can contribute to this knowledge. None of this would have been possible without the support of key people throughout these years.

First and foremost, I would like to express my deepest appreciation and gratitude to my supervisor, Dr. Nadja Kunz, for her support and guidance while I carried out my research. Her assistance and insightful feedback helped me to mature my research ideas and shape this dissertation. The years working with her as Teaching Assistant in the Water in Mining course molded my evidence-based teaching concepts and my interest in academic teaching. I am grateful for the respect, guidance, and advice provided by Dr. Bern Klein and Dr. Kevin Hanna throughout my doctoral research. I would like to thank Dr. Klein for his valuable suggestions and constant motivation, even before I began my research. I would like to thank Dr. Hanna for his significant stimulus to improve the research with an environmental perspective.

I am forever grateful to my wife, Adna Zas Friz, for her love, patience, and amazing dedication to our family and to our beautiful children, Iago, Mikel, Luzio, Laszlo, Izabella, and baby M. The daily smiles in their faces provided me the strength for constant and persevering work over the course of the research.

To Adna, my eternal partner. Love you forever.

To Iago, Mikel, Luzio, Laszlo, Izabella, and baby M.

Always follow your dreams with love and a positive and humble attitude. That way there are no little things; always big.

“*You must study… but that is not enough. One has to study… to gain the world and conquer it for God. Then we can raise the level of our efforts: we can try to turn the work we do into an encounter with the Lord and the foundation to support those who will follow our way in the future. In this way, study will become prayer*” (St. Josemaria Escriva; Furrow, no. 526).

Chapter 1: Introduction

1.1 Background

The minerals and metals mining sector has the potential to bring about economic development and improve the welfare of societies around the world (United Nations General Assembly 2012; ICMM 2016). According to the United Nations General Assembly, mining industry production is important to all regions with mineral resources, but particularly to countries with developing economies and those in remote and rural zones. In the Andean Region, mineral exports accounted for nearly 40% of all combined exports for the period 2015–2017, and the mining sector constituted 10 and 20% of the GDP of Peru and Chile, respectively, in 2017 (CEPAL 2018). Additionally, the mining industry offers genuine opportunities to achieve sustainable development throughout the mining life cycle within host regions, and more specifically, in the watershed areas surrounding the operations (Kunz and Moran 2014). For instance, based on personal practical experience, mining companies can collaborate with local authorities to deliver basic sanitation services to local communities, implement irrigation systems to support local crop production, provide opportunities for leadership and training for girls and women, and support other long-term sustainable community development projects.

Mine closure policy and planning defines a vision of the end result and sets out concrete objectives to implement that vision (VanZyl et al. 2002). For a mining project to positively contribute to development in a lasting way, closure objectives and potential impacts should be considered from project inception. Every mine operation is unique, and an integrated mine closure plan requires an interdisciplinary, science-based process to restore disturbed land and its hydrological behaviour (Wolkersdorfer 2008). During the closure and reclamation phases, the complete site plan focuses on long-term water management issues, such as treatment to ensure downstream water quality (Hawley and Cunning 2017). Ideally, the final landforms at the site should fit in with the surrounding natural terrain and be shaped to maintain long-term stability against erosive forces (Botin 2009). Furthermore, the diverse services and economic activities established in mine closure plans need to be defined through continuous dialogue with communities, local authorities, and government, allowing them to envision future social, environmental, and economic conditions (Beckett et al. 2020).

Effective mine closure planning is essential for all mining operations, but it is particularly critical within mountainous watersheds. Many ore deposits are located in remote, ecologically vulnerable, and less developed areas containing indigenous lands and territories (Robb 2005; CCSI et al. 2016). Among the ten largest mines in the world, six are located in mountain areas: Kennecott Copper (Utah, USA), Grasberg (Papua, Indonesia), Chuquicamata (Antofagasta, Chile), Goldstrike (Nevada, USA), Yanacocha (Cajamarca, Peru), and Carajas (Para, Brazil). Mountain areas cover 24% of the world's land surface and are home to 12% of the global human population with an additional 14% living in their immediate vicinity; all the world's major rivers originate in mountains and more than half the world's mountain areas play a vital role in supplying water to downstream regions (Macchi and ICIMOD 2010). Fragile mountain watershed ecosystems are particularly vulnerable to adverse impacts of climate change, land use change, land degradation, and natural disasters (United Nations General Assembly 2012). Nonetheless, current accounting models for mine rehabilitation for most open mines are inexpensive ecosystem restoration designs with poor conditions for re-establishment of conditions for local flora and fauna (Franks 2015; Jambhulkar and Kumar 2019).

Mining activities over the life-of-mine disturb the surrounding land and contribute to changes in biodiversity, wildlife, vegetation, soil, stream flow, ground and surface water quality, and other valuable environmental components. To mitigate these impacts, companies develop impact management plans during the mine permitting process and continually update the plans according to local regulatory requirements. A changing climate will result in otherwise unforeseen environmental impacts (Macchi and ICIMOD 2010), and in the near future, this may necessitate reappraisal of land reclamation strategies (ICMM 2013). Design criteria for various extreme weather conditions are important to consider in planning for environmental issues related to mining activities (VanZyl et al. 2002). Therefore, it is troubling that not all mines have incorporated yet climate change projections into the engineering design of key infrastructure such as tailings storage facilities, water management infrastructure, and waste rock disposal (Ma et al. 2018; Labonté-Raymond et al. 2020). The mining industry and the governments of countries where mines are active are beginning to recognise that the changing climate and its impacts represent both physical and investment risks to mining operations and that these need to be addressed in climate adaptation plans (Delevinge et al. 2020). Yet strategies for managing these risks tend to focus on the mine site in decarbonisation and infrastructure design review, without sufficient attention to adaptation strategies, local context knowledge, and an integrated watershed perspective (IISD 2019).

To overcome gaps that currently exist in the mining sector, the mine closure design should consider adaptation strategies to cope with future climate risks. To be effective, these strategies require incorporating local context information as a framework for the possible future conditions of ecosystem components, community livelihoods, and hydrologic connectivity within the landscape. Ideally, the development of closure plans should include extensive stakeholder involvement to ensure that they achieve broader societal acceptance (VanZyl et al. 2002). Moreover, there is growing pressure on mining companies to share hydrogeological and water monitoring data with local authorities and Indigenous groups to improve watershed management and build trust and legitimacy (IFC 2017). This integration of the context surrounding the mine site will provide a holistic vision to define the mine closure design.

The mining sector strongly depends on water, and mine operations located in mountainous regions are more at risk of water scarcity, even for the closure stage. Rising temperatures and disrupted precipitation patterns due to climate change have reduced snow and glacier cover, degraded ground ice and permafrost, reduced ice cover on rivers and lakes, and changed stream and river levels and flow patterns around the world (United Nations 2015). These alterations to hydrologic systems have substantial effects on ecosystems and the human communities they sustain. Adapting to these changes requires establishing reliable baselines through continual, long-term monitoring of water-related variables (CCSI et al. 2016) and then implementing adaptation strategies to reduce risks to ecosystems, communities, and the economy. Thus, the land restoration and revegetation objectives could be achievable.

When an ecosystem is conserved and managed sustainably, it can provide ecosystem services that not only benefit humans, but help them adapt to climate change (Millenium Ecosystem Assessment 2005). These include provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease outbreaks; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious, and other nonmaterial benefits. The key provisioning services provided by mountains include freshwater, food, fibre, medicinal plants, fodder, timber, habitat, and genetic resources. Even with their abundant ecosystem services, mountains remain among the poorest studied ecosystems in this regard (P. Egan and Price 2017; McDowell et al. 2019).

The mining industry has an opportunity to improve social-ecological adaptation by communities within mountainous regions. A healthy ecosystem can mitigate the impacts of natural hazards, including landslides, flooding, hurricanes, and cyclones and bolster human resilience (Scarano 2017). Ecosystem-based adaptation (EbA) is an approach that uses biodiversity and ecosystem services as part of a holistic adaptation strategy to assist humans in adapting to climate change by reducing vulnerabilities and increasing resilience of both human and natural systems (Flores 2016). The scope and nature of typical mining activities highlight common opportunities to leverage EbA strategies in mine closure design.

1.2 Research Objectives

The two overarching objectives of this research are to:

1. examine, identify, and describe potential threats and opportunities posed by climate change to mine closure design in mountainous watersheds; and
2. develop a novel framework that could be used to guide decision making by mine managers to improve climate risk management and adaptation strategies during mine closure and land reclamation stages.

In addressing these objectives, this thesis aims to make a practical contribution to the mining sector by managing climate-related risk, enhancing societal trust of industry, and ultimately promoting sustainable development. Specific research questions are as follows:

i) What practices do mining companies currently use to adapt to climate change risks?

ii) What practices could facilitate adaptation to climate change risks in mountainous watersheds during mine closure?

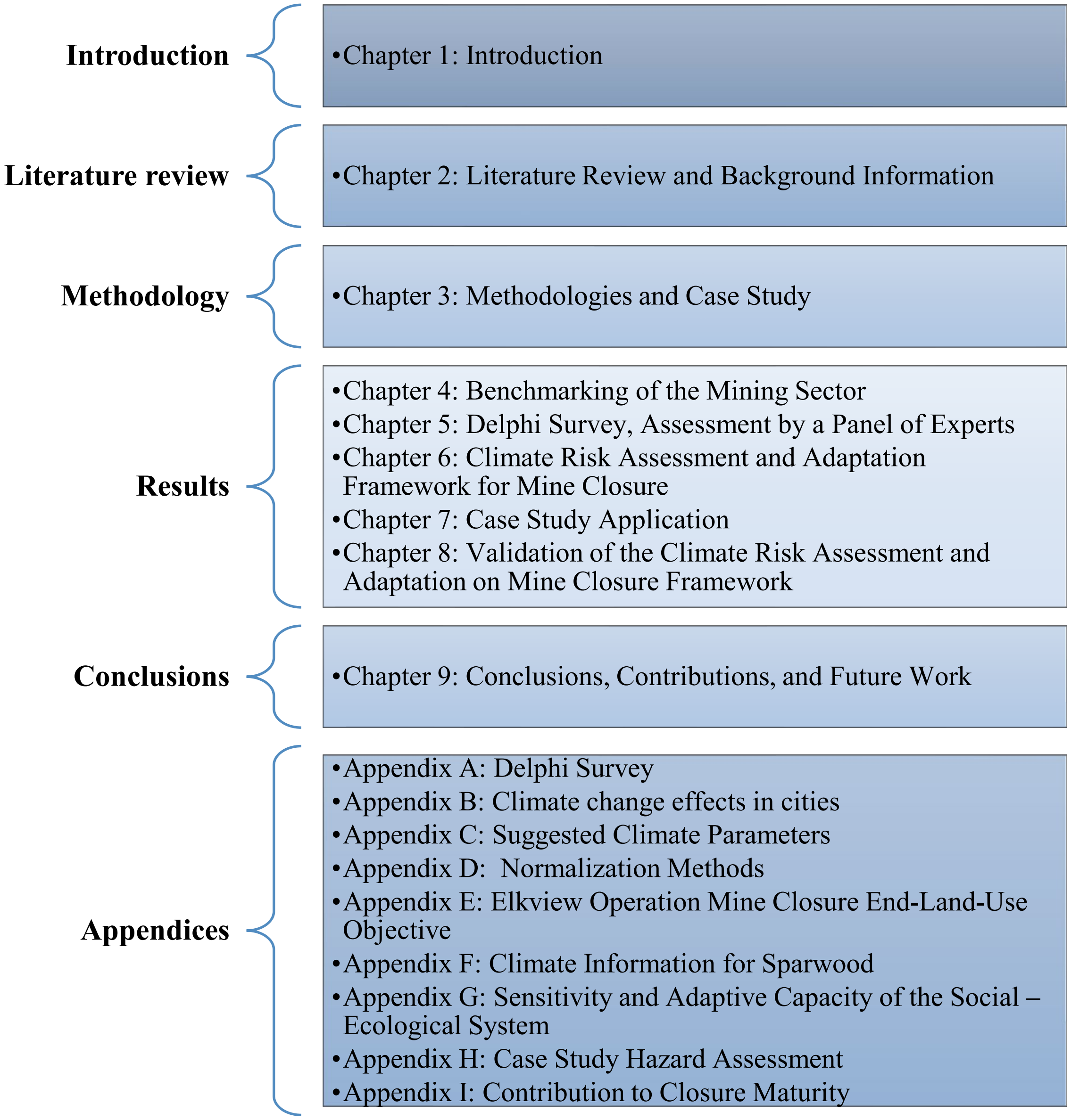
iii) How could a novel approach to climate risk management contribute to assessing mine closure component responses to impacts of a changing climate on mountainous watersheds?

iv) How could an EbA approach contribute to mine closure practices at the watershed scale in a mountainous region?

1.3 Thesis Structure

An overview of the dissertation structure is shown in Figure 1.1. Chapter 2 provides a comprehensive literature review and background information related to climate change in mountain ecosystems and the mining sector, mine closure and reclamation, climate risk assessment and adaptation in watersheds, and EbA in mountainous regions. Chapter 3 describes the methods to perform trend analysis, conduct a Delphi survey, design a climate risk conceptual framework, and conduct case study. Chapters 4–8 present research results. Chapter 4 applies a trend analysis and benchmarking to determine practices that mining companies currently use to adapt to climate change risks. Chapter 5 applies a Delphi survey with a panel of experts to propose practices that could facilitate adaptation to climate change risks in mountainous watersheds during mine closure. Chapter 6 develops a framework for climate risk assessment and adaptation, which is tested by applying it to a mine closure plan in Chapter 7. Chapters 6 and 7 address the third and fourth research questions above. Chapter 8 details a process for validating the proposed framework. Chapter 9 discusses the results, summarises the conclusions and contributions to knowledge, and addresses opportunities for extending the research on climate risk for mine closure.

Figure 1.1 Thesis structure



Chapter 2: Literature Review and Background Information

2.1 Vulnerability of Mountainous Regions to Climate Change

It is well recognised that Earth's climate system is warming based on the strong evidence of increasing mean global temperature (IPCC 2018). Land, oceanic, and atmospheric temperatures have increased, glaciers are melting, precipitation patterns and distributions are changing, and growing seasons have been altered (McNeeley et al. 2017). These changes can only be explained by anthropogenic increases in atmospheric greenhouse gas (GHG) and aerosol concentrations from fossil fuel combustion and land-use changes such as mining (Elmhagen, Eriksson, and Lindborg 2015; Charron 2016; Palko and Lemmen 2017).

Climate-related risks are growing parallel with global climate change and the associated higher climate variability. The Intergovernmental Panel on Climate Change (IPCC) stated that climate-related risks for natural and human systems are higher for an increase of 1.5°C of the mean global temperature at the end of 2018. The changes in the climate system will increase the likelihood of severe, pervasive, and irreversible impacts on people and ecosystems (IPCC 2014e; Bott 2014), which have potentially serious consequences for human health, livelihoods, and community assets, especially for vulnerable groups (The World Bank Group 2017). The manifestation of climate risks depends on the magnitude and rate of warming, geographic location, levels of development, and system vulnerability to climate adverse effects as well as on the selection and implementation of adaptation and mitigation options (IPCC 2018).

The Paris Agreement—adopted in December 2015 by 195 member countries at the conclusion of the 21st Conference of the Parties—aims to limit the global average temperature rise to well below 2°C and pursue efforts to limit the increase to 1.5°C (UNFCCC 2015). This commitment revealed the increasing interest of world governments in responding to the challenges of climate change. Country signatories acknowledged that "*climate change is a common concern of humankind and the Parties should, when taking action to address climate change, respect, promote and consider their respective obligations on human rights, the right to health, the rights of indigenous peoples, local communities, migrants, children, persons with disabilities and people in vulnerable situations and the right to development, as well as gender equality, empowerment of women and intergenerational equity*" (UNFCCC 2015).

Despite these global efforts, Canada's climate warmed by 1.7°C between 1948 and 2016 (Bush and Lemmen 2019) and is projected to continue to warm. According to Bush and Lemmen (2019), "*both past and future warming in Canada is, on average, about double the magnitude of global warming.*" In particular, northern Canada warmed by 2.3°C in 1948–2016 and is projected to continue to warm more in winter than summer (Zhang et al. 2019). Precipitation has increased in many parts of Canada, and annual precipitation is projected to increase everywhere in Canada over the 21st century, but there has been a shift toward less snowfall and more rainfall (Bush and Lemmen 2019). Recent unprecedented warm and dry conditions on the west coast of Canada have caused wildfires, water shortages, human illness, droughts, glacier depletion, and loss of sensitive aquatic ecosystems (Courtney 2021; Mangione 2021; Menounos 2021). The objectives of land restoration defined by the mining sector will be negatively influenced by these effects.

Mountains supply myriad ecosystem services, from minerals to forests to unique plant and animal species (Parrott, Robinson, and Hik 2018). They are regions with outstanding natural and cultural heritage (Ariza, Maselli, and Kohler 2013) that provide vital resources to a significant percentage of the human population. Climate change influences physical, biological, and human components of mountain ecosystems to a greater extent than sea level environments (Egan and Price 2017; Hock et al. 2019), which has implications for downstream communities and industry users. For example, a critical resource offered by mountains is water. Rising winter temperatures are projected to produce more rain than snow and earlier snowmelt. At the same time, higher temperatures, lower precipitation, and less runoff in summer will lead to more frequent droughts, affecting the provision of ecosystem services such as fresh water for consumption and agricultural purposes and water balance in watersheds (Schreier 2017). Despite differences in methodologies, several studies have found consistent patterns in water-related disasters and risks in mountain systems such as floods and droughts (P. Egan and Price 2017). Rapidly changing mountain environments will intensify hazards and risks associated with weather extremes for local communities and infrastructure. Thus, there is a critical need for projections based on a range of emission scenarios combined with expert knowledge to advise impact assessment, climate risk management, adaptation strategies, and the development of government plans development (Flato et al. 2019).

Fragile mountain ecosystems are particularly vulnerable to the adverse impacts of climate change, deforestation, land use and degradation, and natural disasters (United Nations General Assembly 2012). Biodiversity located in mountains or high elevation ecosystems may also be particularly sensitive and exposed to the gradually increasing temperature, because many animals and plants living in such areas occupy small geographical ranges that will be further reduced (Jump, Huang, and Chou 2012; IPCC 2013; Bott 2014) due to changes in habitat and thermal niches (Christmann and Oliveras 2020). The vulnerability of mountain landscapes and the associated risks for the approximately 915 million people that benefit from mountainous ecosystem services has been highlighted as an area of concern in international development forums (Hanna 2018; McDowell et al. 2019).

Risk assessment is central to identifying the most vulnerable areas and communities and quantifying key impacts of a changing climate (P. Egan and Price 2017). The temporal dynamics of risk assessments permit analysis of current and future potential climate hazards. Risk assessments can then be used to identify, judge, and select specific adaptations and disaster risk reduction interventions during planning and design (Secretariat of the Convention on Biological Diversity 2019a). Climate risk assessment will help allocate resources to where they are most needed and design appropriate monitoring plans to support the adaptation objectives.

Given the pressures imposed on mountain systems by global climate change, such as the reductions of crop yields or ecological imbalances due to hydrological disruptions, a long-term planning and holistic management—including of social elements—of ecosystems is needed to support climate change adaptation strategies (United Nations General Assembly 2012). The EbA approach has gained broad acceptance as an emerging strategy for disaster risk reduction (P. Egan and Price 2017). Sustainable approaches to adapt to climate change will support ecosystem services inside and outside of mountainous areas, increasing downstream collaboration. Further, identifying and targeting those ecosystem services that might be improved will be key to designing future adaptation strategies for humans whose livelihoods depend on mountain ecosystems.

2.2 Climate Change in the Mining Sector

The 21st Conference of the Parties goals were to constrain the increase in global average temperature to less than 2°C and pursue efforts to limit it to 1.5°C increase above pre-industrial levels, improve the ability to adapt to adverse climate change, and promote lower carbon emissions (UNFCCC 2015). This agreement brings new challenges and opportunities for society in planning economic development, design technology, and cooperation through capacity building and transfer (Hermwille 2016). There are at least three ways in which the mining sector and climate change are interlinked through: First, the role of mined products in climate change mitigation; second, the impacts of mining on climate change; and third, the climate variability effects on mining operations. With the Paris Agreement's objective to mitigate and reduce GHG emissions by moving away from fossil fuels, new solutions for the energy transition are under development and the mining sector is no exception to this trend. Indeed the push for renewable energy will require the extraction of specific metals, for example aluminum, cobalt, copper, lithium, zinc, manganese, platinum, cadmium, molybdenum, and indium (WBG 2017), to support renewable power technology, including solar photovoltaics, wind turbines, energy storage batteries, and electric mobile equipment (Hondo and Moriizumi 2017; UNDP and UN Environment 2018). Thus, when managed effectively, mining projects can catalyse further economic development; supporting mining regions makes sustainable development a possibility (United Nations General Assembly 2012).

A changing climate presents challenges to communities and ecosystems close to mining and metals operations, which can impact critical climate-sensitive resources and are often located in vulnerable geographies (ICMM 2013) like mountain regions. For instance, expansion of extractive industries in the Andes Mountains of Ecuador, Peru, Chile, and Argentina poses challenges for local communities and the systems surrounding the area due the increases competition for scarce water resources during droughts and degrades the biological resources upon which livelihoods and social relationships depend (Bebbington et al. 2015). In the Western Balkan Mountains of Bulgaria and Serbia, legacy environmental problems related to war and abandoned industrial and mining sites exacerbate the water pollution risk due projected precipitation increases. In this region, approximately 60 abandoned sites are considered to be of significant environmental and security concern and even pose transborder water risks (Alfthan et al. 2015). A similar situation is faced in the Carpathian Mountains of the Czech Republic, Slovakia, Poland, Hungary, Ukraine, Romania, and Serbia. Mining activities have polluted the Danube and Maritsa river basins with heavy metals, which have the potential to disperse due to enhanced soil erosion and runoff from high precipitation events over short periods (Bird et al. 2010; Alberton et al. 2017). In the South Caucasus Mountains of Armenia, Azerbaijan, and Georgia, water shortages and pollution from mining facilities negatively affect aquatic ecosystems (Shatberashvili et al. 2015).

The Canadian mining industry is also vulnerable to the consequences of climate change. In the last 30 years, mines across Canada have been impacted by significant climate events (Pearce et al. 2009). For instance, headwater catchments in Elk Valley, a mountainous region in the province of British Columbia, were contaminated by water from coal mine waste rock dumps, which migrated through groundwater strata and into surface water after heavy rainfall events (Szmigielski et al. 2018). The Canadian mining industry may be especially vulnerable to climate change effects (e.g., wildfires, floods, windstorms, water scarcity, and sea-level rise) because mining facility design assumed a stable climate (Pearce et al. 2009). As with the examples above from South America and eastern Europe, these effects would increase social conflicts among local resource users particularly water users (Phillips 2016). Indeed, most mining operations around the world are substantial water users and can compete with agriculture and human settlements within the catchments where they operate.

The magnitude and geographical range of climate change effects remain uncertain (Institute of Environmental Management & Assessment 2015), and their relationship with the mining sector is even more poorly understood because the topic has received limited attention from researchers (Pearce et al. 2009; Odell, Bebbington, and Frey 2017) . There is relatively little scientific research on water resources, climate change risk, sustainability, and resource management for many arid regions of the world, such as the Andean Mountains (Rangecroft et al. 2013; Odell, Bebbington, and Frey 2017). Such uncertainties make it difficult to assess the potential impacts on current and future mining operations and projects or closure plans. However, it is possible to consider a range of potential factors contributing to climate change impacts, based on the available literature and the use of climate risk protocols designed for cities and public infrastructure (CALEMA 2012; ICLEI: Local Governments for Sustainability 2013; Engineers Canada 2016; The World Bank Group 2017). Extreme climatic conditions will disturb the stability and efficacy of mine infrastructure and equipment, environmental protection and site closure practices, and accessibility of transportation routes (Nelson and Schuchard 2011). It can be reasonably argued that the long-term success and prosperity of mining companies will depend on their ability to manage their climate change impacts with mitigation plans and to reduce risk with adaptation programs (Pearce et al. 2011). Therefore, effective management systems becomes increasingly necessary to handle the climate change risks (Schoolmeester et al. 2016).

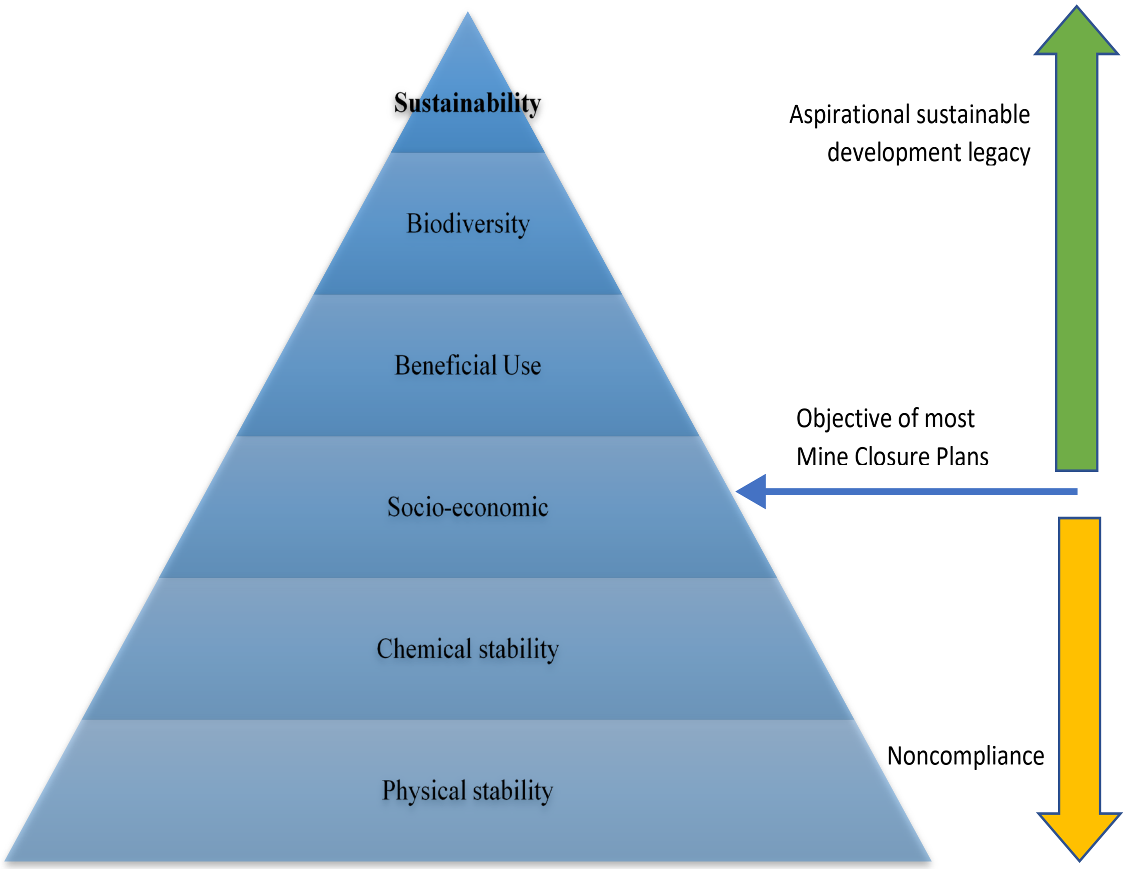
The main impacts of climate change relate to physical risks during operations that will affect financial performance, damage assets on site, including employee health and safety due heat waves, and interrupt supply chains (ICMM 2013). Therefore, International Council on Mining & Metals (ICMM) member companies have incorporated climate change considerations into internal risk management processes at the facility scale, but they have recently recognised that our understanding of climate-related physical risks and opportunities is incomplete (ICMM 2019a). Moreover, shareholders, investors, and insurance firms are beginning to contemplate the consequences of climate risk to the long-term financial performance of companies and are pressuring mining companies to minimise carbon liabilities and develop adaptation plans (Nelson and Schuchard 2011; Rüttinger and Sharma 2016; Thistlethwaite and Wood 2018). For example, in 2016, some of the world's most profitable mining companies received a request from a group of shareholders (The Church of England and the Environment Agency Pension Fund, among others) to collaborate on a comprehensive plan to reduce GHG emissions by 2035 (The Church of England 2016; Glencore 2016; Wildsmith 2017). The plan would include ongoing operational emissions management, low-carbon energy investment strategies, relevant strategic key performance indicators, and public policy positions relating to climate change. The Church of England (www.churchofengland.org) considers climate change to be a financial and physical risk to their investments and co-led the creation of Climate Action 100+ (www.climateaction100.org) to improve climate performance and emissions disclosures by the world's largest corporations.

2.3 Mine Closure and Reclamation

Myriad factors reduce the capacity of the soil to provide ecosystem services and make land restoration difficult, with the potential to reduce the corresponding capacity of the soil to provide ecosystem services (Secretariat of the Convention on Biological Diversity 2019a). Land-use changes affect the hydrological cycle and water quality, particularly in mountainous regions where integrated watershed management is not properly applied (Schreier 2005). Mining activities alter soil structure, which, in combination with climate change, can have severe negative consequences such as soil compaction, erosion, loss of soil organic carbon, land degradation, loss of biodiversity (Sudmeier-rieux et al. 2006; Shatberashvili et al. 2015; Schreier 2017), and lower water retention capacity (Barnhisel, Darmody, and Daniels 2000; Stevenson, Hunter, and Rhodes 2014) with associated negative impacts on vegetation growth rates (Yousef and Ouarda 2015). The term Restoration was officially defined by the Society for Ecological Restoration as "*the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed*" (Gann et al. 2019). The term Rehabilitation or Reclamation is used "*for ecological repair activities that aim to restore ecosystem functioning (…) making severely degraded land fit for cultivation for some human use*" (Gann et al. 2019), "*to be safe, stable, non-polluting and consistent with the agreed post mining land use*" (ISO 2020). Therefore, to recover ecosystem health, a structured and interdisciplinary restoration plan is required that incorporates knowledge of local climate change effects in the decision-making process.

Unplanned closure of mine sites was common throughout the world until the 1960s, when communities and farmers took legal action against mine operators who polluted land and water (Cowan, Mackasey, and Robertson 2010; Hockley and Hockley 2015). In the 1980s and 1990s, several countries and nine Canadian provinces developed and implemented mine closure regulations (Hockley and Hockley 2015). In general, current worldwide mine closure legislation, standards, and guidelines provide a hierarchical framework to support design criteria for closure plans that at least minimally address physical and chemical stability concerns and return the land and water to the pre-mining state (Figure 2.1). The socio-economic transition factors in this hierarchy are influenced by the jurisdiction where the operation is located and the technical aspects and standards of each mining company (McHaina 2003; Beckett and Keeling 2019). To be sustainable in the long term, robust advanced planning is required that considers the rehabilitated land-use potential risks. Figure 2.1 illustrates the steps required in mine closure planning to accomplish both regulatory compliance and the aspirational sustainable development legacy (APEC 2018).

Figure 2.1 Hierarchy of mine closure needs



Adapted from (APEC 2018)

In recent years, several organisations have developed or updated guidelines related to mine closure (ICMM 2019b; IGF 2019; APEC 2018; MAC 2008) to integrate the international closure design experience gained by the industry. Furthermore, the International Organization for Standardization is finalizing a series of international standards (ISO 21795) that will provide requirements and recommendations for mine closure and reclamation management to promote consistency and quality in planning (ISO 2017). This is important because, without useful standards for mine closure and reclamation, potential risks and opportunities could be ignored (Murphy, Nahir, and Didier 2019), with negative effects for society, the environment, and mining companies. Despite these promising new developments, current approaches to mine closure design focus at the mine level and do not consider the broader integrated system of people and the natural ecosystem.

Planning for sustainable development as a final objective of mine closure design requires an interdisciplinary perspective that combines measures for environmental and biodiversity protection, social inclusion, economic diversification, and public safety. Most regulations consider at least the socio-economic transition factors in Figure 2.1. The unique potential risks posed by climate change are not necessarily given sufficient attention in current guidelines. A closure design approach that is reactive to climate change will be less expensive in the short term than a proactive adaptation overdesign based on uncertain projections, but will carry potentially larger future risks (ICMM 2019b). At the same time, there is not a clearly accepted practice to apply climate risk information to closure design (ICMM 2019b; Labonté-Raymond et al. 2020; Punia 2021). This is an important knowledge gap and one that this dissertation aims to fill.

2.4 Climate Risk Assessment and Adaptation for Watersheds

The climate of mountain regions plays an important role in numerous environmental systems. For example, fluctuations in water quantity and quality affect aquatic life and have socio-economic impacts on people living within and downstream of the affected watershed (Beniston 2006). There is a growing awareness that mountain water supplies are under pressure because of increased climatic variability and snowpack reduction; that land use changes are impacting the hydrological qualities of the surrounding area; and that maintaining sufficient water quantity and quality is needed for ecosystem services to continue supporting the livelihoods of the populations living around the affected watershed (Krecek et al. 2012).

Mountain watersheds are highly complex, extremely variable, and sensitive to human land use changes (Schreier 2005) and natural hazards and extreme weather events, which are already increasing in both magnitude and frequency with climate change (Oppenheimer et al. 2014). Temporal and quantitative shifts in precipitation and snowmelt affected by temperature alter water flow in rivers and streams beyond the hydrological system capacity, with potentially large impacts on species habitats (Parrott, Robinson, and Hik 2018). These events could materialise in short periods of time, with consequently high volumes of water triggering intense floods, debris flows, landslides, and avalanches in the catchment zone (Borga et al. 2014; Beniston 2006). In disturbed lands, like those that occur in areas affected by mining operations, the resulting soil structure changes may reduce the soil's maximum water-holding capacity (Moret-Fernández, Peña-Sancho, and López 2016).

Canada's Changing Climate Report (Bush and Lemmen 2019) describes anticipated changes in the seasonal availability of fresh water and the increased risk of water supply shortages in the summer. Warmer winters and earlier snowmelt will combine to produce higher streamflow in winter, and reduced snowpack and glacier ice will produce lower streamflow in summer (Derksen et al. 2019). Warmer summers will increase evaporation of surface water and contribute to reduced summer water availability, despite more precipitation at some locations. The imminent warmer climate will intensify some weather extremes (Bonsal et al. 2019) such as droughts or thunderstorms. Extreme hot temperatures will become more frequent and more intense in Canada, increasing the severity of heatwaves and contributing to higher wildfire risks. While inland flooding results from multiple factors, more intense rainfalls will increase urban flood risks. The purpose of the National Assessment is to enhance understanding of climate change impacts and adaptation in Canada and provide the evidence base for informed decision making (Bush and Flato 2018). Yet it remains uncertain how warmer temperatures and smaller snowpacks will combine to affect the frequency and magnitude of snowmelt-related flooding at the watershed level (Zhang et al. 2019): local assessments are required to address this issue.

The impacts of climate change are highly variable and location-dependent (Oppenheimer et al. 2014). The risk is often represented as probability of injury, damage, loss, loss of function, or negative environmental impact created by hazardous events or trends multiplied by the impacts of these events or trends. The interaction of climate-related hazards to vulnerable systems with low adaptation capacity is expected to lead to severe, and in some cases, irreversible impacts (Papathoma-Köhle, Promper, and Glade 2016). Understanding the relationship between local settlements and local climate hazards is a critical first step in developing adaptations to manage future climate risks. Understanding the current climate risks, vulnerability of species, ecosystems, and ecological processes is essential to understand how risk patterns and potential benefits are shifting due to climate change and inform implementation of design adaptation strategies for the mining sector with a sustainable management perspective (Jones and Boer 2004; Field et al. 2014; Gross et al. 2016).

A risk assessment measures the risk created by identifiable hazards (IPCC 2007). The risk of a climate-related impact is the consequence of the interaction between the vulnerability and exposure of the social and ecological systems and the climate-related hazard in a specific area (Field et al. 2014). This interaction is conceptualised in Figure 2.2.

- The Hazard is "*the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources*" (IPCC 2014d).

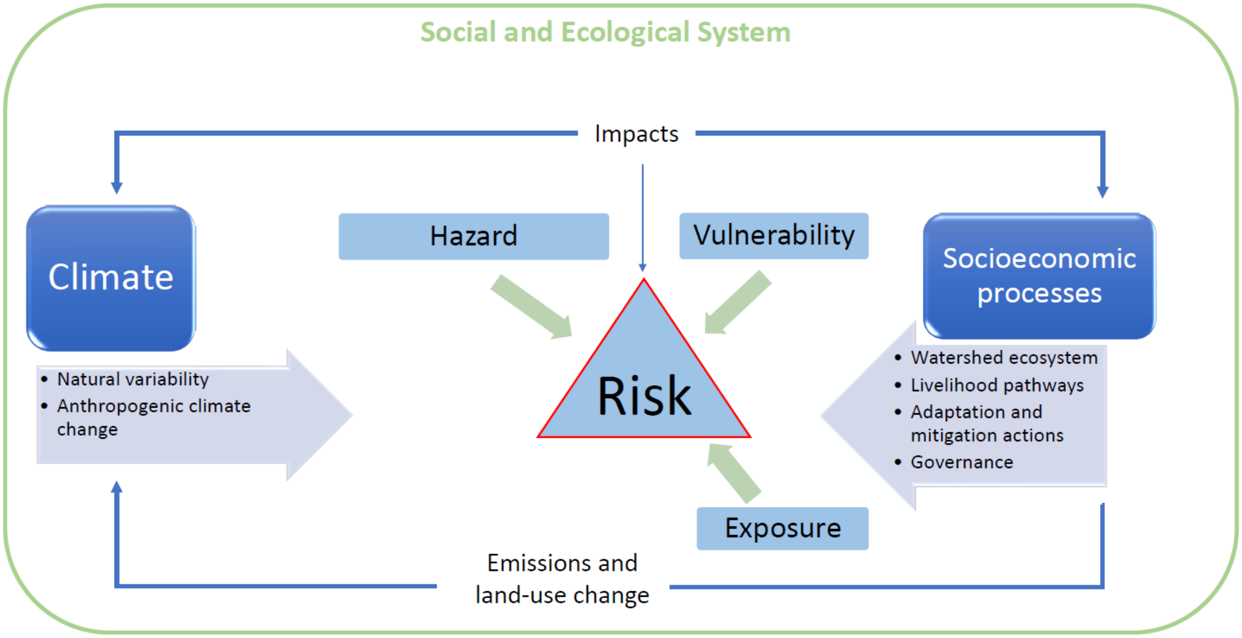
- Vulnerability to climate change is defined as "*the propensity or predisposition to be adversely affected*" (IPCC 2014e). The vulnerability elements are the sensitivity and the adaptive capacity, and they strongly depend on context and the internal characteristics of the affected component. Sensitivity is described as the "*degree to which a system is affected, either adversely or beneficially, by climate variability or change*" (IPCC, 2007). Adaptive capacity is the ability of institutions, systems, and individuals to adjust to climate change (including climate variability and extremes) and to moderate potential damage, to take advantage of opportunities, or to cope with the consequences of potential damage (Millenium Ecosystem Assessment 2005; IPCC 2007).

- Exposure denotes "*the presence of people, livelihoods, environmental services and resources, economic, social and cultural assets, public infrastructure*" (IPCC 2014a), institutions, species or ecosystems, in locations that could be adversely affected by physical events. Exposed elements are subject to potential future damage or detriment.

- Adaptation is defined as "*the process of adjustment in natural or human systems to actual or expected climate stimuli and its effects*" (IPCC 2014c). In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to climate change and its effects (Field et al. 2014).

Figure 2.2 Climate risk concept interactions

Climate risk in the social-ecological system is a consequence of the interaction between climate-related hazards and the vulnerability and exposure elements of people and the watershed ecosystem. Climate change will affect local weather and the socio-economic processes that influence the level of climate risk. Greenhouse gas emissions and land-use changes influenced by humans exacerbate climate change, altering climate patterns.



Adapted from (Field et al. 2014)

Climate risk assessment can be performed at a range of scales. For example, at the mine operation scale, it can analyse all potential impacts of climate change on infrastructure. At the scale of the watershed surrounding the operation, impacts on the serviceability and functionality of the social-ecological system (SES) as well as broader socio-economic and environmental effects can be assessed (Engineers Canada 2016). These assessments will inform the scientific understanding of climate-sensitive systems under changing climate conditions and aid development of adaptation strategies that reduce climate-sensitive risks (Füssel and Klein 2006).

The number of scientific publications that assessed climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation (Field et al. 2014). However, the majority of the literature related to climate change and mining is focused on mitigation actions for reducing GHG emissions during operation, strategies for energy efficiency, implementing clean technology, and carbon pricing (Pearce et al. 2009). Adaptation practice analyses in the mining industry are very limited and only establish general principles for integrating adaptation planning in business. An example is the *Energy and Greenhouse Gas Emissions Management Guide – Towards Sustainable Mining* (MAC 2014). At the time of writing this dissertation, the Mining Association of Canada (MAC) published the *Guide on Climate Change Adaptation for the Mining Sector* (MAC 2021). The focus of the climate risk methodology in the guide is solely on site operations and adaptation strategies are limited to infrastructure improvements and procedure reviews with only general consideration of the closure stage. The concept of climate risk, as defined by IPCC and previously described, is not fully considered in the MAC document. Given a lack of concrete guidelines in the sector, there is an urgent need to incorporate climate risk assessment practices and adaptation strategies that can support a holistic approach to designing sustainable mine closure plans.

2.5 Ecosystem-Based Adaptation in Mountainous Regions

When a mountain ecosystem is in good health, it helps to protect against the impacts of extreme events, particularly hydrological events such as floods and droughts. This is an example of regulating ecosystem services, which are particularly critical to protect downstream areas, where the effects of such hazards are often greatest and occur over long distances (P. Egan and Price 2017). Therefore, well-managed mountain ecosystems can provide adaptive and cost-efficient flood risk management solutions that will be especially useful in light of uncertain climate change scenarios (Sebesvari, Rodrigues, and Renaud 2017). If conserved and sustainably managed, ecosystems and their inherent capacity as ecosystem service providers can have a vital role in helping people adapt to a changing climate (Sudmeier-rieux et al. 2006).

The concept of using ecosystems to adapt to climate change, EbA, has arisen as a promising approach due to growing recognition of the multiple environmental and socio-economic benefits they provide (Potschin et al. 2016). The term was officially defined by the Convention on Biological Diversity as "*the use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change that may include sustainable management, conservation and restoration of ecosystems, as part of an overall adaptation strategy that takes into account the multiple social, economic and cultural co-benefits for local communities*" (Secretariat of the Convention on Biological Diversity 2009). Therefore, incorporating EbA strategies into mine closure design has the potential to reduce the potential climate risk to land restoration processes.

Of the following four examples of EbA activities included in a joint document by the United Nations Environment Programme – International Ecosystem Management Partnership and the International Institute for Environment and Development (Swiderska, King-okumu, and Islam 2018), the last two relate to mountains.

- Restore coastal defence through the maintenance and/or restoration of mangrove forests in order to reduce the intensity of tropical storms and risk for coastal communities.
- Conserve agrobiodiversity to provide specific gene pools for agriculture adaptation to climate change.
- Conserve and restore forests to stabilise land slopes, protect and restore watersheds, and prevent landslides.
- Manage wetlands and floodplains to maintain water flow and quality for communities facing changing rainfall patterns.

The joint effects of external and internal pressures affect the hydrological cycle and water quality in mountainous watersheds in ways that are not entirely predictable. It is challenging to analyse the effects of land-use changes and climate change separately because both disruptors occur simultaneously (Schreier 2005). Therefore, it is important to have a comprehensive approach to closure design that accounts for both disruptors, includes land restoration, and incorporates adaptation strategies that promote the use of ecosystem services along the SES.

EbA involves conservation, sustainable management, and restoration of ecosystems that provide key services and increase the resilience of communities to disruptor effects throughout the watershed (Baig, Rizvi, and Pangilinan 2016). Conservation protects the function, structure, and species composition of ecosystems, recognizing that all components are interconnected (Olivier et al. 2012). Sustainable management of resources promotes the long-term sustainability of ecosystems and ongoing delivery of essential ecosystem services to society (Terton and Dazé 2018). Restoration strengthens and assists the recovery of ecosystem functions that have been degraded, damaged, or destroyed (Swiderska, King-okumu, and Islam 2018). These ecosystem service elements cover different social, economic, political, and ecological settings and their connections within a SES, defined as "*complex systems of people and nature, emphasising that humans must be seen as a part of, not apart from, nature*" (Berkes et al. 1998). Thus, mine closure design should consider this integrated system of people and ecosystem as the basic unit of study, informed by an interdisciplinary analysis and a holistic perspective of the watershed.

Among mitigation measures, investments in adaptation are most susceptible to uncertainties due to local climate impacts (Jones et al. 2014). Nonetheless, ecosystem solutions can also prolong the lifetime of mitigation infrastructure, protecting investments in engineered defenses such as the use of wetlands to prevent water erosion (Secretariat of the Convention on Biological Diversity 2019a). Studies have found that an EbA approach can improve aspects of the hydrological cycle (e.g., groundwater recharge, runoff reduction) and soil quality (e.g., erosion control) that will improve land restoration (Taffarello et al. 2017). There is the added potential to obtain carbon credits (e.g., sequester carbon in wetlands; Schreier 2005) and other benefits, including pollination services and livelihood diversification by providing habitat for different species (Seddon et al. 2016).

The promising role of ecosystem services as part of adaptation to climate change and disaster risk reduction has been well recognised (Chettri et al. 2014; Egan and Price 2017; Faivre et al. 2018; Karki et al. 2018), except for ecosystem services provided by mountains due their vast area distribution and challenging geography (Martín-López et al. 2019). The potential to apply EbA approaches within the mining industry is even further understudied. This creates a promising opportunity to consider EbA within climate risk assessment to enhance comprehension of the range of potential future conditions in the SES, and ultimately, to design and plan mine closure within mountainous regions.

2.6 Discussion of Literature Review

Compared with other time periods, global climate change in our present era is a consequence of different internal and external factors, among which anthropogenic forces, which produce a persistent change in the composition of the atmosphere and land-use patterns, are the most significant and attributable factors. This change will increase the likelihood of climate-related risks for natural and human systems, the impacts of which will depend on the magnitude and rate of warming, geographic location, levels of vulnerability and exposure, and adaptation and mitigation alternatives.

The signatory countries of the Paris Agreement are struggling to achieve the goal of limiting the global average temperature rise to below 2°C and pursue efforts to limit the increase to 1.5°C. However, action is slow. According to Canada's last *Changing Climate Report*, past and projected future warming rate in Canada is, on average, approximately double the magnitude of the global rate. New practices beyond mitigation and reduction of GHG emissions are required to address this discrepancy.

Some consequences of climate change impacts will be high, or even catastrophic, for the most vulnerable systems. Mountainous regions are one such example, which provide the world with a multitude of ecosystem services, from minerals to forests to unique species of plants and animals. Moreover, mountains represent approximately 25% of Earth's terrestrial surface area and are home to approximately 25% of the global population. There remain huge deposits of minerals in mountainous regions, and some of them will provide the metals for the technology required to transition to decarbonised energy production. Mountains are considered the water towers of the world: all rivers originate there. However, increased climatic variability and snowpack reduction are threatening the hydrological resource in these regions. Consequently, it is critical to understand the factors that would increase the hazards in these areas to reduce risk and improve opportunities to manage natural resources in a sustainable and holistic manner.

A changing climate presents physical risks to the mining and metals industry, impacting core operations, including the health and safety of employees, physical assets, processes, and operation maintenance activities. These risks also extend beyond the mine site because these industries are often located in challenging geographies and manage climate-sensitive resources (i.e., water and energy) that are critical in the SES. Climate risk assessment is crucial to identify the areas and communities most in danger as well as the key impacts of a changing climate. Executing a climate risk assessment will help to define adaptation strategies, allocate resources where they are most needed, and design monitoring plans.

Mining activities alter the structure of the landscape, which in combination with climate change, can have severe consequences. The impact of these land-use changes on hydrology and water quality is a major topic of concern because they are associated with higher risk of additional hazards such as landslides, slope instability, avalanches, mudflows, and mudslides. Interactions between climate-related hazards and vulnerable systems with low adaptation capacity, like mountain watersheds, is expected to lead to severe—and in some cases irreversible—impacts, such biodiversity loss, water pollution, and extensive wildfires. Therefore, the long-term success of land restoration by mining companies will depend on their ability to manage climate change impacts with adaptation plans to reduce the climate-related risk. Despite their importance, interactions between mine closure and climate change have received limited attention by mining companies and academic research. This dissertation and future research on the EbA approach, which involves conservation, sustainable management, and restoration of natural resources, could be provide the framework to develop mine closure plans to limit the adverse effects of climate and land-use changes.

Chapter 3: Methodologies and Case Study

As mentioned in Section 1.2, the two principal objectives of this research are to:

1. examine, identify, and describe potential threats and opportunities posed by climate change to mine closure design in mountainous watersheds, and
2. develop a novel framework that could be used to guide decision making by mine managers to improve climate risk management and adaptation strategies during mine closure and land reclamation stages.

In addressing these objectives, this thesis aims to make a practical contribution to the mining sector by managing climate-related risk, enhancing societal trust of industry, and ultimately promoting sustainable development. To meet these objectives, four research questions were established to be addressed through a multi-method research approach (Table 3.1).

Table 3.1 Research questions and methodology

Research Questions	Methodology	Academic Contribution
What practices do mining companies currently use to adapt to climate change risks?	Trend analysis	Benchmark climate change adaptation practices
What practices could facilitate adaptation to climate change risks in mountainous watersheds during mine closure stage?	Delphi survey	Identify potential adaptation options for mine closure in mountain regions
How could a novel approach to climate risk management contribute to assessing mine closure component responses to impacts of a changing climate on mountainous watersheds?	Case study: Climate risk assessment Ecosystem-based Adaptation (EbA) strategies	Improve understanding of climate change impacts on mine closure components in mountain regions
How could an EbA approach contribute to mine closure practices at a watershed scale in mountainous regions?		Assess relevance of EbA and develop adaptation strategies to inform mine closure design

Questions 1 and 2 aim to improve our conceptual understanding of actual and possible practices applied in the mining sector worldwide in relation to climate change risks. More importantly, the studies will inform the gap between current and potential practices for the land restoration and mine closure stages within mountain ecosystems. Questions 3 and 4 improve our technical understanding of current climate risk assessment methodologies and allow development of hypotheses regarding how incorporation of an EbA approach could benefit the mine closure design process. To design a detailed novel framework of climate risk for mine closure, a selection of current instruments applied to climate risk assessment on public infrastructure in urban and rural areas will be scrutinised. The framework will consider and incorporate the results from questions 1 and 2. The novel framework will be applied to a real closure plan as a case study to understand potential local climate-related hazards and adaptation capacity at a watershed level. The assessment will contribute to the planning of adaptation measures based on ecosystem services for the mine closure stage from a holistic watershed perspective.

This innovative framework that includes the EbA approach and a SES perspective will address the gaps in the literature highlighted in Chapter 2. It will also support application of new strategies based on EbA to mine closure design in mountainous regions.

3.1 Trend Analysis: Climate Change Benchmarking in the Mining Sector

Researchers have argued that the mining sector is not giving enough attention to adaptation plans in areas disturbed by mining operations and that the climate change risk in watersheds surrounding mining activities requires more understanding (Pearce et al. 2009; Lomax 2016). To develop the knowledge base in this area, a systematic literature review was conducted of current publicly available data and self-reported information provided by mining companies. Information sources included corporate sustainability reports and the CDP (formerly the Carbon Disclosure Project). The assessment used a benchmarking methodology to identify and understand the management of climate change impacts and risks in the mining sector in order to answer the first research question and core purpose of the trend analysis: *What practices do mining companies currently use to adapt to climate change risks?*

Current business sustainability and environmental reports include useful information regarding climate change mitigation practices. These reports provide practical and summarised data from corporate activities and actions in an established structure (Bennett, James, and Klinkers 1999; Burritt, Schaltegger, and Zvezdov 2011). A common methodology to draw information from these reports based on scoring/benchmarking techniques permits examination of businesses in the same topic as the study (Demertzidis et al. 2015). Benchmarking has been described as a performance measurement tool, whose effectiveness depends on its practical value. According to the United States National Research Council, benchmarking is the "*systematic process of measuring one's performance against recognized leaders for the purpose of determining best practices that lead to superior performance when adapted and utilized*" (National Research Council of the National Academies 2005). Companies studying best practices have the greatest opportunity to gain a strategic, operational, and financial advantage (Kelessidis 2000).

This study reviewed the top 10 mining companies by market capitalisation, that is, the largest firm size by market value in the mining industry (Marciniak and Smith 2018). These companies were ranked in April 2017 by S&P (Table 3.2), a provider of worldwide financial and commodity market analytics (S&P Global Market Intelligence 2017; Ahmed 2018). Mining companies were defined as those involved in extraction of a broad range of metals and minerals, including precious and base metals, industrial minerals, coal, and uranium. The best-in-class approach was used to rank the mining companies by applying standard market benchmark analysis (Collins et al. 2006). This selection process has been chosen in previous studies because the degree of climate change disclosures of companies is related to their market size (large companies) and management commitment level (Stanny and Ely 2008; Lewis, Walls, and Dowell 2014). The peer group selected for this study initially included Southern Copper Corp., but it is a majority-owned, indirect subsidiary of Grupo México SAB de CV, and both publish the same Sustainability Reports. Therefore, Freeport-McMoRan Inc. was chosen as the 10th company (Table 3.2).

Table 3.2 Top 25 metal and mining companies ranked by market cap[1]

Ranking						Market cap change from (%)	
Current	End-March 2017	End-April 2016	Institution name	Trading symbol-exchange	Market cap (US$B)	End-March 2017	End-April 2016
1	1	1	BHP Billiton Group	BHP-ASX	89.10	(2.6)	11.9
2	2	2	Rio Tinto	RIO-LON	73.98	–1.0	17.4
3	3	3	Glencore Plc	GLEN-LON	56.55	0.3	64.8
4	4	5	Vale SA	VALE5-BSP	43.47	–8.4	60.2
5	6	6	Southern Copper Corp.	SCCO-US	27.34	–1.4	19.1
6	5	4	Coal India Ltd.	533278-BOM	26.73	–4.6	–2.2
7	7	7	PJSC Norilsk Nickel Co.	GMKN-ME	24.10	–3.1	5.5
8	8	9	Grupo México SAB de Cv	GMEXICO.B-MEX	22.72	–2.3	14.2
9	10	14	Anglo American Plc	AAL-LON	20.11	–6.2	39.3
10	9	8	Barrick Gold Corp.	ABX-US	19.49	–12.0	–13.6
11	11	11	Freeport-McMoRan Inc.	FCX-US	18.43	–4.6	5.1
12	13	10	Newmont Mining Corp.	NEM-US	18.03	2.9	–2.8
13	12	20	Hindustan Zinc Ltd.	500188-BOM	17.67	–6.1	61.5
14	14	15	PJSC Polyus	PLZL-ME	14.74	–2.1	4.8
15	17	13	Potash Corp. of Sask.	POT-TSX	14.14	–1.2	–4.9
16	16	16	Fresnillo Plc	FRES-LON	13.84	–3.5	15.2
17	18	17	Agrium Inc.	AGU-TSX	12.95	–1.5	8.5
18	24	27	PJSC Alrosa	ALRS-ME	12.68	6.6	50.8
19	20	18	Saudi Arabian Mining Co.	1211-TSE	12.58	–1.3	10.5
20	15	28	Fortescue Metals Group Ltd.	FMG-ASX	12.37	–16.4	52.6
21	19	19	Newcrest Mining Ltd.	NCM-ASX	12.14	–6.8	9.4
22	26	16	Franco-Nevada Corp.	FNV-TSX	12.12	3.9	–3.0
23	25	34	Albemarle Corp.	ALB-US	12.06	3.1	62.4
24	21	37	Teck Resources Ltd.	TECK.B-TSX	11.97	–5.0	69.0
25	23	12	Goldcorp Inc.	GG-US	11.94	–4.3	–28.8

[1] Data as April 28, 2017. Company list obtained from mining-focused companies included the most recent Industry Monitor. Source: (S&P Global Market Intelligence 2017)

In all cases, when available, the climate change performance data and climate-related risk assessments as reported by each company in the 2017 CDP are reviewed. Sustainability Reports published during 2017 and 2018 of the global top ten mining companies were reviewed to understand the development trends regarding climate change risk management and adaptation. This research seeks to identify “best practices” employed by companies, rather than measure the best performance among them. A common set of measures related to climate change was defined and integrated into a data collection system.

Four questions were used to assess the current practices that the mining sector uses in climate change management: (1) What are mining companies doing about climate change? (2) What are the most important climate-related risks for mining companies? (3) What future impacts do the companies foresee they will face in extreme weather scenarios? (4) How are mining companies planning to adapt to climate change risks and impacts? The results will improve our understanding of current practices and more importantly, the gap between current and best practices in the mining sector.

The first assessment considered current approaches employed by these mining companies to manage the impacts of climate change. Table 3.3 lists the objective for each parameter that was used to review the information provided in the latest sustainability report for each company (available until February 2018). At the same time and when available, climate change performance data and risk management information reported by each company in the 2017 CDP were reviewed.

Table 3.3 What are mining companies doing about climate change?

	Parameter	Objective
a.	Development of policies and corporate guidelines	Assess the establishment of specific policies or corporate guidelines related to climate change management
b.	Highest management level decision-maker for climate change	Assess who is responsible for making decisions for the strategy and direction of the company in regard to climate change management
c.	Reporting of climate change data	Assess the mechanism the companies use for sharing and disclosing their climate change information
d.	Mechanism for climate change risk identification	Assess the process established in each company for describing risks and modeling future impacts

The second assessment considered the expected climate-related risks that each company reported for their operations. The research risk parameters (Table 3.4) were selected based on the literature review (Ford and Pearce 2010; Nelson and Schuchard 2011; Pearce et al. 2011; Bowyer et al. 2014; Odell, Bebbington, and Frey 2017). Each parameter received one point (01) for each company that identified the risk in its latest sustainability report (until February 2018).

Table 3.4 What are the most important climate-related risks for mining companies?

Parameter	Objective
a. Temperature	Assess the recognised and reported risks that the companies could have related to a changing climate When the report showed this parameter as a direct risk for any of its operations, one point (01) was assigned to the reported parameter
b. Heat waves	
c. Sea-level rise	
d. Precipitation	
e. Floods	
f. Storms	
g. Wind	
h. Drought	
i. Snow	
j. Fog	
k. Wildfires	

The third assessment considered expected impacts related to climate change risks reported by each company for operations. Each impact parameter selected based on the literature review (Table 3.5) received one point for each company that recognised a type of impact in the latest sustainability report (until February 2018).

Table 3.5 What future impacts do the companies foresee they will face in extreme weather scenarios?

Parameter	Objective
a. Infrastructure disturbance	Assess the impacts recognised and reported by the companies that could occur due to climate-related risks When the report showed this parameter as a direct impact for any of its operations, one point (01) was assigned to the reported parameter
b. Supply chain routes	
c. Product delivery routes	
d. Workforce health	
e. Water access	
f. Productivity reduction	
g. Reputational damage	
h. Incremental cost	
i. Policy and regulations	
j. Energy access	

The fourth assessment considered the adaptation plans that each company reported for their operations related to climate change risks. Each research adaptation plan parameter (Table 3.6) received one point (01) for each company that recognised a kind of adaptation plan for climate change in the latest sustainability report (until February 2018).

Table 3.6 How are mining companies planning to adapt to climate change risks and impacts?

Parameter	Objective
a. Risk scenario assessment	Assess the actions developed and reported for adaptation to climate change by the mining companies When the report reviewed showed this parameter as an adaptation action for any of its operations, one point (01) was assigned to the reported parameter
b. Energy efficiency	
c. Research collaboration	
d. Stakeholder communication	
e. Staff training and education	
f. Emergency response plans	
g. Water management plans	
h. Greenhouse gas emissions control	
i. Review of business strategy	

3.2 Delphi Survey: Assessment with a Panel of Experts

Anticipating future impacts of climate change is always uncertain, and when analytic modeling has reached its limit, expert judgment can be used to inform decision-makers (Morgan and Keith 1995). Experts are individuals with specialised knowledge—in this case on topics within the mining sector related to climate change adaptation in mountainous regions—and demonstrated experience and involvement in projects and/or publications related to the topics. Making use of expert high-level insights and aggregated knowledge allows for assessing the climate change adaptation strategies in a resource-efficient, participatory, and consensus-building manner (Haida et al. 2017). Approaches such as the "Delphi method' have been developed to obtain consensus summaries (Morgan and Keith 1995) across experts. The effects of climate change will impact multiple sectors, requiring a wide variety of experts and decision-makers to cooperatively reach solutions. Thus, the Delphi survey methodology was selected to engage climate change experts from academia, the mining industry, and public institutions.

The Delphi survey technique is extensively used to gather data via an anonymous, written, multi-stage survey process (von der Gracht 2012). It is widely used to assemble current or future data on economic, business, environmental, social, and other areas (Nguyen et al. 2017). The technique involves assembling an anonymous panel of experts to reach consensus on a complex technical problem. It allows the researcher to obtain immediate access to professional information and solid knowledge on a given matter without undertaking a primary investigation (Baker 2006). The Delphi method is a structured, iterative consultation and survey process to forecast and build consensus (Hanna and Noble 2015) that typically consists of two or more rounds of analysis and data interpretation on future developments and incidents (Gotay 2013).

The process begins once the experts agree to engage with the study, with continuous focus on group communication between panel experts. In the classical Delphi study, the first round of questions about a particular problem is presented in an online forum to facilitate brainstorming and obtain opinions from a panel of experts (Gotay 2013). The group of experts reply anonymously to the questionnaire and receive feedback afterwards in the form of a statistical representation of the “Group Response,” then the process repeats itself (Adekunle and Adeyinka 2017).

The objective of this study is to use consensus building to answer the second research question: *What practices could facilitate adaptation to climate change risks in mountainous watersheds during mine closure?* Consensus was considered achieved if greater than 70% of participants agreed with a statement, starting with the second round. Once consensus is reached the rounds of the Delphi study will conclude. Consensus is expressed as percent agreement and most of Delphi surveys are completed in two or three rounds (Diamond et al. 2014). Levels of agreement and number of rounds are aligned with criteria applied in previous Delphi studies (Slade et al. 2014; Diamond et al. 2014; Nguyen et al. 2017; Vogel et al. 2019)

A non-probability purposive sample of 90 participants was invited via email to participate in the Delphi survey. A maximum of 30 potential participants was invited from each of three types of organisations in North America, South America, Europe, and Asia-Pacific: universities, mining companies and/or mining associations, and global institutions or organisations related to climate change and adaptation management. Individuals were selected using the support of the professional networking site LinkedIn’s search function, which allows a Boolean search using the inclusion criteria defined for each group in the Sampling Methodology (Table 3.7). Former Delphi studies suggested a minimum of 12 respondents to be sufficient to allow consensus to be achieved (Vogel et al. 2019). This study used a minimum of 15 experts (five per group) to assess the adaptation strategies that could be applied in the mining sector for mine closure planning and land restoration. The search function on LinkedIn was also used to identify individuals with a specific skill, in a specific position within a company, or working at a specific location. A user can search a host of keywords, people's names, job titles, company names, and locations. The data can be filtered by degree of relationship and multiple other options to help target specific results.

Table 3.7 Sampling methodology - Delphi survey

Group	Selection criteria for individuals
Academic / Scientific (*n* = min 5)	Individuals will be selected using the LinkedIn search function. Individuals must have PhD level and more than 10 years' experience in climate change and/or adaptation strategies, with interest in mountainous regions Individuals must have at least 05 (five) publications in journals related to climate change and/or adaptation strategies between the years 2007 - 2017. Individuals must have been cited at least in ten peer-reviewed papers or publications
Mining Industry / Associations (*n = min 5*)	Individuals will be selected using the LinkedIn search function. Individuals must have at least 10 years' experience in environmental and/or sustainability areas Individuals must have at least four years' experience in mine closure, restoration or land reclamation Individuals must have a senior-level decision-making capacity (Superintendent, Manager or Senior Manager, Director) Individuals must have been actively working in 2018
Public Institutions / Organisations (*n = min 5*)	Individuals will be selected using the LinkedIn search function. Individuals must have at least 10 years' experience in climate change and/or adaptation strategies Individuals must have experience as team members in the design and/or execution of at least five projects related to climate change and/or adaptation strategies in mountainous regions Individuals must have been actively working in the year of the survey (2018).

The uncertainty of climate-related impacts and the adaptation practices needed to address them in the mine closure stage could be addressed by using the subjective judgments of various experts obtained via structured interviews or questionnaires (Hagerman et al. 2010). According to the IPCC, knowledge integration should start with an assessment of the sensitivity of the environmental service to climate change, followed by identification and prioritisation of locally applicable adaptation requirements (Oppenheimer et al. 2014). In the context of future climate risk, a comprehensive mine closure plan should include climate risk expert advice and contribute to strengthening knowledge and identifying innovative strategies as part of a proactive approach to managing these risks in the mining industry.

The survey began with a group of general questions established in the Research Questionnaire (Appendix A.1) to identify objectives and problems the study should address. The first round was implemented as an open questionnaire to prioritise the selected problems. In the second round a closed questionnaire with Likert scales (Appendix A.2) was used to re-assess the importance of the panel responses from the first round (Rowe and Wright 1999).

The Qualtrics online survey tool was used. This software also supported qualitative data analysis, organisation, and reporting of the results. Qualtrics complies with the British Columbia Freedom of Information and Protection of Privacy Act (FIPPA) because the survey data are kept secure, and they are stored and backed up in Canada (Toronto, ON and Montreal QC, respectively; UBC Survey Tool 2019). All research was carried out under the approval of the UBC Behavioural Research Ethics Board (BREB, approval number H18-01644).

3.3 Framework Development

The Climate Risk Assessment and Adaptation Framework (CRA-AF) for mine closure conceived and developed in this research is based on a set of guiding principles and procedures that describes a step-by-step method of risk assessment for evaluating climate change's impact on mine closure plans. These principles include:

- The objective is to assess climate risk on mine closure components and identify adaptation strategies based on this analysis.
- The assessment of climate risk is a multi-disciplinary process that relies on the social – ecological system.
- The process is results oriented, aiming for sustainable land restoration with a holistic perspective.

Section 3.3.1 describes a pragmatic procedure to answer the third research question: *How could a novel approach to climate risk management contribute to assessing mine closure component responses to impacts of changing climate on mountainous watersheds?* Section 3.3.2 describes the procedure to identify adaptation measures based in ecosystem services to answer the fourth research question: *How could an EbA approach contribute to mine closure practices at a watershed scale in a mountainous region?* The CRA-AF is designed in Chapter 6 and applied in a case study in Chapter 7. In Section 7.6, the CRA-AF results are compared with the current mine closure plan of the case study. The observations, conclusions, and recommendations derived from the application of the CRA-AF provide a context to support effective decision making about mine closure infrastructure operation, planning, and development. In addition, it enables scholarly analysis and knowledge accumulation of the climate risk and adaptation strategies in the mining industry.

All research was carried out under the approval of UBC’s Behavioural Research Ethics Board (BREB, approval number H18-03514).

3.3.1 Climate Risk Assessment for Mine Closure

As explained in Chapter 2, an effective risk assessment process should aim to indicate all potential impacts of climate change on mine infrastructure and the watershed surrounding the operation. Risk assessment is a process used to establish a measure of the risk created by identifiable hazards. As defined by the IPCC (IPCC 2007), risk is the possibility of injury, damage, loss, loss of function, or negative environmental impact created by a hazard. Risk of climate change impacts results from the interaction of vulnerability, exposure, and hazard in a specific area (Field et al. 2014). This includes not only impacts on the serviceability and functionality of the mine system, but also broader socio-economic effects in the SES.

While the need to study and analyse climate risk in the mining sector has been increasingly highlighted over the past years (Hodgkinson, Hobday, and Pinkard 2014; Bebbington et al. 2015), the majority of current climate risk assessments still focus largely on the mine site infrastructure impacts, its financial consequences, and the mitigation of GHGs. Moreover, climate risk is not fully understood in areas surrounding mines with strong social and ecological connections. Therefore, identification of risk reduction and adaptation strategies is based on deficient assumptions. To address these gaps and challenges, this dissertation builds on and extends the climate risk assessment concept to the mine closure stage based on methodologies that have already been successfully applied to assess climate risk within urban infrastructure. In response to the climate change challenges, an increasing number of cities worldwide have developed plans to achieve GHG reduction and infrastructure adaptation based on an understanding of future climate risks (Bulkeley and Betsill 2005; Benson and Clay 2004; Jha, Bloch, and Lamond 2012). Consequently, the perspective used by cities to design climate risk assessment protocols are key to develop successful mine closure climate-related risk strategies. This dissertation also extends the analysis by incorporating the SES spatial context.

Many climate risk assessment studies are related to coastal cities, where the effects of sea level rise are an important risk component due the general tendency for population growth in these areas (Hunt and Watkiss 2011). Further, the consideration of windstorms, floods from heavy precipitation events, extreme heat, and droughts have also informed approaches to assess the effects of extreme events on public infrastructure. Protocols for cities outline a risk-scoring methodology based on professional reasoning and apply standard risk assessment methodologies to generate quantitative information regarding the engineering vulnerability of an infrastructure system (Engineers Canada 2016).

The novel CRA-AF was designed based on the experience gained through assessing climate hazards to cities (Hallegatte and Corfee-Morlot 2011; Hunt and Watkiss 2011; CALEMA 2012; ICLEI 2017), vulnerability of public infrastructure to climate hazards (Public Infrastructure Engineering Vulnerability Committee or PIEVC; Engineers Canada 2016), and climate risk in agricultural and rural areas (Fritzsche et al. 2014; Hagenlocher et al. 2018; Barandiaran et al.

2019; Mafi-Gholami et al. 2019). Mining facilities could be compared with similar types of public infrastructure. In urban and rural cities some comparable examples are water supply management systems, storm water and wastewater services, transportation networks, power grids, pipelines, land use and management, among others. A comparative analysis was performed for four protocols commonly used to assess climate risk for public infrastructure in urban and rural areas: (1) PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment (Engineers Canada 2016); (2) The Vulnerability Sourcebook (Fritzsche et al. 2014); (3) ICLEI – Local Governments for Sustainability (ICLEI 2017); and (4) California Adaptation Planning Guide (CALEMA 2012). These were selected due to the experience of each institution applying the protocols in different locations and the guidelines developed for the execution. The Table 3.8 shown the sequences and components of each step applied for the protocols to assess the infrastructure climate risk.

Table 3.8 Infrastructure climate risk protocols steps

PIEVC	The Vulnerability Sourcebook	ICLEI	California Adaptation Planning Guide
Project Definition	**Preparing the vulnerability assessment**	**Initiate**	**Exposure**
Identify the Infrastructure Identify Climate Parameters Identify the Geography Identify Jurisdictional Considerations	Understand the context of the vulnerability assessment Identify objectives and expected outcomes Determine the scope of the vulnerability assessment Prepare an implementation plan	Identify stakeholders Build climate change adaptation team Identify an adaptation champion Take a first look at climate change impacts and existing adaptation actions Pass council resolution and community charter	Identify the climate change effects a community will experience
Data gathering and sufficiency	**Developing impact chains**	**Research**	**Sensitivity**
State infrastructure components State Geography Identify relevant climate parameters Identify infrastructure threshold values Identify potential cumulative or synergistic effects State climate baseline State changing-climate assumptions Establish changing-climate probability scores	Identify potential impacts Determine exposure Determine sensitivity Determine adaptive capacity Brainstorm adaptation measures (optional)	Initiate research on climatic changes Refine impacts and consider service areas for each Vulnerability assessment (study of sensitivity and adaptive capacity) Risk assessment (consequence and likelihood of impacts) and prioritization	Identify the key community structures, functions, and populations that are potentially susceptible to each climate change exposure.
Risk Assessment	**Identifying and selecting indicators**	**Plan**	**Potential impacts**
Establish infrastructure risk tolerance thresholds Risk assessment workshop Identify relevant infrastructure responses Establish interaction severity Calculate risk scores	Selecting indicators for exposure and sensitivity Selecting indicators for adaptive capacity Check if your indicators are specific enough Create a list of provisional indicators for each factor	Establish adaptation vision and objectives Set goals Identify options and actions Identify possible drivers and constraints Evaluate actions against drivers and constraints Determine appropriate baseline and indicator data Examine financing and budget Establish implementation schedule Create action plan Launch plan	Analyze how the climate change exposure will affect the community structures, functions, and populations (impacts).
Engineering Analysis	**Data acquisition and management**	**Implement**	**Adaptive Capacity**

PIEVC	The Vulnerability Sourcebook	ICLEI	California Adaptation Planning Guide
Calculate existing load Calculate changing-climate load Calculate other change loads Calculate total load Calculate existing capacity Calculate the projected change in existing capacity Calculate additional capacity Calculate the projected total capacity Calculate vulnerability ratio Calculate capacity deficit Identify conclusions and recommendations	Gather your data Data quality check Data management	Begin implementation Solidify support from Council and community Use appropriate implementation tools Follow terms of action plan Report on successes regularly to maintain momentum	Evaluate the community's current ability to address the projected impacts.
Recommendations and Conclusions	**Normalisation of indicator data**	**Monitor / Review**	**Risk and Onset**
Declare assumptions State conclusions State recommendations Statement of vulnerability/resiliency	Determine the scale of measurement Normalise your indicator values	Asses new information and review drivers Track implementation progress Evaluate effectiveness of actions using baseline data and indicators Communicate accomplishments Investigate future adaptation options and actions Revise adaptation plan Launch next round of adaptation plan	Adjust the impact assessment to account for uncertainty, timing, and adaptive capacity.
	Weighting and aggregating indicators		**Prioritize Adaptive Needs**
	Weighting indicators Aggregating indicators		Based on the vulnerability assessment, prioritize the adaptive needs.
	Aggregating risk components to risk		**Identify Strategies**
	Aggregate the three risk components hazard, vulnerability, and exposure into a single composite risk indicator		Identify strategies to address the highest priority adaptation needs.
	Aggregating vulnerability components to vulnerability		**Evaluate and Prioritize**
	Aggregation of exposure and sensitivity to potential impact		Prioritize strategies based on the projected onset of

PIEVC	The Vulnerability Sourcebook	ICLEI	California Adaptation Planning Guide
	Aggregation of potential impact and adaptive capacity to vulnerability Aggregation of several sub-vulnerabilities to an overall vulnerability		the impact, projected cost, co-benefits, and other feasibility factors.
	Presenting the outcomes of your vulnerability assessment		**Phase and Implement**
	Plan your vulnerability assessment report Describe your assessment Illustrate your findings		Develop an implementation plan that includes phasing of strategies and a monitoring system to assess effectiveness.

The PIEVC protocol consists of five steps (Table 3.8), each supported by an associated guide for protocol execution (Engineers Canada 2016). Initial steps focus on defining the boundaries of the project and features of the public infrastructure, including climate parameters, future climate assumptions, and identification of potential effects on infrastructure. Then, vulnerability is assessed in the context of performance expectations. The protocol is a structured procedure that uses standard risk assessment processes to quantify the probability of occurrence and its severity. The results provide an overall changing-climate risk profile of the infrastructure and identifies areas of particularly high exposure and vulnerability.

The nine steps in the Vulnerability Sourcebook protocol (Table 3.8) aim to reduce the vulnerability of developing countries and rural areas. The protocol begins by determining the scope of the assessment and identifying the major climate impacts to the system of concern, mainly small agriculture producers or fishers in mangroves zones. An impact or "cause-effect" chain is used as an analytical tool that helps rationalise, systemise, and prioritise the factors that drive risk in the rural system (Fritzsche et al. 2014). This protocol introduces assessment of climate time horizons for current or medium- to long-term future vulnerability.

ICLEI applies five steps (Table 3.8) to assess the sensitivity and adaptive capacity of municipal infrastructure, defining risk assessment as the conjunction between consequence and likelihood of impacts. The methodology guides communities to review their current knowledge on how the local climate is changing, identifying potential future impacts to major service areas in the community (ICLEI 2017). The guide addresses a set of goals with an action plan that includes financing and budget issues and an implementation schedule. This protocol introduces the concepts of community engagement and partnership opportunities to ensure support of local and municipal public servants and community members. A monitoring and communication process is also considered.

The California Adaptation Planning Guide protocol comprises nine steps (Table 3.8) to estimate regional exposure to projected climate changes for various emissions scenarios. The focus of the analysis is community structures and functions and impacts on the population (CALEMA 2012). The guide provides processes to climate vulnerability assessment at the local community and regional scale, including environmental and socio-economic characteristics. The protocol promotes the use of adaptation strategies across sectors for an integrated management plan.

The comparative analysis identified a variety of potential impacts of climate change on infrastructure in cities (Appendix B). These data will inform the CRA-AF to incorporate knowledge on climate risk to infrastructure and populations. The assets that are more exposed to climate change impacts are summarised as follows:

1. Land use: residential and commercial buildings, industrial sites, farmland, water supplies, energy production plants, forest, floodplain management, recreation, community services
2. Transportation infrastructure: roads, bridges, and tunnels; passenger and freight rail; ports and inland waterways; airports
3. Public health: hospital capacity overloaded after natural disasters due to deficiencies
4. Water supply and sanitation: unsafe water and substandard sanitation infrastructure
5. Solid waste: operational chain of collection, transfer, and disposal

6. Energy: lighting, heating, and cooling in residential and commercial buildings and fuel for transportation and industry

In general, these urban infrastructure assets could be comparable with mine site assets in that climate change will affect land uses, water infrastructure, waste management areas, transportation conduits, and power lines. Therefore, climate risk protocols designed for cities and their application provide a sequence of procedures and actions that could be considered for the mining sector.

3.3.2 Ecosystem-Based Adaptation Assessment

Results of the climate risk assessment informed EbA assessment, a continuous process and combination of activities (Terton and Dazé 2018) to further explore connections between livelihoods and ecosystem services and the benefits they provide to community members. To ensure the sustainability and effectiveness of the adaptation measures, it was necessary to form adaptation packages—a group of adaptation alternatives that integrate infrastructure-ecosystem-based solutions (FEBA 2017). The adaptation strategies need to clearly articulate the desired state of the ecosystem and/or its services to be achieved through conservation, sustainable management, or restoration; how the ecosystem and watershed area adapt to changes in mine closure components; and which local climate risks are addressed.

This stage of the research used the Adaptation, Livelihoods and Ecosystems Planning Tool (AlivE; Terton and Dazé 2018), which was published by the International Institute for Sustainable Development and United Nations Environment Programme – International

Ecosystem Management Partnership and produced by the Ecosystem-based Adaptation through South-South Cooperation project with funding through the Special Climate Change Fund. This tool supports evaluation, analysis, and strategic design to facilitate implementation of priority EbA options at the community level. Here, it was used to inform development of the CRA-AF related to the EbA planning process for mine closure design. The ALivE tool is organised into five steps (Table 3.9).

Table 3.9 Adaptation, livelihoods, and ecosystems planning tool steps (Terton and Dazé 2018)

ALivE
1. Understand the context
Analyse the natural context and socio-economic activities at the local area scale Explores the provision of ecosystem services and benefits to the community related to natural hazards reduction
2. Analyse risk to ecosystems and livelihoods
Analyse current and potential future climate-related hazards and impacts on livelihoods and ecosystems, including vulnerable groups
3. Identify and prioritise ecosystem-based adaptation (EbA) options
Describe adaptation outcomes for livelihood strategies Identify more advantageous EbA options for a specific context
4. Design project activities to facilitate implementation of EbA options
Plan actions required to achieve selected EbA options; involves participation of diverse stakeholders
5. Identify key elements to monitor and evaluate EbA options
In accordance with EbA options, define short- and long-term indicators to measure adaptation outcomes

The field of decision analysis provides the tools and frameworks (e.g., multi-attribute value theory and multi-attribute utility theory) to identify and prioritise EbA options for a comprehensive and inclusive planning process to select alternatives and aid decision resolution (Kueppers et al. 2004; Miller and Belton 2014). Multi-attribute decision processes are commonly used for environmental management (Langhans, Jähnig, and Schallenberg 2019) because they facilitate participation of various groups of community representatives and local experts, providing the elements for an integrated adaptation process (Kueppers et al. 2004). Groups are weighted in a decision matrix of the adaptation strategies based on their land use preferences and livelihoods (Lechner et al. 2017). The decision matrix is a table: the potential EbA options are row labels and the set of criteria to be evaluated and ranked are column labels on five recognised criteria for EbA success (Bertram et al. 2017; Secretariat of the Convention on Biological Diversity 2019b):

1. ability to reduce current and future climate risks;
2. ability to generate social benefits for vulnerable social groups;
3. ability to restores, maintains, or improve ecosystem health;
4. enhance sustainable use of biodiversity and ecosystem services at local level; and
5. build integration management of ecosystem services with multi-sectoral approaches.

The benefits of a decision matrix are that it (1) allows EbA options to be quantified simultaneously in a participatory and transparent manner; (2) can be used to sort EbA options that do not provide positive impacts for the SES; and (3) can identify EbA options to be considered with priority for review and approval in the mine closure design.

3.3.3 Outcomes

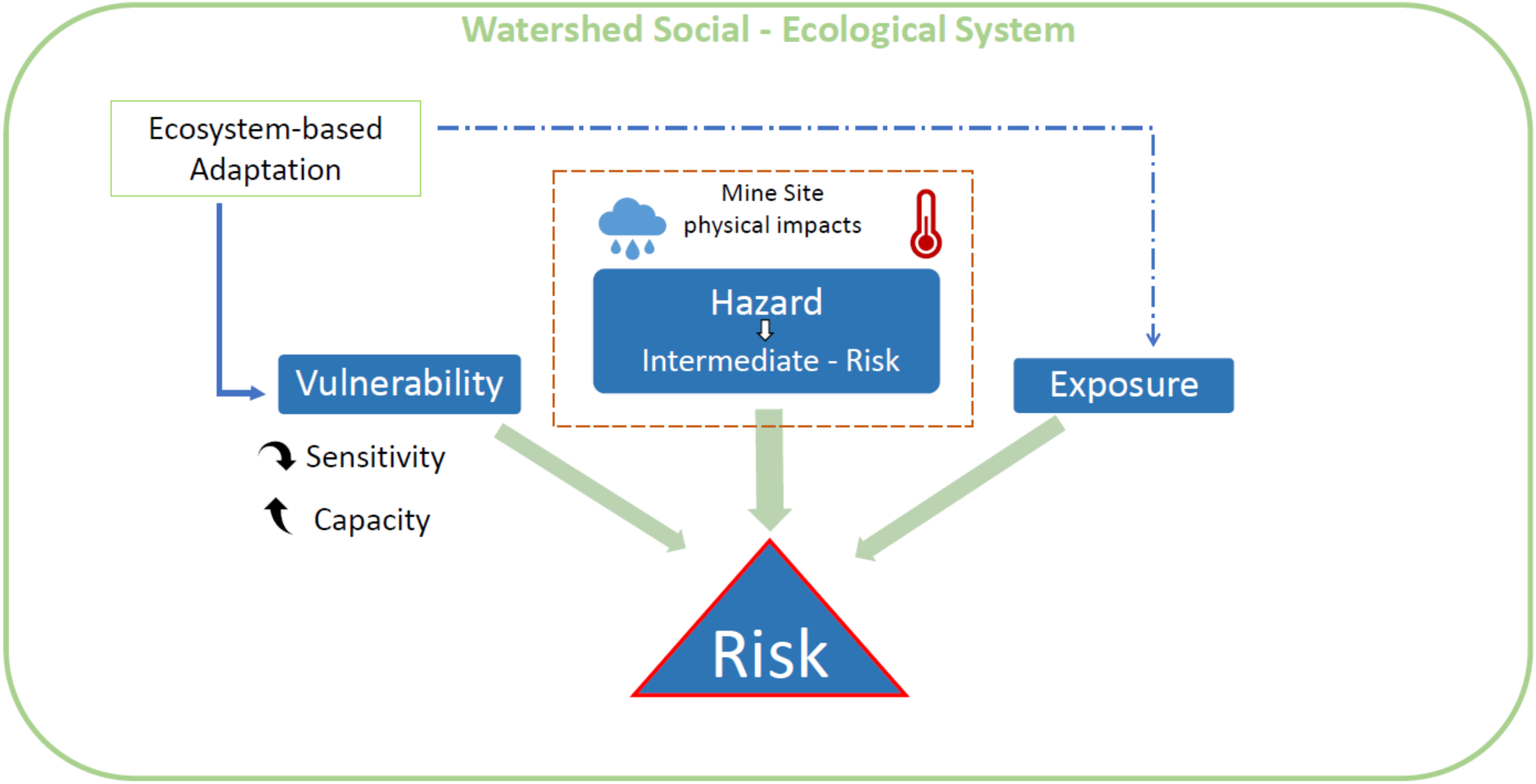
Informed by the analysis in sections 3.1 and 3.2, CRA-AF incorporated a systematic planning process (EbA) based on a qualitative and quantitative assessment technique to assess climate-related risks to mine closure in a mountainous region. The CRA-AF will help the mining industry to:

- identify climate-related hazards, vulnerabilities, and exposures in the SES;
- analyse relationships between ecosystems, livelihoods, and climate risk;

- identify and prioritise EbA options for mine closure design; and
- define actions to implement the selected EbA options.

CRA-AF was designed based on the IPCC assessment report (AR5) (IPCC 2014e; see Section 2.4). Climate-related risks of mine closure are the combination of climate-related hazards from the mine site and vulnerability and exposure factors in the watershed SES (Figure 3.1). EbA strategies adjust vulnerabilities and exposures to reduce risk. This climate risk approach was confirmed in the latest IPCC assessment report (AR6) (IPCC 2021) published at the time of writing this dissertation.

Figure 3.1 Climate risk assessment and adaptation framework



3.4 Case Study Selection and Rationale

As described above, the impacts of climate change on natural and human systems are locally constrained, and climate risk conditions are site-specific. Case studies are useful to examine these impacts: they are widely employed because they permit intensive and detailed examination of samples in a real setting (Murty 2015). In an analysis of the concepts of three case study methodologists, Robert Yin, Sharan Stake, and Robert Merriam, Yazan (2015) determined that case studies are one approach to study, describe, and analyse an integrated system. They allow deep investigations to understand "how" or "why" of a particular circumstance. In case studies, a practice-oriented research plan is designed to achieve specific study objectives. The focus on a particular context allows testable hypotheses to be generated (Rowley 2002). The real-life object of study is not manipulated, unlike experimental research. Instead, the knowledge is constructed along with a deep understanding of the interaction between the phenomenon and context, with the information available about the case (Dul and Hak 2008). In this research, the phenomenon is the CRA-AF and the context is the closure plan for the mine selected below.

Case studies are particularly convenient for discerning adaptation opportunities when the future climate conditions are analysed, because they add to knowledge of human-environment systems experience and reactions to extreme climate events (Ford et al. 2010). The physical sciences have been used historically for case studies to review future climate change impacts, identifying lessons and best practices from past responses at regional and local scales (IPCC 2007; Ford et al. 2010). Moreover, case studies have been considered as a practical methodology in previous IPCC Assessment Reports (e.g., IPCC 2007).

In the case study methodology, the case is selected from a group of cases, and the reasons for choice is based on the desired characteristic of the study (Gerring 2009). The criteria used for the mine selection here were: (1) mine operation in British Columbia, Canada; (2) mine operation located in mountainous area; (3) mine closure plan available; (4) climate change projections available for the area where the mine operation is located; (5) social-ecological system (community and watershed) within the area influenced by the mine influence with available local context information.

The study region is the Canadian Rocky Mountains in the south interior of British Columbia, where Elk Valley hosts four Teck Resources metallurgical coal operations: Fording River, Greenhills, Line Creek, and Elkview. These operations all met the criteria defined above. However, the Elkview Operations (EVO) are located the farthest south, and the nearby community of Sparwood experiences cumulative effects from all active operating mines upstream on the Elk River. Thus, after qualitative case selection, an inductive approach was applied, and the EVO site was chosen as the case study. A single case study is appropriate when it is used to test a unique framework (Yin 1994; Rowley 2002) such as the novel CRA-AF designed in this research.

The case study methodology presented in Chapter 7 used publicly available documents, publications, observations, and interviews (Rowley 2002) from Sparwood, the EVO, and the Elk Valley watershed. After application of CRA-AF, the mine closure practitioner will be able to clarify and resolve potential climate risk affecting the land restoration process.

The research plan comprised the execution of activities as follows: (1) Mine site visit; (2) meetings with the management team at the mine site; (3) risk assessment and adaptation workshop. During the site visit, on 28–29 October 2019, a general visit of the actual infrastructure was performed, with emphasis on the Lagoons, tailing storage facility and open pit. Lagoons C and D were visually inspected in more detail to understand the potential exposures and vulnerabilities of the SES if a climate-related hazard occurred. The Sparwood community and surrounding areas of the Elk River were also visited. The research plan and CRA-AF were presented to the Water and Tailings Management team at the mine site. The EVO team noted the recent release of publicly available documents related to the site's tailings management, which were available on the Teck Resources Limited website (www.teck.com). A second meeting on 11 May 2020 was virtual due to SARS-CoV-2 virus (COVID-19) restrictions. It included participation with the Environmental and Tailings Management team from EVO. Attendees expressed concerns regarding the feasibility of field activities, and the EVO team suggested using publicly available information for the research.

The climate risk and adaptation workshop was postponed due activities at the site operation. By the end of March 2020, the spread of COVID-19 in British Columbia led the Provincial Government to take initial emergency measures and the EVO to adopt measures to slow the virus outbreak. Local community members voiced concerns about the virus and called for actions to reduce the risk and exposure from mine workers travelling in and out of the operations (Fischer 2020). Ultimately, the workshop was postponed indefinitely.

Based on the Supervisory Committee recommendation, a validation workshop with a panel of experts in mine closure and climate change adaptation took place online to ensure that the CRA-AF had been designed correctly. Therefore, subjective expert judgement informed understanding and improvements to integrate evidence into CRA-AF (Beaudrie, Kandlikar, and Ramachandran 2011). The platform Zoom was used, as suggested by UBC Office of Research Ethics: "*Zoom is a useful tool for online research interviews and focus groups*" (UBC 2020). The format followed the online Focus Group qualitative method, including an online survey: each participant received an email with the link to the meeting and a passcode for access. Chapter 8 presents the details and results of the validation workshop.

The following sections provide an initial description of EVO and local climate data. The specific details of the case study are presented in the Section 7.1 as part of the results of the application of the CRA-AF designed in Chapter 6.

3.4.1 Case Study – Elkview Operations

The Teck Coal Limited EVO approach to climate change is defined by the recently published Position and Policy on Climate Change (Teck Resources Limited 2021), with the main focus on reducing the carbon footprint of the corporation as a whole. Using EVO to apply the CRAA-AF on its mine closure plan will help to identify strategies for adaptation to climate change with a science-based and critical thinking process, helping decision-makers in the mining industry design effective policy.

The EVO site is located on privately owned land approximately 3 km east of Sparwood in the East Kootenay region of southeastern British Columbia in the front ranges of Canadian Rocky Mountains (Teck 2019). This scenic region is characterised by the extensive Elk Valley, forested slopes, and rocky crests at higher elevations (Figure 3.2). The Elk River originates in Elk Lake in the Columbia Mountains and flows southwesterly through Elk Valley, eventually joining the Columbia River. The area has a long history of industrial use, including forestry and coal mining. Mining at the EVO mine site near Sparwood commenced in 1898 and progressed until 1969 when the first large-scale open-pit operation in the Elk Valley began operations (Dupley 2019). EVO was authorised under Environmental Management Act Permit 3821 in 1975; the permit has undergone several amendments from initial project specifications (Teck Coal Limited 2017).

Elkview produces metallurgical coal, which is exported by sea to the Asia-Pacific region, where it is used to make steel. For the period 2017–2021, EVO planned to mine 56.0 M tonnes of coal, producing 37.4 M clean tonnes of coal and 1.0 B tonnes of waste rock (Teck Coal Limited 2018b). The Permitted Life of Mine Plan represents a 28-year period from 2018 to 2045 and details the planned mining sequence for current reserves (Teck 2019). Metallurgical coal production for the year 2019 was 25.7 M tonnes (Teck Resources Limited 2019). The total surface development at EVO as of December 2017 was 4,254.5 ha with a total of 1,142.7 ha reclaimed.

Figure 3.2 Location of Elkview operations in British Columbia, Canada (Teck Coal Limited 2017)

EVO has the longest active reclamation permit in the province and since 1898, different owners have held different reclamation priorities. Twenty years ago, the mine closure plan aimed to provide winter range habitat for elk (*Cervus elaphus nelsoni*; Przeczek 2003) and the progressive closure activities was executed with that objective. The current reclamation program updated in 2017 considers all ecosystems as the principal component in closure planning. The strategy focuses on multiple and compatible end-land-use objectives over different time spans instead of pursuing a single habitat type to achieve ecological function (Teck Coal Limited 2018a). EVO chose this reclamation approach because it seeks to include physical, chemical, and biological restoration processes. The mine closure plan assumes that disturbed land and ecosystems will be returned to pre-mining native ecosystems. The company has already established ecosystem types for the post-mining restoration process based on pre-mining conditions and ecosystem indicators.

3.4.2 Climate Information

The CRA-AF requires identification of those components of the mine closure infrastructure that are likely to be sensitive to changes in particular climate parameters (Appendix C) as defined from results of trend analysis (Chapter 4), the Delphi survey (Chapter 5), and comparative analysis with cities (Section 3.3). The climate parameters to consider in the CRA-AF are specific to the region where the mine is situated. They include historical weather conditions and projected climate trends at the local level that could potentially affect mine closure components (Engineers Canada 2016).

Climate data from the Sparwood climate station (Climate ID: 1157630) were obtained from Climatedata.ca. This open access portal collates data from all climate data portals in Canada and provides tools to search for specific types of data (ECCC 2019). Climatedata.ca works with the Bias Correction/Constructed Analogues with the Quantile mapping algorithm (ECCC 2019) developed by Maurer and Hidalgo (2008) to downscale daily climate model projections of temperature and precipitation, including indices of extreme events (Werner and Cannon 2016). The data from this portal were based on the Global Climate Models and produced statistically downscaled multi-model ensemble datasets of temperature and total precipitation parameters (ECCC 2019).

Each climate model uses climate historical data from the phase years 1950–2005, and the projections are for the period 2006–2100 (ECCC 2019). The research tested two concentration scenarios: the first is more optimistic, with atmospheric GHG concentrations declining after 2040, and the second is less optimistic, with a continuous increase in atmospheric GHG concentrations in the 21st century (IPCC 2014e). Detailed climate projections scenarios for Sparwood community are presented in Appendix F.

3.5 Integrating EbA into Standards and Planning

To incorporate the CRA-AF in the design of mine closure and land restoration, it is critical to integrate EbA approaches into the relevant standards and planning processes of the mining company. The CRA-AF case study results were contrasted with the current EVO mine closure plan to assess potential gaps and opportunities. Then, CRA-AF steps were compared with the ICMM integrated mine closure guidelines (ICMM 2019b) to define the contribution of the novel framework and assess how CRA-AF could provide guidance on identifying entry points to incorporate climate risk and EbA strategies into the mine closure plan.

The advantages of an integrated risk and adaptation assessment approach, as opposed to assessing only infrastructure vulnerability, are that it addresses a large proportion of impacts that are triggered by hazardous events at the mine site and integrates both climate change adaptation strategies and disaster risk reduction approaches in the mine closure design (Secretariat of the Convention on Biological Diversity 2019a).

Effective adaptation and disaster risk management strategies and practices also depend on a rigorous understanding of the dimensions of exposure and vulnerability in the SES (Cardona et al. 2012). Some examples of adaptation selected from the reviewed protocols are:

- Stormwater management plan
- Separation of sanitary and stormwater sewers
- Coastal flood risk assessment and sea level rise adaptation response
- Flood-proofing policies
- Water conservation
- Development of a hot weather plan
- Building zoning changes
- Urban forest management plan

3.6 Methodology Summary

A changing climate may result in environmental impacts that are quite large, and this may require reassessment of mine closure strategies and the management of associated ecosystem services. This need will be more critical in vulnerable areas that are exposed to the climate-related hazards, such as mountain ecosystems. EbA is an approach that uses biodiversity and ecosystem services as part of a holistic adaptation strategy to assist human beings to adapt to climate change, by reducing vulnerabilities and increasing resilience of both human and natural systems

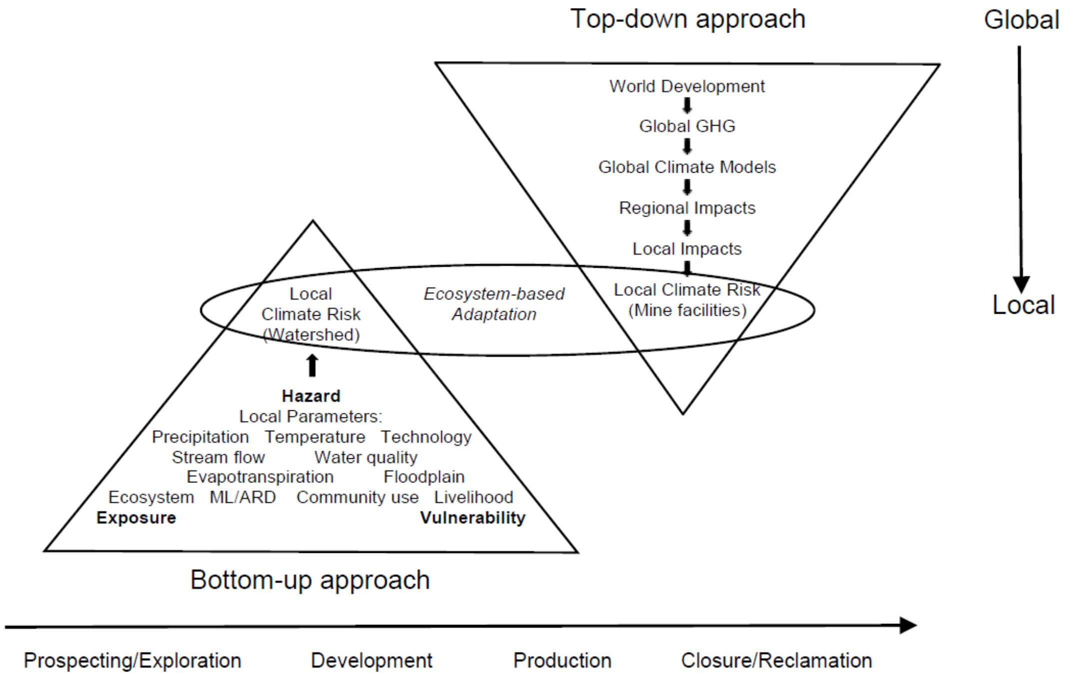
A lack of information in relation to the future climate risks in the watershed surrounding the mining sites exists. Given the pressures posed by global warming to mountain systems—where important mining activities take place—a long-term vision and holistic management of ecosystems in land restoration and mine closure will support and advance climate change adaptation planning and action. Nonetheless, in the last years the mining sector was not given enough attention to the adaptation plans in areas that have been disturbed by the operations (Labonté-Raymond et al. 2020; Punia 2021).

A systematic review was conducted of publicly available data and self-reported information provided by the global top 10 mining companies by market capitalisation. The assessment used benchmarking to identify and understand the current business management context of climate change impacts and risks in the mining sector. This review will inform current practices in the industry.

A group of experts was assembled to reach consensus on adaptation practices to account for climate risk in land restoration processes. When analytic modeling is limited and uncertain, eliciting expert judgment by using structured questionnaires can inform decision makers. This process provides the opportunity to collect and inform knowledge based on a large group of professional subject matter experts. This is a "top-down" approach that uses global and regional data to inform practices at a local level (Figure 3.3).

The result of the survey will improve the understanding of the current and potential climate change adaptation practices used in the mining sector in different countries. More importantly, the studies will close the gap between current and potential practices for the land restoration and mine closure stages in mountain ecosystems.

Figure 3.3 Approach from global-to-local risk assessment to inform ecosystem adaptation practices during mine closure design



Source: Adapted from Dessai, Lu, and Risbey (2005)

By comparison, understanding the capacity of a local system, as in the case study, to respond a potential hazard and applying that adaptation at a watershed level represents a "bottom-up" approach to support the planning of adaptation measures based on ecosystem services. The adaptation strategies need to clearly articulate the required state of the ecosystem and/or its services can be achieved through restoration, sustainable management or conservation; how the ecosystem helps the adaptation of the mine closure components and its watershed SES; and which local climate risk is addressed.

The EVO was selected as a case study to help understand how CRA-AF can assess mine closure infrastructure and design sustainable practices at the watershed scale. The CRA-AF will indicate the mine closure and watershed SES components that could be affected by climate change. This assessment will identify the interactions between climate hazard, vulnerability, and exposure that could lead to risk. The holistic risk assessment approach addresses the large proportion of impacts of hazardous climate events while integrating both climate change adaptation and risk reduction approaches at the watershed level.

Chapter 4: Results: Trend Analysis

This chapter presents the results of trend analysis of 10 companies (Table 3.2). The section is organised according to four research questions:

(1) What are mining companies doing about climate change?

(2) What are the most important climate-related risks for mining companies?

(3) What future impacts do the companies foresee they will face in extreme weather scenarios?

(4) How are mining companies planning to adapt to climate change risks and impacts?

4.1 What are Mining Companies Doing about Climate Change?

From an analysis of the corporate reports, three of the ten companies developed public-facing policies and corporate guidelines relating to climate change: BHP Billiton, Vale, and Anglo American (Table 4.1). BHP first established a policy in 2007 that outlined company efforts to manage climate change—basically GHG reduction plans—and recognised the importance of addressing risks associated with climate change (BHP Billiton Limited 2017a). Continuing with their governance improvement, BHP launched the Climate Change: Portfolio Analysis report in 2015, which described BHP's approach to portfolio evaluation and scenario planning, including the implications of a transition to a lower emissions future (BHP Billiton 2016). In 2011, Anglo American established Climate Change Policy 2011, which expressed their commitment to address the causes of climate change and to help protect Anglo American employees and assets, local communities, and the environment against potential climate change impacts (Anglo American 2016). In 2017, Vale established management commitments, such as the Sustainability Policy, Global Mitigation Policy, and Adaptation to Climate Change Policy (Vale 2017). The three companies operate in different regions. In all cases, the host country environmental legal framework is used as the basis of policies, and then the companies apply their own guidelines and standards as a corporate mandate.

Table 4.1 Actions Executed by Top 10 Mining Companies to Manage Climate Change Risks

Company	Policy developed?	Management decision	Reporting	Risk identification
BHP Billiton Group	Yes	Board and Managers	CDP, TCFD	Corporate Risk Management
Rio Tinto	No	Board Sustainability Committee	CDP, WRI, WBCSD	-
Glencore Plc	No	Board HSEC Committee	CDP	On-site assessment
Vale SA	Yes	-	CDP, WRI	Corporate Risk Management
Grupo México SAB de Cv	No	-	Registro Nacional de Emisiones	-
Coal India Ltd.	No	-	-	-
Norilsk Nickel Co.	No	-	-	Risk Management Policy
Anglo American Plc	Yes	Board Group Technical Director	CDP	ORM, IDM
Barrick Gold Corp	No	Climate Change Board Committee	CDP, CPLC	Scenario development
Freeport-McMoRan Inc.	No	-	CDP	Sustainable Development Risk Register

CDP: Carbon Disclosure Project; CPLC: Carbon Pricing Leadership Coalition; HSEC: Health, Safety, Environment and Community and Human Rights; IDM: Investment Development Model; ORM: Operational Risk Management; TCFD: Taskforce on Climate-related Financial Disclosures; WBCSD: World Business Council for Sustainable Development; WRI: World Resources Institute

The other seven companies stated in their annual reports that they are in the process of developing climate policies to integrate with their corporate commitments, though not all provided public information related to this progress at the time of the study. In general, they consider climate as part of their environmental programs.

The second stage of analysis sought to identify the highest level of direct responsibility for climate change action within each organisation, as reported in the 2017 CDP. Five of the ten companies have board responsibility for climate change management (Table 4.1). This is important because it clarifies the level of recognition that each company could have in considering climate change-associated risks and the management decision authority to evaluate and define climate change adaptive actions (Linnenluecke, Griffiths, and Winn 2013). This concern was raised by shareholders in recent years, as mentioned in Section 2.2.

For instance, the BHP executive board views climate change as a priority issue for governance and strategy; however, it is site management that has primary responsibility for responses to climate change and accountability for performance against climate change metrics. GHG reduction targets are considered in senior executive and leadership remuneration (BHP Billiton Limited 2017a). At Rio Tinto, climate change actions are debated at senior levels of management and by the Board Sustainability Committee. The executive committee approves climate change position statements and related documents, such as the 2017 Climate Change Report (Rio Tinto - CDP Disclosure Insight Action 2018). Glencore has established the Health, Safety, Environment and Community and Human Rights committee, which has responsibility for sustainability, including climate change (Glencore 2016). At Anglo American, climate change is reviewed by the Group Technical Director of the Board, who is supported by the Group Head of Safety and Sustainable Development, the Head of Environment, and the Lead for Energy and Carbon Effectiveness (Anglo American - CDP Disclosure Insight Action 2018). At Barrick, a Climate Change Board Committee was established to improve the existing energy management plan and develop a comprehensive climate change strategy (Barrick - CDP Disclosure Insight 2018).

The remaining five companies did not mention a specific management group in charge of this issue in their sustainability reports. Although Freeport-McMoRan does not have a specific management group working on climate change, the board is responsible for risk oversight. Reviews of certain areas are conducted by relevant board committees that report to the full board. But there is not enough information to understand which level has the authority to make decisions regarding climate change management and responses (FCX - CDP Disclosure Insight Action 2018).

The third stage of analysis is disclosure of GHG emissions data for each company, which, along product life cycles, will help define climate-related risk and management strategies (Özsözgün and Emel 2016). Of the 10 companies analysed, seven voluntarily submitted GHG emission data to CDP: BHP, Rio Tinto, Glencore, Vale, Anglo American, Barrick, and Freeport-McMoRan (Table 4.1). Anglo American reported to CDP for the first time in 2006. Since then, the company continues to participate in the global environmental disclosure system for business (Anglo American - CDP Disclosure Insight Action 2018). In 2016, Barrick joined the Carbon Pricing Leadership Coalition, led by the World Bank as Secretariat (Barrick Gold Corporation 2017).

Additionally, BHP information is aligned with the Financial Stability Board's Taskforce on Climate-related Financial Disclosures (BHP Billiton Limited 2017a). Rio Tinto combined all site information and reports using the GHG Protocol developed by the World Resources Institute and World Business Council for Sustainable Development (Rio Tinto 2017). Vale also used the GHG Protocol Program for its corporate inventory of GHG emissions (Vale 2017). Grupo México

GHG inventories have been verified independently since before this was mandatory (Grupo México 2017).

The data that should be used, the climate modeling process, and the interpretation of the global climate model results are a challenge (Yousefpour et al. 2012) because uncertainty remains regarding the exact risks and impacts that ecosystem surrounding mining operations will encounter due to the changing climate. Companies use a variety of mechanisms to identify climate risks, including corporate risk management frameworks, on-site assessment tools, risk registers, and scenario analysis. An example of a corporate risk management framework is the approach used by BHP, which established the "Our Requirements for Risk Management" standard, creating a protocol around health, safety, environment, and community for management relating to climate change and material risks (BHP Billiton Limited 2017b).

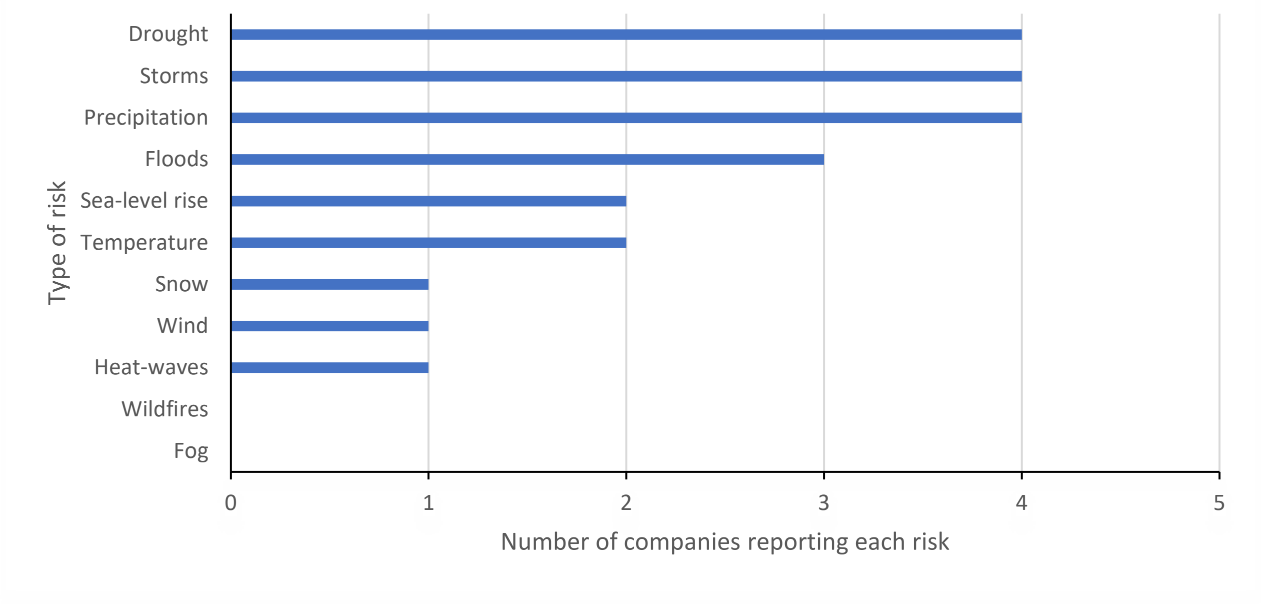
At Glencore, the board assesses and approves overall risks, supported by the Health, Safety, Environment and Community and Human Rights committee (Table 4.1). Sites are required to report climate change-related risks and opportunities annually (Glencore 2016). Vale's sites monitor and update the risks related to climate change every year (Vale 2017). Norilsk Nickel implemented the Corporate Risk Management Framework in 2016, and the Board of Directors adopted a Corporate Risk Management Policy the same year (Nornickel 2017). Rio Tinto recognises the significant risks for businesses and society from climate change but also that it presents opportunities like access to remote areas due to snowpack reduction (Rio Tinto 2017).

Anglo American considers climate change and extreme weather events a material risk to their business in multiple ways and uses two key processes to manage climate change risks: Operational Risk Management for operations and the Investment Development Model for projects (Table 4.1). With these processes, the company defines their potential risk and unwanted events from a variety of perspectives (legal, financial, social, and environmental) that could affect operation sites or new project developments, prioritizing resource allocation to manage the risk. Barrick began working to set climate change targets in 2017. As part of the exercise, the company is identifying initiatives to lower GHG emissions (Barrick - CDP Disclosure Insight 2018). Freeport-McMoRan has introduced a Sustainable Development Risk Register to identify key risks and opportunities across the company (including climate change-related issues) (FCX - CDP Disclosure Insight Action 2018).

4.2 What Are the Most Important Climate-Related Risks for Mining Companies?

As summarised in Figure 4.1, review of these ten company sustainability reports identified nine types of risk related to climate that could affect mining operations. Altered precipitation patterns, storms, and droughts were the most identified types of risks, followed by floods, and then temperature change and sea-level rise. These risks are not mutually exclusive: high-precipitation events and seal-level rise can cause flooding for example.

Figure 4.1 Types of risks considered as operation threats



Altered precipitation patterns can intensify water stress and impact availability of water for some operations (BHP Billiton Limited 2017b). For BHP, extreme floods and drought can affect water management at the operations, with the potential impact of reduced or disrupted production capacity (BHP Billiton Limited 2007). The high degree of uncertainty associated with rainfall magnitude and frequency makes it difficult to predict future risks (Rio Tinto - CDP Disclosure Insight Action 2018). Some operations will require an upgrade to stormwater and water storage facilities (Glencore - CDP Disclosure Insight Action 2018). Glencore has developed a risk register to identify likelihood, consequences, mitigation controls, and action plans for droughts (Glencore 2016). Norilsk Nickel noted that abnormal droughts would cause water shortages in storage reservoirs, with the possibility of failure of turbines producing power (Nornickel 2017). The Grupo México has a program in place to protect the facilities against events such as damage to signaling systems and landslides (Grupo México 2017). Increased likelihood of stronger and more frequent storm systems including, tornadoes, hurricanes and cyclones can impact production (BHP Billiton Limited 2017b). For Rio Tinto, changes in the intensity and frequency of tropical cyclones have the potential to damage infrastructure and interrupt business operations (Rio Tinto 2016).

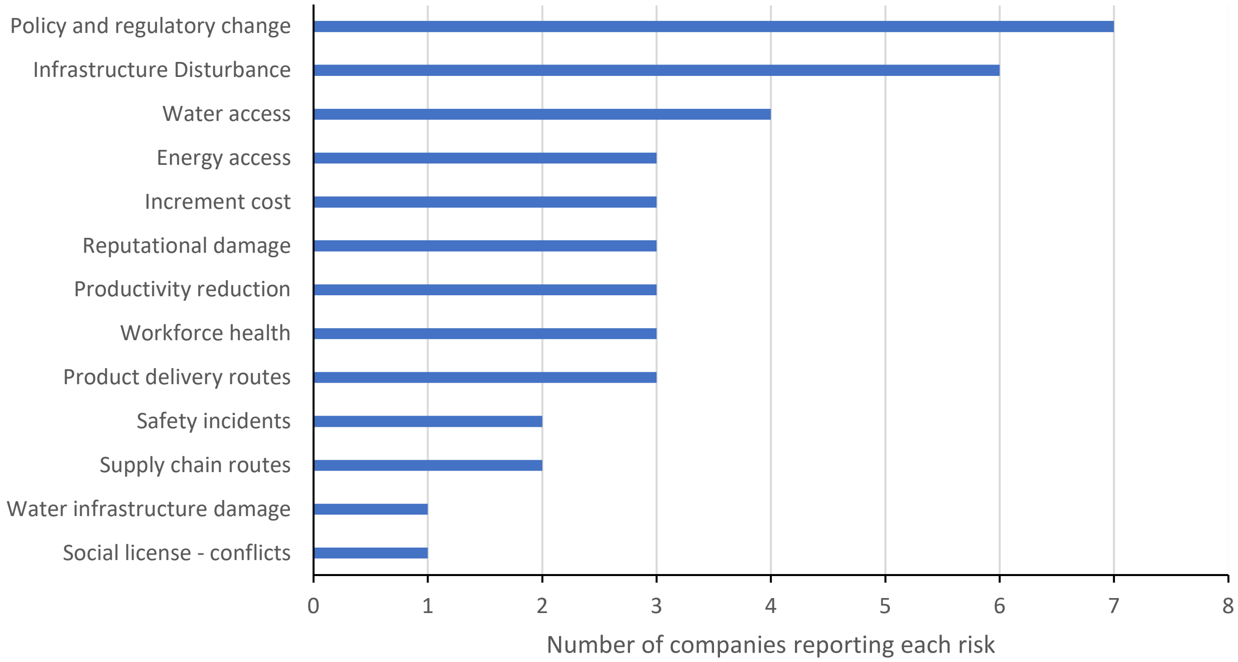
BHP noted that the physical effects of the temperature increase could materially affect workforce performance and adversely affect the financial performance of the assets (BHP Billiton Limited 2017b). At the same time, Glencore acknowledged that raised temperatures in some operations could melt ice, consequently blocking access due to road flooding (Glencore - CDP Disclosure Insight Action 2018). This data review highlights that the same climate change effects could have different impacts when analysed at the local scale.

Port facilities could be adversely affected by rising sea levels, with potential reduction and/or disruption in production capacity, which would adversely affect financial performance (BHP Billiton Limited 2017a). Sea-level rises could have an impact on coastal land stockpiles, and cause infrastructure damage (Rio Tinto 2017). These shipping disruptions have the potential to interrupt product delivery and could affect production rates if they occur for extended periods of time (Glencore 2016). This would result in higher costs for usage of the ports, which in turn may increase the cost of goods (Barrick - CDP Disclosure Insight 2018).

4.3 What Future Impacts Do the Companies Foresee They Will Face in Extreme Weather Scenarios?

Two major concerns were identified regarding potential impacts of extreme weather due to climate change on business operations (Figure 4.2). The first is the change in regulations related to the GHG emissions reduction and the potential for a carbon tax. The second relates to potential infrastructure damage. Policy changes to disincentivise emissions could affect operation costs and investment returns, as noted by seven of the companies assessed. Tailings dams are considered the foremost infrastructure concern, since designers did not consider the risks of climate change. Other concerns included access to water (a resource required for the entire mining cycle), energy access, and infrastructure costs.

Figure 4.2 Future impacts in extreme weather scenarios



As countries worldwide review their laws in relation to lower GHG emissions and are setting reduction targets for specific years; the implications relate to carbon tax costs, equipment design, and energy use. BHP considers the absence of regulatory certainty about climate change in different countries a challenge to manage (BHP Billiton 2016). Rio Tinto is concerned that, as countries work to deliver on their commitments to act to forestall climate change, they may no longer be able to stay competitive (Rio Tinto 2017). Anglo American expressed concern that the financial implications will only become evident as countries develop and implement climate change policies. They emphasis implementing energy- and emissions-saving policies (Anglo American 2017).

To address these concerns, companies reported a range of approaches. For example, Glencore is engaging with policy-makers throughout the public policy development process from design through to implementation with active participation in government public committees (Glencore - CDP Disclosure Insight Action 2018). Vale is monitoring and assessing the development of international policies for risk management and the price of carbon in capital investment decisions (Vale 2017). Likewise, Grupo México views regulatory change as a principal risk and is developing projects to manage this risk as a business opportunity, such as incorporating low-emission technology (Grupo México 2017).

The second greatest concern relates to mine infrastructure safety monitoring and reviews (Figure 4.2), which have become more stringent worldwide as result of infrastructure failures in recent years, some of which are related to increased rainfall. The terrible impact in terms of loss of lives, devastating damage to the ecosystem, and associated costs have heightened concerns about similar future events. Consequently, dam safety reviews are underway at all of BHP's significant operational and non-operational sites. These reviews re-evaluate how climate change might impact risk and design requirements. BHP created a specific corporate team for dams and tailings governance and risk management (BHP Billiton Limited 2017b). Glencore considers the need to treat larger volumes of water over shorter time periods in the case of extreme precipitation a risk (Glencore 2017). Grupo México has implemented internal procedures to protect their facilities against landslides (Grupo Mexico 2017). Norilsk Nickel is reviewing their site infrastructure to ensure safe operating conditions (Nornickel 2017). Anglo American reported that changes in rainfall variability may cause operational disruptions due to floods and droughts, and this may negatively affect land rehabilitation outcomes (Anglo American - CDP Disclosure Insight Action 2018).

The third concern relates to access to water resources (Figure 4.2). The risks and impacts of too much or too little water will have different risks and impacts on the mining industry, and it will depend on where the operation is located and the water access. As BHP notes, the impact of a changing climate may increase competition for limited resources. Grupo México reinforced their water management systems and improved water reuse in the production chain (Grupo Mexico 2017). For Glencore and Freeport-McMoRan, adaptation plans to address water shortage or extreme surplus were discussed in annual scenario planning meetings (Glencore - CDP Disclosure Insight Action 2018). Norilsk Nickel developed a hydrological monitoring system to forecast water levels in rivers and waterbodies surrounding their operations, including a classification system (Nornickel 2017).

Additional future potential impacts are reported for some companies that would reduce productivity and increase costs, for instance, supply chain disruption because of loss of access to infrastructure, such as rail, ports, power, and water. Public or privately operated supply infrastructure may be inadequate, and the impact of climate change may increase competition for its use (BHP Billiton Limited 2017a). There is a risk transportation infrastructure will no longer be possible to maintain a steady supply of essential materials and energy to Rio Tinto operations (Rio Tinto 2016). Grupo México considered this topic a growing risk for product transport (Grupo Mexico 2017). BHP and Rio Tinto note that climate change impacts could affect product transportation, business expansion, and the ability to operate efficiently (BHP Billiton Limited 2017a; Rio Tinto 2016) due transit road disruption.

In terms of workforce health, Barrick highlighted that changing temperatures may result in the migration of some diseases (Barrick - CDP Disclosure Insight 2018). This could result in higher rates of illness and/or anxiety about wellbeing for employees, contractors, and members of the surrounding communities.

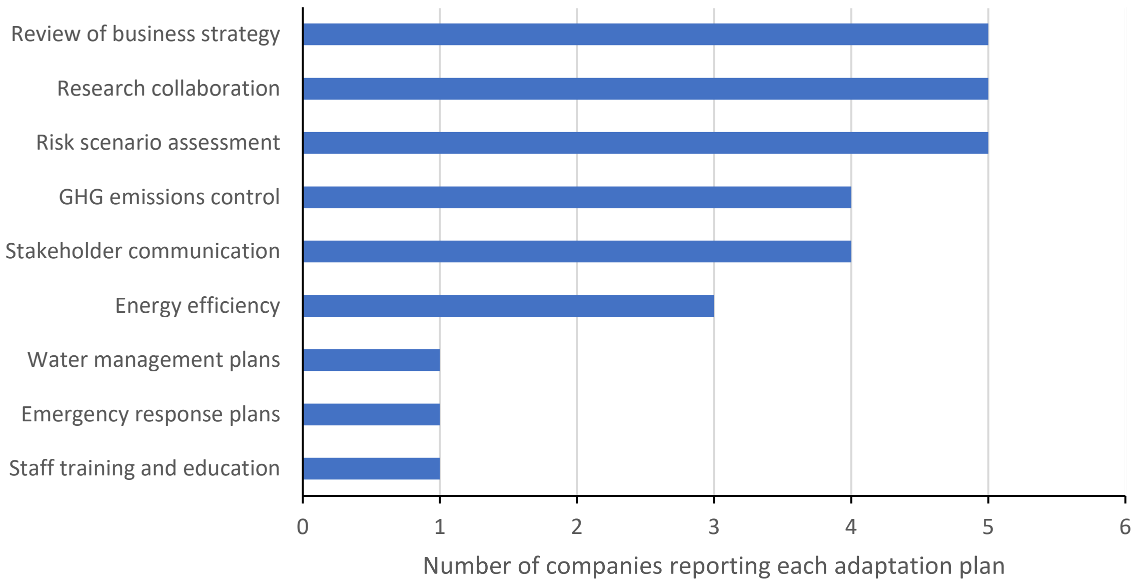
In terms of productivity, companies considered that the risks identified (Figure 4.1) could generate long periods of haul road interruptions resulting in loss of production, delays starting new projects, and impacts on existing commodity markets (Glencore - CDP Disclosure Insight Action 2018). In a scenario in which natural disasters affected the production or distribution of energy, competition for energy resource would intensify. Electricity prices could rise due to carbon taxes, conversion to more expensive, low-carbon alternative energy sources (BHP 2016), or fines for high GHG emissions (Barrick - CDP Disclosure Insight 2018). Freeport-McMoRan noted that new regulations could increase the cost of electricity production and purchase price, but that the magnitude of the impact is uncertain (FCX - CDP Disclosure Insight Action 2018).

Finally, potential litigation and unexpected environmental fines and expenses are considered potentially risky for BHP's reputation if their commitments to climate change action and commitments are not successfully achieved (BHP Billiton 2016). Rio Tinto noted that a poor reputation could make accessing new mineral resources difficult (Rio Tinto 2017). Glencore noted that a poor public perception if climate change is not addressed could impact its business and operations (Glencore 2016).

4.4 How Are Mining Companies Planning to Adapt to Climate Change Risk and Impacts?

New adaptation approaches will be required to effectively manage the complex interactions between climate and social and ecological frameworks (Denton et al. 2015). Mining companies apply common strategies to cope with climate change: reviewing their business strategy, performing risk scenario assessments, and supporting a collaborative research process (Figure 4.3). Few companies are planning to apply innovative strategies, such as water management, but instead, strategies relate to financial risk analysis and cost management via GHG emissions management. For instance, BHP applies a price on carbon internally for their investment decisions (BHP Billiton 2016). Each Rio Tinto operation uses a framework of risk analysis to identify and assess climate-related risk and determine appropriate risk management actions at their operation sites (Rio Tinto 2017). Glencore incorporates energy and carbon cost analysis as well as any anticipated changes in regulation into their annual planning process (Glencore - CDP Disclosure Insight Action 2018).

Figure 4.3 Future climate change adaptation plans



BHP's long-term goal is to achieve net-zero operational GHG emissions in the second half of the 21st century. This will require long-term planning for the long-life assets in their portfolio, a deep understanding of the development pathway for low-emissions technology, and a firm commitment from their leadership (BHP Billiton Limited 2017b). BHP expects that non-hydro renewables like wind and solar will gain market share in the power sector. Despite rapid growth in renewables and electric vehicles, the world will still require roughly 80% of its growing total energy needs to come from non-renewable sources in 2040 (BHP Billiton 2016). Glencore plans to adopt a combination of emission intensity targets and absolute GHG emission reduction targets across their business (Glencore 2017). Vale is contemplating a departure from fossil fuels in their business model. Vale aims to promote debate, information-sharing, and analyses to stimulate innovation. Their strategy will include adoption of corporate policies to handle climate change and leverage efforts to speed up low-emission technologies (Vale 2017).

Vale follows the main trends in mitigation and adaptation strategies and complies with regulatory and economic statutes applicable to each country. Vale has been working on its adaptation strategy since 2010. The company recognises the physical impacts of climate change can affect not only its business, but its workforce, communities, and the surrounding environment, and that good risk management minimises these impacts (Vale 2017).

The research collaboration in which the companies are involved will enhance novel adaptation practices for the mining sector. For instance, Anglo American is working with experts on climate science to better understand and prioritise adaptation controls. Among the key adaptation measures, Anglo American is planning for catchment impacts, long-term water supply security, community exposure, changes in mine and equipment design, hazard monitoring, and emergency preparedness (Anglo American - CDP Disclosure Insight Action 2018).

BHP has made interventions with different climate-action initiatives, such as The Forests Bond, issued by the International Finance Corporation. BHP is a signatory to the World Bank 'Putting a Price on Carbon' statement and a member of the World Bank Carbon Pricing Leadership Coalition. BHP is also a part of the Energy Transitions Commission (BHP Billiton Limited 2017b). Rio Tinto supports carbon capture and storage and low-emissions technologies research for coal by supporting the work of the Cooperative Research Centre for GHG Technology and the Australian Coal21 Fund (Rio Tinto - CDP Disclosure Insight Action 2018).

In terms of energy efficiency, for Rio Tinto, new technology will be key to reducing energy consumption and GHG emissions from their operations (Rio Tinto - CDP Disclosure Insight Action 2018). BHP is evaluating integration of renewable energy sources into operations (BHP Billiton Limited 2017b). Glencore believes there is a significant gap between the energy reality and the various carbon policy scenarios (Glencore 2016).

Vale is committed to promoting a sustainability agenda with its suppliers through the Programa Carbono na Cadeia de Valor (Carbon in the Value Chain Program) and supports the research and development of new technologies to mitigate impacts of climate change (Vale - CDP Disclosure Insight Action 2018). Anglo American has a platform for innovation, called FutureSmart™ mining Open Forums. The Open Forums on Water, Processing, Mining, and Energy have stimulated ideas that are progressing into tangible collaborative solutions (Anglo American - CDP Disclosure Insight Action 2018).

The exchange of information between the mining companies and community members will support the process to build trust and to understand the local needs and community risks associated with climate change. For instance, BHP has contributed to numerous policy reviews throughout their global operating regions. They actively participated in the work of the Energy Transitions Commission (energy-transitions.org). BHP is a member of the Financial Stability Board's Taskforce on Climate-related Financial Disclosures, a voluntary report on the impact an organisation has on the global climate and climate-related financial risk disclosures (BHP Billiton 2016). Rio Tinto is co-chair of the B20 taskforce on Energy, Climate and Resource

Efficiency, which provides recommendations for action by G20 governments to address climate change (Rio Tinto - CDP Disclosure Insight Action 2018).

Vale notes that evaluation of extreme weather scenarios to identify potential climate impacts on their operations and local communities—from natural disasters, desertification, and floods to changes in economic living conditions—can help strengthen approaches to adaptation and emergency response plans (Vale 2017). BHP promotes staff training to promote positive behaviour about longer term goals for GHG emission reduction. These education initiatives target innovation and drive collaboration across BHP's functions and assets (BHP Billiton 2016).

In terms of water management plans, in 2014, Rio Tinto replaced the group-wide freshwater use target with site-specific targets at more than 30 mine sites where water is a material risk. The targets address water supply, ecological impacts, and surplus water management issues (Rio Tinto 2017). Glencore has established water usage reduction projects. Stormwater facilities might need to be updated along with other water storage facilities (Glencore 2017). To estimate and monitor the forest carbon flow resulting from changes in land use, Vale established a database of environmental recovery and suppression activities with georeferenced data aggregated annually (Vale - CDP Disclosure Insight Action 2018).

In 2017, Anglo American's Board approved a climate-change-related indicator for executive financial remuneration. This responsibility has driven Anglo American to incorporate climate change response into their strategy, operational solutions and project design (Anglo American - CDP Disclosure Insight Action 2018).

4.5 Trend Analysis Summary

This section focused on reviewing public information published by mining companies within sustainability reports and the CDP, in order to provide a broad perspective of the companies' approaches to managing climate change risk. The trend analysis distinguished practices employed by mining companies to approach climate change management. The research concluded that many companies within the mining industry are in the early stages of learning how to adapt to climate change impacts. After the Paris Agreement in 2016, many companies had a main focus on climate mitigation, embarking upon strategies for greenhouse gas reduction and pathways for transitioning energy systems towards renewable technologies. Through the research, a notable gap was identified in the specific analysis of the mine closure stage and analysis of the possible risks that climate change would generate.

Most of the mining companies studied have recently (i.e., within the last five years) established policies related to climate change management. These were motivated by global agreements and trends in the reduction of greenhouse gases, as well as the demand from investors who required mining companies to identify, disclose, and define plans to manage climate-related risks. Of the top ten companies assessed, eight of them have complied with CDP's request to report their progress on emission measurement and control. GHG reduction is considered a key performance metric for business, and some companies consider this performance in their senior executive and leadership remuneration.

Based on the reports assessed, the mining companies recognized that climate change would impact the complete mine lifecycle and that it is a relevant risk for their operations. The companies acknowledged that there is still uncertainty of the level of impacts and how they will affect the different regions in the long term. These challenges will require variations in business strategies, investment in new technologies, and additional research. This study also found wide variation in the approaches across the companies studied - some started to assess risks and establish internal policies for managing GHG more than ten years ago, while others are just getting started. Moreover, the research suggested that it is essential to share the knowledge learned, promote best practices, and support the mining industry's transition to a low-carbon market.

The principal risks considered by the mining companies relate to the use of water resources and the different stages of the water cycle (e.g., precipitation, surface water, groundwater, sea water). Either an increase or a decrease in the water balance for short periods of time during an extreme-weather scenario can represent a risk that could affect all stages of the mine life cycle. The exact nature of risks encountered in a given location require more assessment to understand specific potential risks. Tailings and dams are mentioned by some companies as areas of concerns because their initial design did not consider the risks of climate change. Therefore, effective management requires a deep understanding of climate change impacts in watersheds where mining companies operate, and robust research of ecosystem adaptation strategies.

The highest impact reported by the mining companies due to climate change relates to various countries' legal frameworks and global policies regarding carbon taxes and reduction of greenhouse gas emissions. Furthermore, extreme changes in the climate would impact the infrastructure and buildings at each site affecting operations, results, and revenues in different regions. Also, physical changes due to changing temperature patterns may result in the migration of some diseases, which could affect the health of employees, contractors, communities, and the ecosystem. Even these could require variations in protocols for health and safety management.

Most of the interventions defined by mining companies focused on mitigation actions, such as reduction of greenhouse gas emissions and the control of fuel use; and the disclosure and reporting of emissions. However, no solid evidence was available that adaptation plans to cope with climate change impacts have been produced. The research was also unable to identify any companies which had incorporated ecosystem-based or natural solutions as climate change adaptation strategies. A further limitation was that companies lacked a detailed assessment of site-specific contexts in regions with the highest risk of climate change impacts.

The following points could be considered as a synthesis of the analysis:

- 30% of companies had developed policies related to climate risk
- Identification of climate risk is at the corporate level, not site level specific
- The three principal risks reported that could affect the mining companies are the variations in patterns of precipitation, storms, and droughts
- Future impacts reported: new policies for a low-carbon scenario, carbon tax regulations, and water access
- Plans to adaptation: Business review strategy, based on the risk scenario assessment and support GHG research

Knowing the general risks and the impacts, the managements' next step should be planning actions to prevent and control these risks, despite the uncertainty of the changes. The mining industry is still in the process of reviewing and learning how to adapt to climate change impacts. It is concluded that there are opportunities to consider mining operations as part of the watershed in order to support the design of ecosystem-based adaptation plans that could reduce and control the risks associated with climate change, especially in the closure stage and reclamation areas..

Chapter 5: Results: Delphi Survey - Assessment by a Panel of Experts

This chapter presents results of discussions between a small group of experts on mountain ecosystems, climate change, and mining practices, as explained in Section 3.2. Among 90 potential participants invited by email and provided a link to the online survey, 30 completed the survey, with a response rate of 33%. No participants were from the Asia Pacific region (Table 5.1). 57% (17) were in North America, 33% (10) in South America, and 10% (3) in Europe; 57% (17) were from Mining Industry or Mining Associations, 23% (7) were from the Academic or Scientific area, and 20% (6) were members of Public Institutions or Organisations related to mining; 13% (4) had 7–10 years of experience in climate change or sustainability, 64% (19) had 10–20 years of experience, 13% (4) had 20–30 years of experience, and 10% (3) had more than 30 years of experience; Vice President or Director was the most common position at 33% (10), followed by Professor at 23% (7), Manager or Corporate level at 20% (6), Senior Manager at 13% (4), and Superintendent at 10% (3).

Table 5.1 Survey Respondent Attributes

Participant location	**North America**	**South America**	**Europe**	**Asia Pacific**	
	57%	33%	10%	0%	
Work field/sector	**Mining industry / association**	**Academic / scientific**	**Public institutions / organisations**		
	57%	23%	20%		
Years of experience	**7–10**	**10–20**	**20–30**	**> 30**	
	13%	64%	13%	10%	
Current position	**VP - Director**	**Professor**	**Manager - Corporate**	**Senior Manager**	**Superintendent**
	33%	23%	20%	13%	10%

In the first round (Appendix A.1), participants were asked open questions to identify objectives and problems the study should address. The questions were developed in light of literature review findings, and the results capitalised on the trend analysis and knowledge of the researcher. In the second round, each participant received a link to the survey comprising five statements with a Likert scale (Appendix A.2). The Delphi study used descriptive statistics to analyse group responses to each statement. Consensus for each question was defined as follows. These levels of agreement have been applied in previous Delphi studies (see Section 3.2).

Question 1: > 70% of participants agree with a statement.

Question 2: as > 70% of participants consider the statement moderately significant/very significant or not significant

Question 3: > 70% of participants somewhat agree/strongly agree or somewhat disagree/strongly disagree with the statement

Question 4: >70% participants consider the statement very important/extremely important or slightly important/not at all important

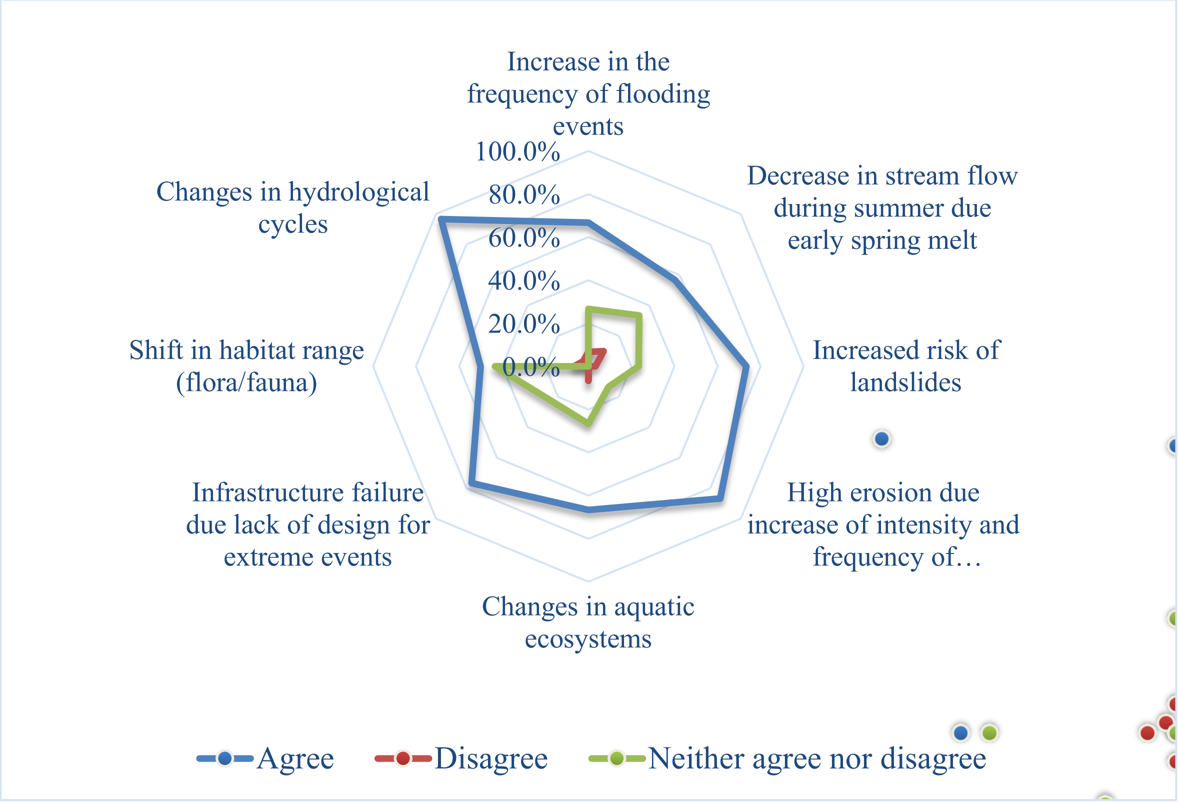
Question 5: > 70% of participants consider the statement very useful.

The responses by the panel of experts collected in the second Delphi round reached consensus. Therefore, a third round was not required. The results and analysis are presented in the following section.

5.1 Potential Climate Change Impacts on Mountains

The first question asked participants to assess the potential impacts that climate change could pose on mountains watersheds. The participants were asked to define their degree of agreement (Agree, Disagree, or Neither Agree nor Disagree) with the potential types of climate change impacts on mountainous watersheds. Consensus reached (96.7%) for the impact that triggers changes in the hydrological cycles, that could produce fluctuations to water availability downstream (Figure 5.1). A consensus (86.7%) was reached that the increase of intensity and frequency of precipitation would produce high erosion in mountainous regions. A consensus was reached (76.7%) that climate change would generate failure of infrastructure due lack of design for extreme events. Finally, the statement that the potential risk of landslides would increase achieved a consensus (73.3%).

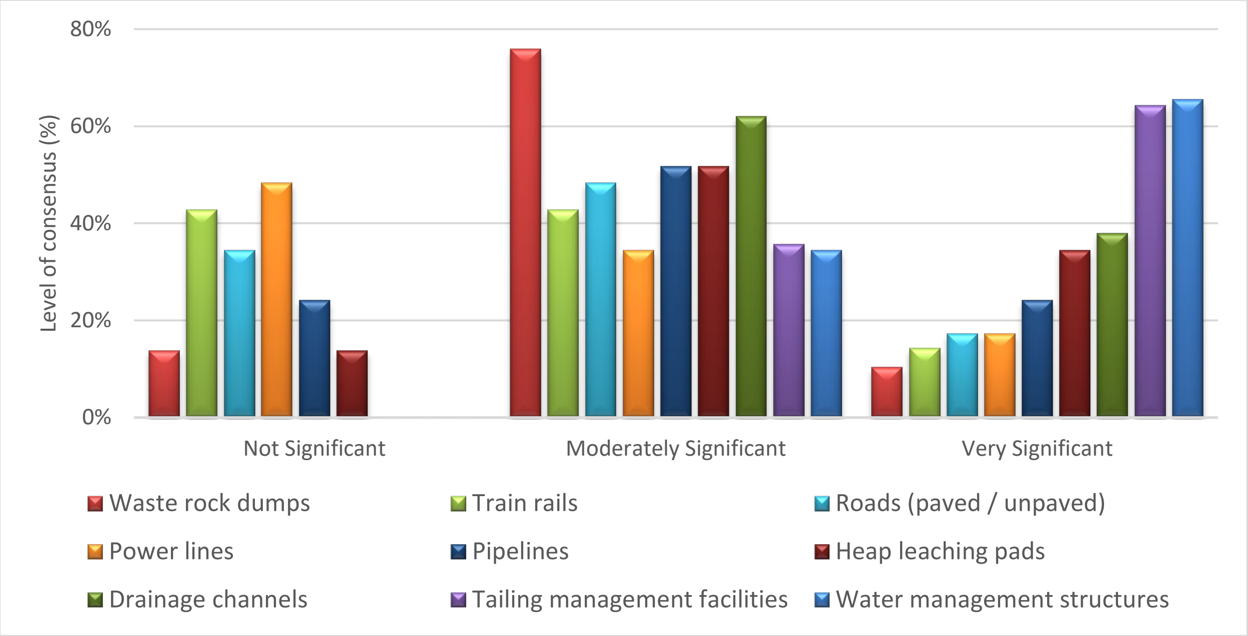
Figure 5.1 Consensus regarding potential climate change impacts on mountains



5.2 Significance of Potential Impacts of Infrastructure Failures

The second question assessed the significance of potential impacts on the watershed ecosystem that a mine infrastructure failure could generate as a consequence of extreme climate events. The Likert scale to measure statements of significance is: Not significant, moderately significant, and very significant. Complete consensus (100%) was reached on three statements (Figure 5.2): failure of the water management structures would cause a very significant impact; failure of the tailing management facilities would cause a very significant impact; and failure of the drainage channels would cause a moderately significant impact. Two statements regarding waste rock dumps and heap leaching pads reached a consensus (84.6%) that their failure would be moderately significant. The highest ranking very significant impact on the watershed ecosystem in a potential infrastructure failure as consequence of climate change was failure of water management structures (65.5%) and failure of tailings management infrastructure (64.3%).

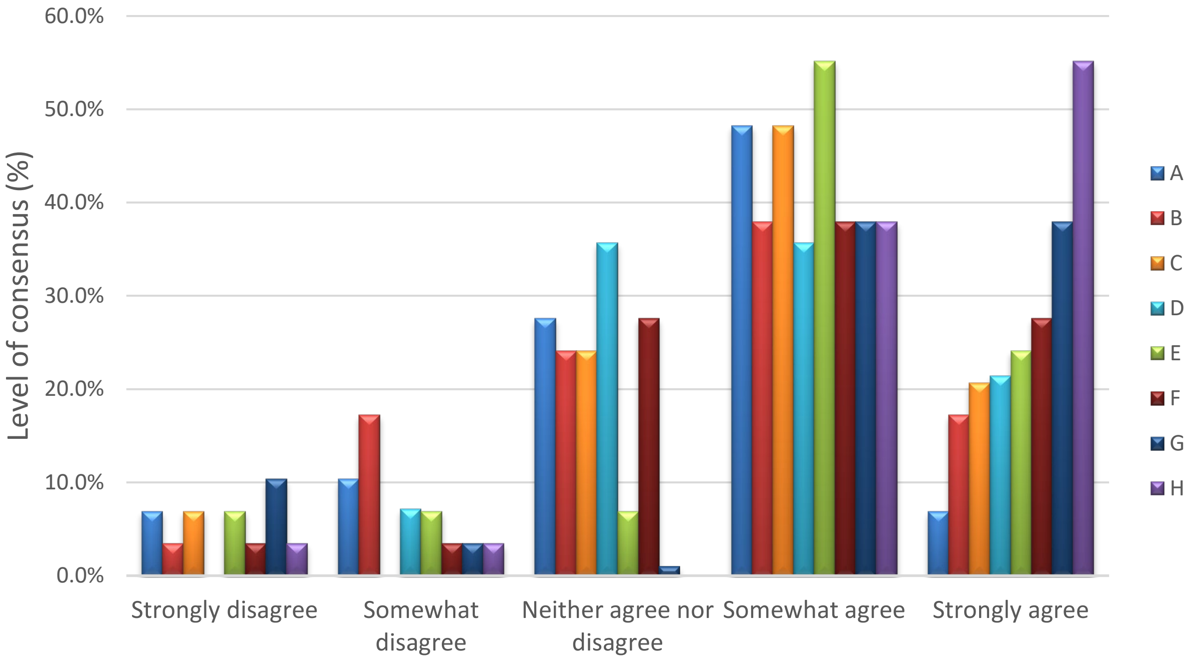
Figure 5.2 Consensus among 30 participants regarding significance of potential types of infrastructure failure



5.3 Impacts of Climate Change on Land Restoration or Mine Closure Activities

The third question assessed the degree of agreement to specific consequences of climate change affecting land restoration or mine closure activities in a mountainous region. The Likert scale to measure statements of agreement is: Strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, and strongly agree. Consensus was reached (92.3%) that hydraulic structures may need to be upgraded to manage more water during the mine closure stage (Figure 5.3). The panel also agreed (80.8%) that long dry periods can limit vegetation growth and that the selection of plants species for revegetation should take future climate conditions into account, rather than choosing species based on historical presence in the area (73.1%).

Figure 5.3 Consensus among 30 participants regarding climate change impacts on land restoration or mine closure

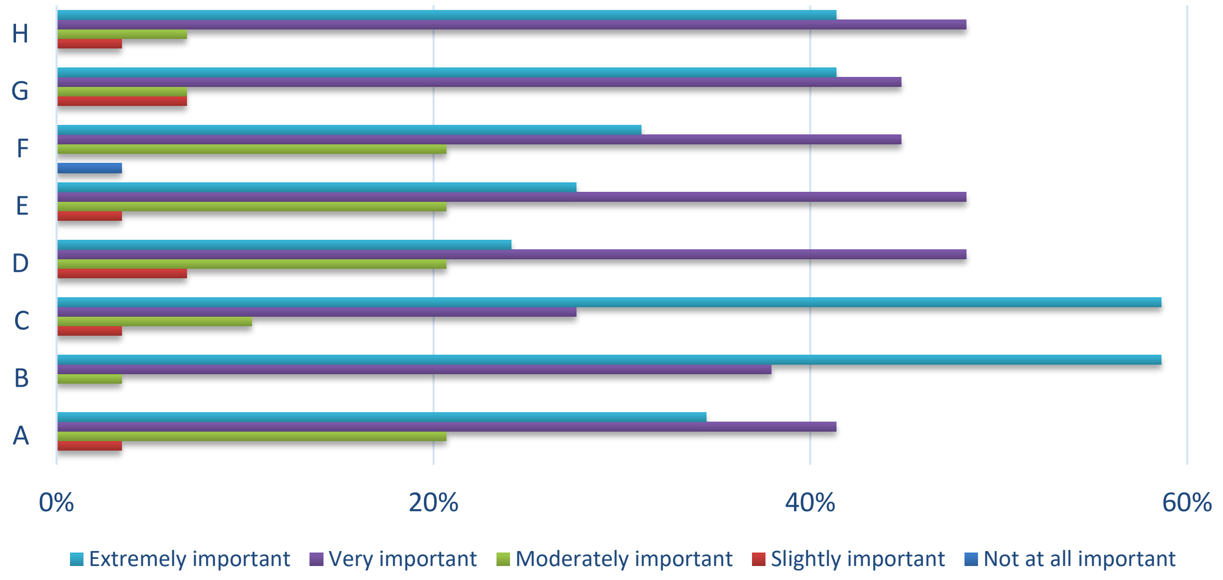


A - Establishment of vegetation to stabilise disturbed areas may be slower; B - Water disposal and treatment will be more difficult; C - Tipping points will affect species ranges and ecosystem resilience; D - Increased rainfall can promote acid rock drainage; E -Long dry periods can limit vegetation growth ; F - Wetter conditions will affect cover and revegetation stability; G - The selection of plants species for revegetation should be considering future change of climate, more than choosing species based on historical presence in interest; H - Hydraulic structures may need to be designed to manage more water

5.4 Degree of Importance for Adaptation Strategies

The fourth survey question assessed the degree of importance for a group of adaptation strategies, in reducing the adverse effects of climate change in mountainous watersheds. The Likert scale to measure statements of importance is: Not at all important, slightly important, moderately important, very important, and extremely important. The panel agreed (96.2%) on the importance of an integrated management of the watershed and long-term plans to reduce the adverse effects of climate change in mountainous watersheds (Figure 5.4). Consensus was reached (88.5%) on the importance of designing future land uses that can withstand extreme weather events. There was a similar level of agreement (84.6%) that designing infrastructure based on risk assessment for future climate scenarios and extreme weather events was an important adaptation strategy, as was the design of emergency response and evacuation plans.

Figure 5.4 Consensus among 30 participants regarding degree of importance for adaptation strategies



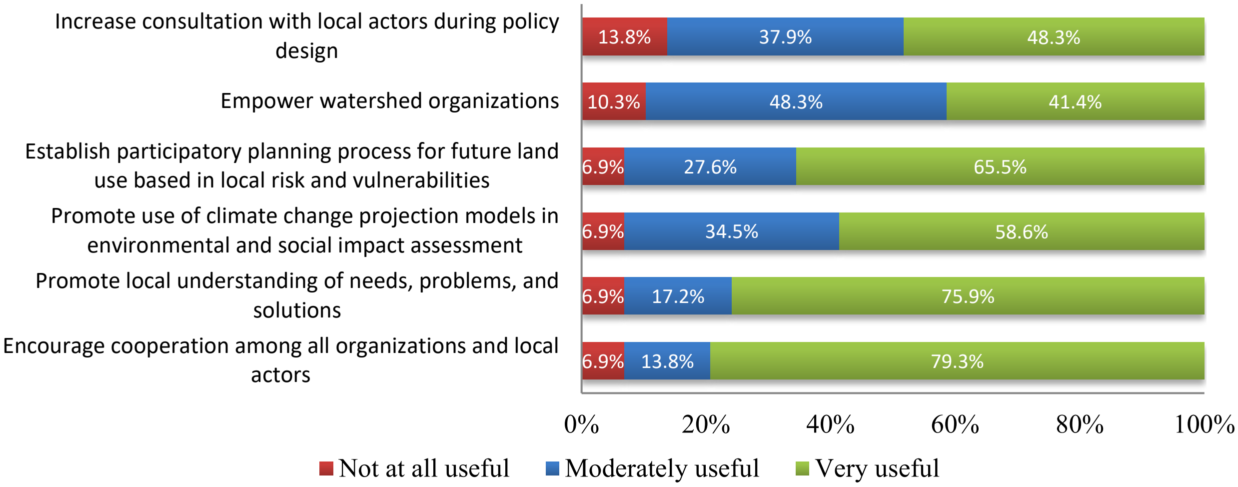
A - Wetlands restoration, management, and conservation; B - Integrated management of the watershed and long-term plans; C - Design infrastructure based on risk assessment for future climate scenarios and extreme weather events; D - Develop climate scenarios with local expert-based narratives; E - Improve management and conservation of ecosystems; F - Execute climate risk assessment of physical and biological systems at watershed level ; G - Design emergency response and evacuation plans ; H - Design and implement future land use that can withstand extreme weather events.

Among the eight adaptation strategies, two were ranked as extremely important to reduce adverse effects of climate change in mountainous watersheds (Figure 5.4): integrated management of the watershed and long-term plans (58.6%) and infrastructure should be designed based on risk assessment for future climate scenarios and extreme weather events (58.6%). From a total of eight statements assessed, seven achieved consensus (defined as >70% participants considering the statement very important/extremely important or slightly important/not at all important).

5.5 How Useful Are Public Policy Strategies to Enhance Climate Change Adaptation Acceptance at the Watershed Scale

A consensus (79.3%) was reached on the utility of policies that encourage cooperation among all organisations and local actors in the watershed (Figure 5.5). The policies that promote local understanding of needs, problems, and solutions also reached a consensus ranking of 75.9%.

Figure 5.5 Consensus among 30 participants regarding usefulness of public policy strategy to enhance acceptance of climate change adaptation at the watershed scale



5.6 Delphi Survey Summary

Through a Delphi survey with a worldwide panel of experts in mine closure and mountain ecosystems, a group of practices and strategies were identified that the mining sector could use to adapt to climate-related risks. Anticipating the future impacts of climate change is always associated with uncertainties. When analytical modelling is limited, expert judgment can be used to inform decision-makers. These could facilitate the mining industry's adaptation to climate risks and promote resilience to climate change in the watersheds surrounding mining operations. From the total of 30 participants in the assessment panel of experts, 57% were from the mining industry, 23% from academia, and 20% from international organizations.

The results show that the extreme events associated with climate variability are anticipated to aggravate potential impacts in the environment that will require the reassessment of the mine closure strategies. The manifestations of these climate risks are related to the warming magnitude, the geographic location, the local vulnerability, and the implementation of strategies for adaptation. Therefore, the design of mining operations and associated mine closure planning must be informed effectively within a framework of the potential future climate scenarios.

The panel of experts assessed in the present research considered that the climate-extreme events would produce very significant impacts on the watershed's ecosystem if an infrastructure related to water management were to suffer a failure in the mine closure stage. The highest impacts would be produced from the water management structures, the tailings management facilities and the drainage channels. These risks will be associated with the potential increment of precipitation and the landscape structure modification in the sites. Therefore, hydraulic structures may need to be increased in design to manage more water during the mine closure stage.

On the other hand, areas with drought risk and extended dry periods would limit the vegetation growth process required in the restoration areas. The removal of topsoil during mine operations results in a loss of organic content and water retention capacity. This condition will require establishing a structured restoration plan to recover the ecosystem's health. Moreover, the vegetation patterns, growth rates, and regime changes in soil moisture would be impacted. Therefore, the selection of plants species for revegetation should be defined under consideration of the future climate change scenarios, rather than choosing native species based on historical presence in the area of interest.

To adapt and reduce the adverse effects of climate change in mountainous watersheds it is extremely important to develop an integrated approach to watershed management with long-term plans. This will support an informed decision-making process, which incorporates an understanding of cumulative effects, and the implementation of future land uses that can withstand extreme weather events as an adaptation strategy. Moreover, the mine infrastructure design must be based on a risk assessment for future climate scenarios and extreme weather events. At the same time, consider the design of emergency response and evacuation plans. Incorporation of climate risk assessment practices combined with adaptation strategies will support an approach to designing sustainable mine closure plans.

A vulnerability assessment process is crucial to identify the areas and communities that are most at risk, as well as the key impacts of a changing climate. The execution of a risk and vulnerability assessment will help in establishing resources to where they are most needed, and in designing monitoring plans. These risks are beyond the mine site area because these industries are often located in challenging geographies and manage climate-sensitive resources (i.e., water and energy) that are critical in the mountain ecosystem.

From the research completed for this chapter, it is concluded that it is important to have a holistic approach and to design adaptation strategies to climate change by promoting the use of ecosystem services and biodiversity during engineering design. A potential strategy entails an Ecosystem-based Adaptation approach which is a process that involves restoration, conservation, and sustainable management of the natural resources, the use of biodiversity, and ecosystem services to help people adapt to the adverse effects of climate change. When the mountain ecosystem is in good health, it will contribute to protecting against natural hazards and the impacts of extreme events, particularly hydrological events such as floods and droughts; and increase the resilience of communities to climate change effects.

The following points could be considered as a synthesis of the results:

- Very significant impact for potential failure: tailing management facilities, and water management structures
- Impacts of climate change on land restoration process: changes hydraulic infrastructure design; and temperature variation will limit vegetation growth

- Adaptation strategies importance: Integrate watershed management, with long-term plans; and design future land uses that can withstand extreme weather events
- Public policy strategy: Cooperation among local actors; and local understanding of needs/problems/solutions

Chapter 6: Results: Climate Risk Assessment and Adaptation Framework for Mine Closure

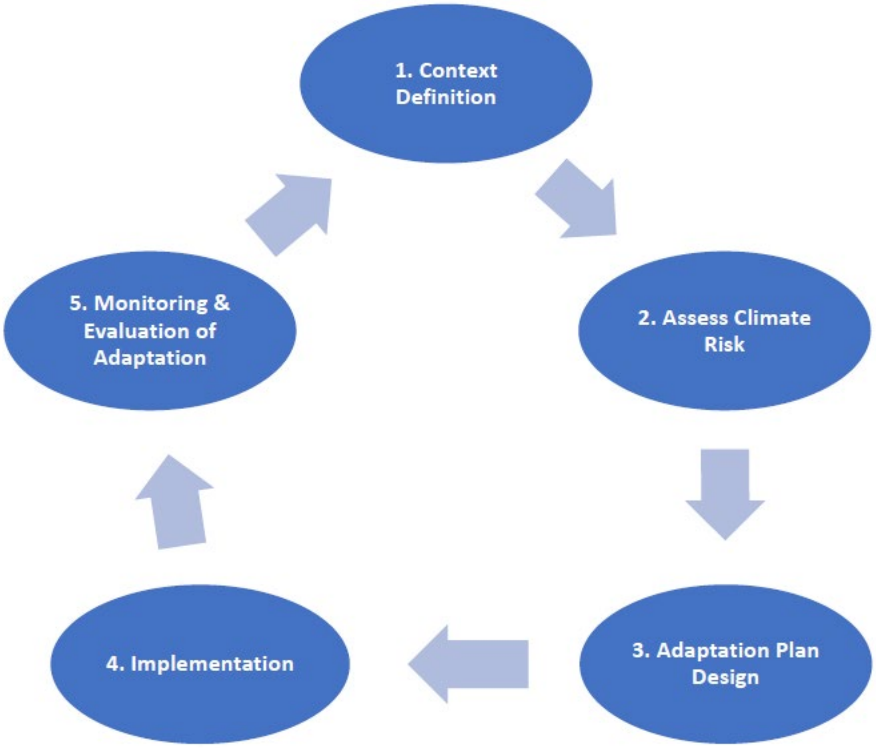
This chapter introduces the novel Climate Risk Assessment and Adaptation Framework (CRA-AF) for mine closure, which aims to: (1) identify the potential climate-related risks within the watershed(s) surrounding a given mining operation and (2) inform adaptation strategies to moderate climate-related risks that may arise in the future mine closure stage. In designing adaptation strategies, the work draws upon an ecosystem-based approach and SES perspective (see Section 2.5). The desired ultimate outcome is to improve decision-making processes for mine closure design and land restoration activities to proactively reduce climate-related risks. The CRA-AF could be applied to an operating mine to review and update the closure strategy or a new potential project to support the closure design in the planning stage.

Application of the CRA-AF could be managed by an external consultant (e.g., consultancy company or independent third party) or a mine site facilitator (e.g., member of the mine closure team). The former would be required to review and work with publicly accessible data: most mining companies around the world make their permitting documents available to the public. The latter would use public data and additional internal information from the mine site, but this approach will require internal time and resources and could take longer. The final decision would depend on the particular situation, taking into consideration the timing and budget for plan execution. This decision will not cause variation in the CRA-AF results.

The CRA-AF provides a sequence of five steps (Figure 6.1) with required information and questions that guide the user (or practitioner) to define the hazard, vulnerability, and exposure factors that lead to climate-related risks in a specific area and their potential adaptation strategies where the mine site is or will be located (in an early stage). These steps were informed by the review of the infrastructure climate risk protocols presented in Section 3.3.1.

Step 1 – Context definition: Understand the context where the climate risk assessment will be applied, that is, the mine infrastructure and components of the mine closure stage, the ecosystem services, local communities, and local climate parameters (present and projected). **Step 2 – Assess climate risk:** This section provides guidance to assess the climate risk based on climate-related hazards, exposure, and vulnerabilities in the social-ecological system. **Step 3 – Adaptation plan design:** Based on the climate risk identified in step 2, this section provides guidance to establish adaptation goals and objectives, identify adaptation options, prioritise EbA options, and identify actions required for implementation. **Step 4 – Implementation:** General guidance is provided regarding identifying and selecting the implementation processes to ensure the success of the adaptation plan. **Step 5 – Monitoring & evaluation:** This section provides guidance to assess whether the previously defined goals have been achieved and to identify challenges encountered during execution.

Figure 6.1 Steps of the Climate Risk Assessment and Adaptation Framework (CRA-AF) for mine closure



6.1 Step 1: Context Definition

6.1.1 Define Local Conditions

The first step of CRA-AF is to set the boundaries of the assessment as defined in the project or operation permits. A general description of each facility and component of the site is required at this point, specifically for those that will remain in the area for the closure stage. Where available, incident reports and records of past events that affected the serviceability of the analysed infrastructure should be considered. At the same time, review the codes, standards, or guidelines for mine infrastructure design, operation, and maintenance facilitates defining the context for the risk associated with local variations on temperature and precipitation patterns (Engineers Canada 2016).

A clear understanding of the major ecosystem services in the surrounding watershed is required, including how they are interconnected with local community livelihoods. The description must characterize the approximate size of each ecosystem, detailing the important fauna and vegetation and their locations, all in reference to the communities and areas of major use related to the watershed object of study. This information could be collected from the environmental impact assessment and other available public documents or reports from the area of assessment. When available, the health of the ecosystem must be reviewed, accounting for trends in the functionality of each service provided at basin level.

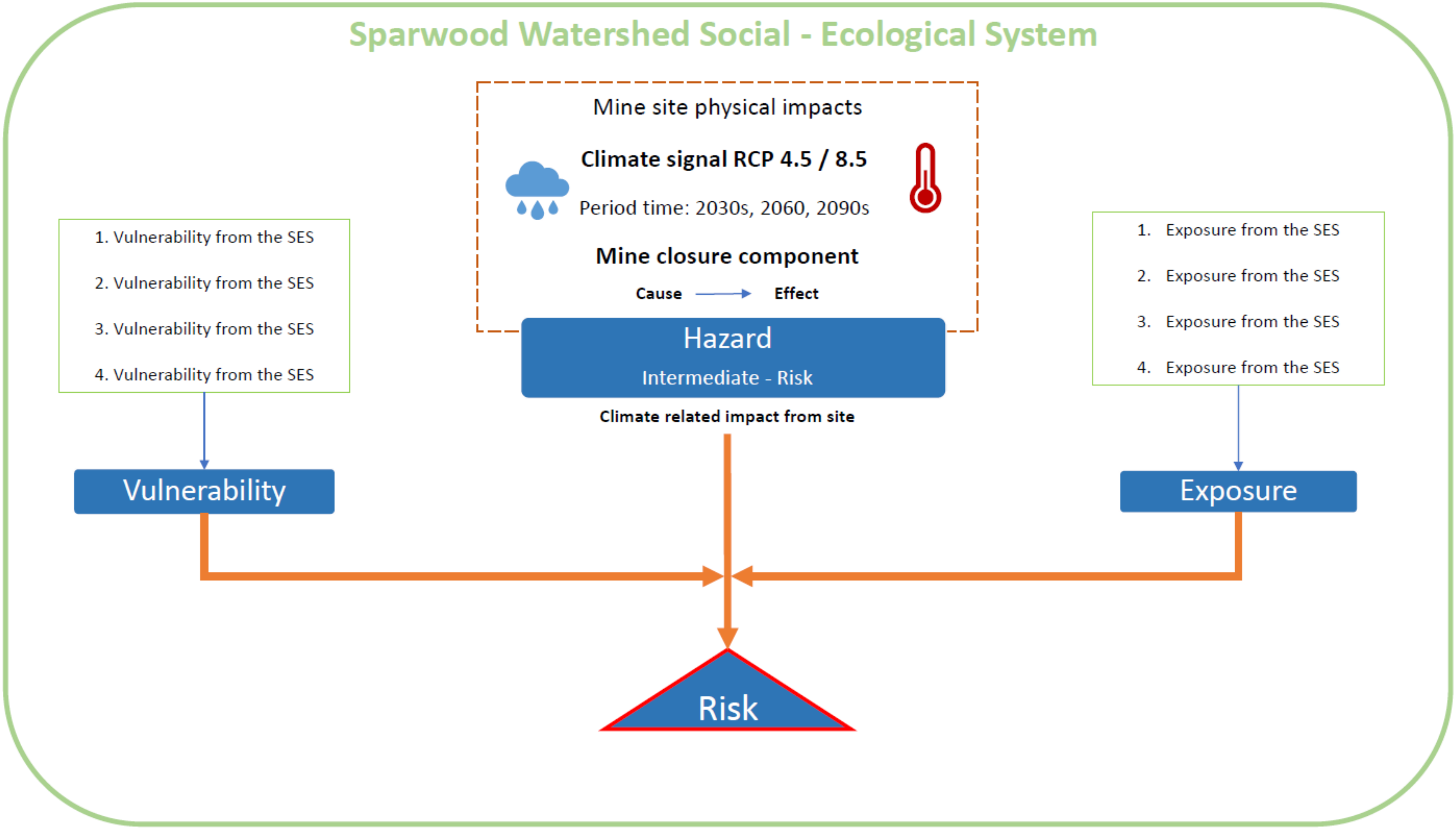
At this stage, stakeholders in the watershed who could be impacted by the hazards are identified, as are the social groups who are particularly vulnerable to climate change impacts. As a part of defining the context, it is also important to assemble data regarding present and projected local climate parameters, including those associated with the infrastructure (design, development, and management) and local SES. Climate data are needed at a screening level (Engineers Canada 2016). Climate trends that may contribute to infrastructure and ecosystem vulnerability should provide information about frequency, duration, dates of occurrence, magnitude, and intensity of weather events at a local or regional level (Snover et al. 2007). This will be subject to the availability of data provided by the site or specialised climate institutions.

Future trends in rainfall, temperature, and climate hazards are based on the projected climate under mid-and a high-emission mitigation scenarios as suggested in (IPCC 2014b). These scenarios are termed Representative Concentration Pathways (RCPs) and designated 4.5 and 8.5, respectively as it is suggested in the IPCC’s Fifth Assessment Report (IPCC 2014b). Future climate trends are analysed for three time periods to inform the assessment sequence: 2030 (average 2021–2050), 2060 (average 2051–2080), and 2090 (2070–2099). These periods allow for understanding of social and ecological dynamics and their relation to climate variability (Berkes, Colding, and Folke 2001). It is important for the analysis to highlight potential combinations of weather events that could increase infrastructure or ecosystem vulnerability.

6.1.2 Define Scope

Once the context is defined, the next step is to analyse the cause-effect or impact chain (Figure 6.2) to better understand, systemise, and prioritise the factors that drive risk in the SES (Fritzsche et al. 2014). It is important to understand the interconnections between climate risks at the site vs. watershed scale because they are mutually independent: initial identification of potential climate-related hazardous events or trends at the mine site level will support identification of potential climate-related risk at the watershed level. This process should include noting how climate-related impacts, including hazardous events, have occurred in the past and take into account risks related to climate trends (Engineers Canada 2016). The cause-effect analysis identify the intermediate risk of a given change at the site level (mine component physical impacts), which may then cause hazardous events or threaten the SES (e.g., surface water runoff increases acid rock drainage), which will lead to second-order risks in the SES (e.g., affecting ecosystem services) due to vulnerability and exposure factors.

Figure 6.2 Impact chain to define factors that drive risk in the social-ecological system



At the same time, major non-climatic drivers in the watershed area that pose potential threats to the ecosystem in the closure stage need to be addressed, for example, future community expansions or urbanisation. Additionally, livelihood effects as result of the impacted ecosystem services and the past socio-economic impacts due to climate events need to be reviewed (UNDP 2012). The scope description needs to include a summary of the site and local geographical features relevant to the study that may influence the climate trends or increase risk. In this perspective, the climate-related risk affecting mine infrastructure is an intermediate risk in the cause-effect chain at the watershed level.

6.1.3 Define Execution Plan

This protocol allows for the study to be executed either by the mining company directly (e.g., by the mine closure team) or by an independent third-party (e.g., by an external consultancy, communities, or regulators). The depth of the assessment will depend on access to information and public data availability. Depending on the location, much of the needed information is available in environmental impact assessments, mine permits, government agency reports or local community documents.

At this stage, staff members or departments within the mining company that will be involved in the assessment process and constitute the mine closure adaptation team should be chosen, and their roles and expected contributions should be established. A team leader should be nominated and given sufficient authority to lead the effort (Engineers Canada 2016). In the independent third-party approach, the assessment will be based on the use of available public information about the mining company and the SES in the watershed area of intervention.

An optional action is to define a list of local institutions to be involved in the assessment process. The specific level of involvement of the community and external stakeholders will depend on the relationship the company has with the community. Open communication with the community and stakeholders will build trust and promote future collaboration on adaptation strategies.

The primary output of step 1 is a list of the mine infrastructure and ecosystem services that potentially will be affected in a climate change scenario, linked by the impact-chain analysis.

6.2 Step 2: Assess Climate Risk

Once the impact-chain and the potential local climate-related impacts are outlined, the next step is to assess the climate risks for the site and watershed in question. This section provides guidance to assess the climate risk in the SES where the mine site is or will be located.

6.2.1 Identify Infrastructure Response Considerations for Mine Closure

For the mine infrastructure components identified in the previous step that will be part of the closure stage, their functional capacity should be set and the mine closure component response to climate events determined. For each climate parameter selected, infrastructure performance reactions need to be identified (Engineers Canada 2016). The functionality of the infrastructure will be at risk if it is placed in conditions beyond its service capacity, which could produce a negative impact on the SES. Some infrastructure responses may be identified in relation to a specific climate parameter based on historical infrastructure reactions (CALEMA 2012).

6.2.2 Select Indicators for Hazard, Vulnerability, and Exposure

After defining the major contributing factors leading to climate-related risk, a general description of the potential hazards, vulnerabilities, and exposure indicators is required, with a brief explanation of the reasons for their selection. The indicators needed for hazard factor quantification numerical data to characterise intensities (e.g., precipitation 100 mm over daily average) and frequencies (e.g., one extreme single-day precipitation event in 10 years). The indicator description should include the unit of measure, the spatial extent the data covers (e.g., watershed, district, region), the time period covered by the data, and the interval at which the indicator values are updated for monitoring purposes (PIEVC 2008).

6.2.3 Determine Climate-Related Hazards

This step will identify and define the hazards affecting the watershed that are generated by climate-related events on the mine closure components. For this stage, the hazard analysis process is adapted from the guidelines of PIEVC Engineering Protocol (Engineers Canada 2016), as mentioned in Section 3.3.1. Based on the climate events identified during the scope definition phase, the impact those changes will have on the closure stage must be assessed. For each impact, the relevant mine infrastructure and how the serviceability or function of each might be affected by the impact is considered. The physical impacts of climate events on the mine infrastructure in the closure stage will produce an intermediate risk that links the initial climate hazard to the risk at watershed level. These intermediate risks will be considered the hazardous factors to analyse in the CRA-AF for the SES, as suggested by The Vulnerability Sourcebook (Fritzsche et al. 2014).

The intermediate-risk of a given event related to the mine site is the product of the probability (likelihood of occurrence of a climate event that triggers an infrastructure component response) and the severity (expected consequence of the infrastructure component response when the specified climate event occurs) of a given event (Equation 6-1) (Engineers Canada 2016). This intermediate-risk assessment process is specific for infrastructure on the mine site. For each climate-related event identified, a list of the relevant impacts in the mine infrastructure will be established and recorded.

Equation 6-1 Intermediate Risk

$$Probability \times Severity = Intermediate\ Risk$$

6.2.3.1 Establish Probability

Professional opinion can advise on the probability of occurrence of a climate event that triggers an infrastructure failure (Engineers Canada 2016). The probability score has a scale from 0 to 7 (Table 6.1) and is a function of the magnitude, frequency, and robustness of the forecast. A score of 0 means that the climate parameter will not change during the time horizon of the assessment in a manner that threatens the infrastructure. A score of 7 denotes the certainty that the climate parameter will change during the time horizon of the assessment in a manner that causes the infrastructure to fail (Engineers Canada 2016). As mentioned in Section 6.1.2, future climate change will be assessed for the time periods 2030, 2060, and 2090 under two RCP scenarios (4.5 and 8.5) with respect to the baseline period 1950–1980.

Table 6.1 Probability Score for Occurrence of a Climate Event that Triggers Infrastructure Failure (Engineers Canada 2016)

Score	Definition
0	Negligible Not applicable
1	Highly unlikely Improbable
2	Remotely possible
3	Possible Occasional
4	Somewhat likely Normal
5	Likely Frequent
6	Probable Very frequent
7	Highly probable Approaching certainty

Based on professional judgment, the probability score will be defined based on the following considerations (Engineers Canada 2016):

$$Probability = \int (a, b, c, d)$$

a. Threshold triggered

Will the climate parameter change over the time horizon of the assessment?

Yes / No

b. Magnitude of event

What is the impact of the magnitude of the climate event on the frequency of trigger events?

H = High

M = Medium

L = Low

c. Frequency of event

What is the impact of the frequency of climate events on the frequency of trigger events?

H = High

M = Medium

L = Low

d. Robustness of forecast

How robust is the climate projection and/or weather data?

H = High

M = Medium

L = Low

6.2.3.2 Establish Severity

In the next step, the severity of each event will be quantified. The severity score has a scale from 0 to 7 (Table 6.2). The score 0 means there are no known or estimated negative consequences should the event occur. The score 7 means a significant known or estimated consequence (failure) will result if the event occurs (Engineers Canada 2016).

Table 6.2 Severity Score (Engineers Canada 2016)

Score	Definition
0	No effect
1	Measurable
2	Minor
3	Moderate
4	Major
5	Serious
6	Hazardous
7	Catastrophic

For each interaction of climate-related events and mine closure infrastructure, the intermediate risk will be calculated. Table 6.3 shows the range classification of intermediate risk at site level, which will be classified in a total of five categories. These categories are consistent with the Climate Action Secretariat of public sector (Climate Action Secretariat 2019) and the ISO 31000 process (ISO 2018).

During the site closure design, medium-high and high-risk cases at the mine site level will be considered climate-related hazards for the SES because they will have watershed-level effects.

Table 6.3 Reference intermediate risk or hazard. Adapted from Climate Action Secretariat (2019)

Risk score	Threshold	Response
< 12	Low-risk	No action required
12–19	Medium-low	No action required but interactions to be reviewed with changes in climate
20–27	Medium	Action may be required; interactions to be monitored with changes in climate Engineering analysis may be required
28–36	Medium-high	Action may be required Engineering analysis recommended
> 36	High-risk	Action required

6.2.4 Social-Ecological System Vulnerability Assessment

At the watershed level, the vulnerability assessment will begin by understanding which of the main societal and ecological drivers that make up the SES could contribute to the risk. The focus is to understand the processes involved in climate-related impacts and both the biophysical and socio-economic implications. Key community structures, functions, and social groups must be identified in the area of assessment that are potentially susceptible for each climate-related hazard or intermediate risk identified previously at site level.

The vulnerability assessment is based on the concepts from IPCC (IPCC 2014e) and adapted from (Fritzsche et al. 2014). The vulnerability rating is a function of the sensitivity and adaptive capacity of the system. This refers to the susceptibility to harm arising from climate-related impacts. If the functionality of an ecosystem service is likely to be affected as a result of local climate trends, it should be considered sensitive to climate change (GIZ EURAC & UNU-EHS 2018). To determine the sensitivity capacity, the limiting factors of the ecosystem services that may be affected by climate change must be identified to understand and how climate change will affect the functionality of a given service area. Part of assessing which ecosystem services would be affected is identifying which species of concern exist in the assessment area.

In order to evaluate SES sensitivity, climate-related hazardous effects on SES functioning must be determined. The sensitivity is determined by factors that directly affect the consequences of the hazard (Field et al. 2014). To identify how the SES would be affected by these changes today, it is necessary to know if the ecosystem services are subject to any existing stressors, and if the impact occurs, how it will affect ecosystem service functionality. To represent the sensitivity of the SES to climate-related hazards, a value scale from 1 (no sensitivity) to 5 (worst-case scenario) is assigned (Table 6.4).

Table 6.4 Sensitivity ranking in the social-ecological system. Adapted from (ICLEI 2017)

If the climate hazard occurs, will it affect the functionality of the ecosystem service?		
S1	No	Functionality will stay the same
S2	Unlikely	Functionality will likely stay the same
S3	Yes	Functionality is likely to get worse
S4	Yes	Functionality will get worse
S5	Yes	Functionality will become unmanageable

The adaptive capacity is the ability of a system to change its characteristics to moderate potential damage or take advantage of opportunities to climatic stimuli or their effects with minimum disruption or cost (Brooks et al. 2005; Bott 2014). The adaptive capacity depends on those abilities of the SES that would reduce the potential climate-related impacts of a given service area. This step will be supported by an understanding of the factors that influence the social capacities to manage the changing conditions in the SES: available expertise, technology, organisations, and financial resources.

To assign a value to the adaptive capacity for each climate-related impact, it is important to ascertain how the impacts will affect SES services as well as the potential service disruption and whether that service can accommodate these changes. Similar to the sensitivity valuation, a scale of 1 to 5 represents the adaptive capacity of the ecosystem services (Table 6.5).

Table 6.5 Scale of adaptive capacity in the social-ecological system. Adapted from (ICLEI 2017)

Can the ecosystem service adjust to the projected climate-related impact with minimal cost or disruption?		
AC1	No	Will require substantial costs (> 30% cost overrun) and expert intervention
AC2	No	Will require significant costs (16–30% cost overrun) and expert intervention
AC3	Maybe	Will require some costs (6–15% cost overrun) and expert intervention
AC4	Yes	Will require small costs (0.5–5% cost overrun) and expert intervention
AC5	Yes	No to little costs (< 0.5% cost overrun) and expert intervention

With the ratings of the sensitivity and adaptive capacities defined for each climate-related impact, the vulnerability rating for each ecosystem service can then be assigned (Table 6.6): V1 (low), V2 (medium-low), V3 (medium), V4 (medium-high), and V5 (high).

Table 6.6 Sensitivity and adaptive capacity matrix (ICLEI 2017)

	S1	S2	S3	S4	S5
AC1	V2	V2	V4	V5	V5
AC2	V2	V2	V3	V4	V5
AC3	V2	V2	V3	V4	V4
AC4	V1	V2	V2	V3	V4
AC5	V1	V1	V2	V3	V4

The result of this process is the SES vulnerability assessment for all climate-related hazards or intermediate-risks identified at the site level. With the aim to focus on those societal and ecological drivers more vulnerable, only the SES components defined as having high or medium-high vulnerability are used in the next step of the CRA-AF. It is expected that Medium-low and Low vulnerabilities will be maintained under review and no further action will be required unless they become more severe (ICLEI 2017).

6.2.5 Determine the Exposure Level of Relevant Components of the SES

Exposure refers to the presence of ecosystems, communities, environmental functions, natural services, or cultural assets in the SES that are important for local livelihoods and that could be adversely affected by hazards from the mine site (IPCC 2014c). The ecosystems that provide, regulate, or support the most valuable services defined in the watershed and interact with the climate related hazards receive an exposure value in this step. The degree of exposure can be expressed by absolute numbers, densities, or proportions of the elements at risk (GIZ EURAC &

UNU-EHS 2018). It should express the relevance of the exposed element in the SES. For instance, exposure of trees to wildfire is related to tree density in the forest and to the relative areas of wildland/urban interface in cities.

The ecosystem services identified in the context definition step (Section 6.1) will be assessed to define their exposure in the SES. The process evaluates how these ecosystem services could be adversely affected by climate hazards (GIZ EURAC & UNU-EHS 2018). Any existing stress in the watershed should be considered in the analysis along with how observed and projected local trends in rainfall, temperature, and extreme events affect ecosystem services.

6.2.6 Normalise Indicator Values

The hazard, vulnerability, and exposure indicators need to be transformed into a common scale using unit-less values. This standardised value will range from 0 (optimal, no improvement necessary or possible) to 1 (critical, system no longer functions) (Fritzsche et al. 2014). Normalisation allows different factors to be directly compared, enabling evaluation of the criticality of an indicator value with respect to the risk.

The method of normalisation depends on the indicator scale. Therefore, the first step is to determine the scale of measurement (metric, nominal, or ordinal) for each indicator (Fritzsche et al. 2014) by the occurrence or circumstance observed in the SES and how it is described. For metric indicator values, the min-max method is applied, and for the categorical indicator values (nominal and ordinal), the five-class evaluation scheme is applied (Fritzsche et al. 2014). Normalisation methods are described in Appendix D.

6.2.7 Analyse Climate Risk Scores

The various indicators used to describe hazard, vulnerability, and exposure must be aggregated into a single indicator to associate the data representing a single component of the mine closure plan. The common, simple, and transparent procedure is weighted arithmetic aggregation (Fritzsche et al. 2014). The procedure consists of simple summation of the individual indicators divided by the number of total indicators as follows (Equation 6-2), where *CI* is the composite indicator, *I* in the individual indicator, and *n* is the number of indicators:

Equation 6-2 Composite indicator

$$CI = \frac{I_1 + I_2 + \dots . I_n}{n}$$

Once the three components of risk are defined, a final aggregation process is used to obtain an overall risk quantified in a single term. A direct and simple approach is the weighted arithmetic mean, which combines the three components as follows:

Equation 6-3 Aggregation of risk components

$$Risk = \frac{Hazard + Vulnerability + Exposure}{3}$$

The results are classified into risk classes (Table 6.7).

Table 6.7 Climate risk classes (GIZ EURAC & UNU-EHS 2018)

Metric risk class, range 0 to 1	Risk class, range 1 to 5	Description
0–0.2	1	Very low
> 0.2–0.4	2	Low
> 0.4–0.6	3	Intermediate
> 0.6–0.8	4	High
> 0.8–1	5	Very High

6.3 Step 3: Adaptation Plan Design

Based on the climate risks identified in the previous step, this section provides guidance to establish adaptation goals, identify adaptation options, prioritise EbA options, and determine the actions required for implementation. The analysis is based on the AlivE tool (Terton and Dazé 2018; see Section 3.3.2).

6.3.1 Establish Adaptation Objectives

Establishing adaptation objectives will facilitate integrating plans for mine closure, such as the mine proposed infrastructure with the watershed ecosystem services. These objectives will take into consideration future impacts related to climate change and actions required to reduce vulnerability and exposure in the SES (Terton and Dazé 2018). The adaptation objectives should be expressed in reference to the climate-related events that are threatening the SES in the watershed where the mine closure components and activities will take place. Some objectives might be specific, whereas others might be general. The adaptation objectives will address the mining impacts in the SES.

6.3.2 Identify Adaptation Outcomes for Vulnerable Livelihood Strategies

In this step, the initial impact chains and the final risk assessment process will be used to identify adaptation options for livelihood strategies that are vulnerable to environmental changes (GIZ EURAC & UNU-EHS 2018). Impact chains can provide entry points and first guidance to identify adaptation options, including conventional engineering-based, ecosystem-based, and combined solutions (GIZ EURAC & UNU-EHS 2018; Terton and Dazé 2018). It is important to list any actions that might improve the SES adaptive capacity.

In the process of developing the adaptation outcomes, it is important to clearly explain:

- the desired state of the ecosystem and/or its services to be achieved through conservation, sustainable management, or restoration;
- how the ecosystem(s) help people to adapt; and
- which climate risk is addressed.

6.3.3 Identify EbA Options for Vulnerable Livelihood Strategies

With the desired adaptation outcomes identified, current and future climate impacts well understood, and adaptation options proposed, EbA options can be identified with the aim to inform the design of mine closure strategies. The EbA options should be actions that reduce or control climate impacts (CBD 2018) and help vulnerable populations cope with extreme weather events and harness the available ecosystem services (Brooks et al. 2005). Thus, for each adaptation outcome, it is necessary to identify potential EbA options for restoration, sustainable management, or conservation of ecosystem services.

Key questions that will support the analysis are:

- What conservation plans or policies have already been developed in the area for adaptation? How is the mine company involved?
- What sustainable management process should be applied to achieve the desired adaptation outcomes?
- Which restoration strategies should be pursued to address adaptation needs?

6.3.4 Prioritise and List Effective EbA Options for Vulnerable Livelihood Strategies

An important aim of mine closure is to restore the land impacted by the mine operation to a defined an end-land use objective while supporting sustainable development. Planning for this process should include reviewing input from stakeholders in the watershed who often possess interconnected and conflicting interests, values, and plans (Bainton and Holcombe 2018).

As explained in Section 3.3.2, based in the AlivE tool (Terton and Dazé 2018), a multi-attribute decision process is defined to assess potential EbA options in terms of their effectiveness for climate change adaptation. In a decision matrix (Table 6.8), the alternatives are evaluated and ranked based on five recognised criteria of EbA success (Bertram et al. 2017; Secretariat of the Convention on Biological Diversity 2019b). Each potential EbA option is weighted high (3), medium (2), or low (1) for each criterion, and the sum of the weighted values is the EbA score. Options with a score of 10 or more represent the most effective EbA options for the mine closure design (Terton and Dazé 2018). In the hypothetical matrix in Table 6.8, EbA option B would be expected to have significant environmental and socio-economic benefits for the SES.

Table 6.8 Hypothetical decision matrix for Ecosystem-based Adaptation (EbA) success

		EbA success criteria					
Adaptation outcome	Potential EbA options	Reduces current and future climate risks	Generates social benefits for vulnerable groups	Restore, maintains, or improve ecosystem health	Enhances sustainable use of biodiversity and ecosystem services at local level	Builds integrated management of ecosystem services with multi-sectoral approaches	EbA Score
	A	1	2	1	3	1	**8**
	B	2	3	3	1	3	**12**
	C	2	1	1	1	2	**7**

6.3.5 Identify Actions Required for Implementation of Priority EbA Options

The EbA options that have been prioritised and selected in the previous step will be considered for their potential implementation in the mine closure design. Actions that are critical to successfully implement these EbA options for land restoration need to be identified.

6.4 Step 4: Implementation

To progress from a list of effective EbA options to a formal action plan requires establishing project timelines, roles and responsibilities, and resources relevant to accomplishment of the objectives. This section will provide general guidance towards identifying and selecting the appropriate implementations tools to ensure the success of a progressive mine closure plan.

6.4.1 Identify Roles and Responsibilities for Priority EbA Options

Actors need to be named who will be involved in effective implementation of each EbA option. These include mining company department(s) and potential stakeholders (e.g., local governments, community groups, non-governmental organisations). The roles and responsibilities of each actor must be designated, including support from the management level.

6.4.2 Identify Opportunities from and Barriers to Priority EbA Options

This step identifies factors that positively affect successful implementation of each chosen EbA option while simultaneously contributing to the conservation of biodiversity (GIZ 2016). Examples include positive effects on health and well-being (e.g., clean water, increased food access), livelihood opportunities and sources of income (e.g., eco-tourism, birdwatching), and the environment (e.g., carbon sequestration, erosion regulation). At the same time, factors that may create barriers to implementation of each EbA option are identified such as lack of community support, high technical expertise requirements, and funding deficiencies (Terton and Dazé 2018).

6.4.3 Identify Project Activities to Support Implementation of Priority EbA Option and Key Actions

Project activities are identified and described that can bolster the critical actions required to implement each prioritised EbA option, taking into consideration actors and resources required as well as opportunities and barriers (Terton and Dazé 2018). These activities will be influenced by the resources the community members need to respond to climate risks such as information, knowledge, and development capabilities.

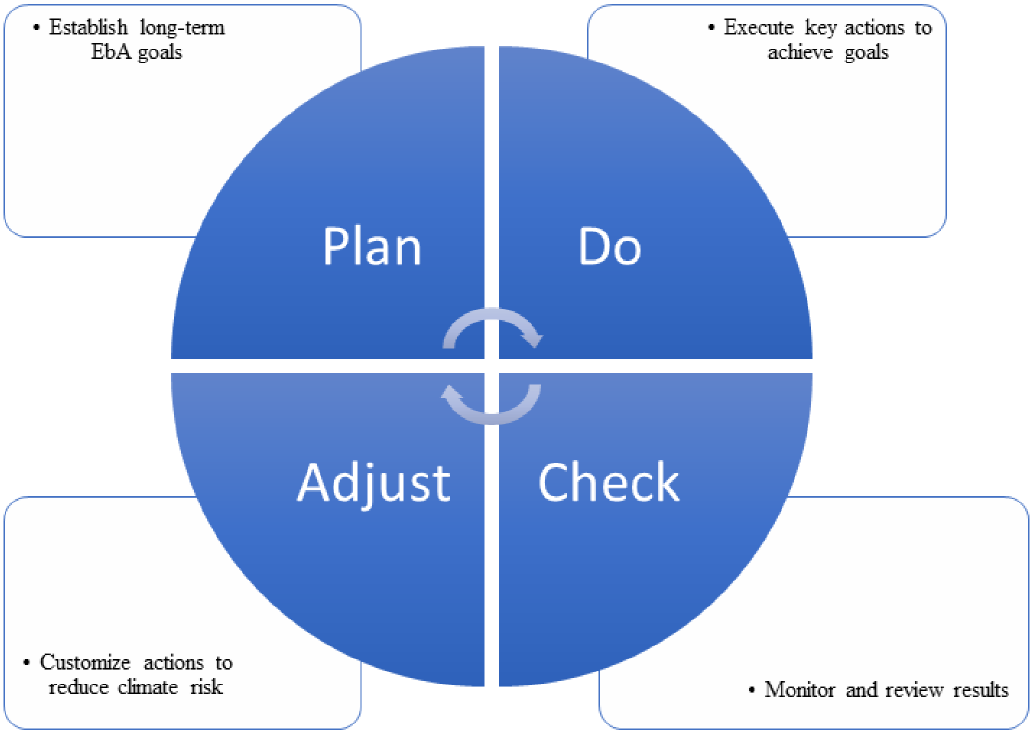
6.5 Step 5: Monitoring and Evaluation

This section provides guidance to assess whether the goals previously defined in the adaptation plan design have been achieved and to identify the challenges encountered in the execution. This process could be used to monitor the climate risk at watershed level and evaluate mine closure design strategies. Furthermore, this section will help in communicating the actions taken and results achieved to internal and external stakeholders.

Monitoring and evaluation is particularly important in climate change adaptation implementation because decisions for adaptation measures are typically made under uncertainty. Thus, monitoring and evaluation is an essential process to define the status of EbA interventions and the understand if the objectives have been accomplished (GIZ UNEP-WCMC and FEBA 2020). It can support required adjustments to the adaptation strategy and help identify future needs and trigger points for adaptive management (Fritzsche et al. 2014).

Uncertainties increase as a result of current and predicted future climate variability as well as the lack of knowledge of how species, habitats, ecosystems, and people respond to these uncertainties. Adaptive management is an option to decrease such uncertainty and increase the likelihood that adaptation outcomes will be achieved. The management of ecosystems is a cyclical process in which adaptation actions are followed by targeted long-term monitoring actions (Bours et al. 2014). The results of an intervention through these monitoring efforts can be applied to adapt and improve the performance of ongoing or future EbA-related activities (Terton and Dazé 2018). The Plan-Do-Check-Adjust decision cycle model can be used for adaptive management improvement (Figure 6.3).

Figure 6.3 Plan-Do-Check-Adjust decision cycle



6.5.1 Identify Long-Term Indicators to Measure Adaptation Outcomes

The contributions of EbA options to adaptation outcomes, such as improved ecosystem resilience and reduced community vulnerability may not be readily apparent for several years. Therefore, many EbA projects measure the implementation of project activities but do not assess the actual adaptation outcomes that EbA can deliver (Terton and Dazé 2018). Nonetheless, securing resources for continuing monitoring and evaluation over the long term is crucial for EbA interventions, given the long time periods required to manage and restore ecosystems (GIZ UNEP-WCMC and FEBA 2020).

In the development of the adaptation plan, a set of indicators is established that can be used to create baselines against which to measure the effectiveness of the adaptation actions. These indicators can also help assess how the watershed vulnerabilities are changing based on implemented actions, increasing or decreasing the risk of climate change impacts (Terton and Dazé 2018). Indicators should aim to measure the two components of the adaptation outcome:

a. Desired state of ecosystem: the ways restoration, management, and conservation are affecting ecosystems and ecosystem services under climate change.
b. Growing community adaptation capacity for climate risk management: the capability of people to cope with the effects of potential damage due to climate change (Terton and Dazé 2018).

6.5.2 Identify Short-Term Indicators to Measure EbA Options

Short-term indicators are focused on immediate outcomes and will support the analysis of effectiveness and progress of the implementation of the prioritised EbA options (GIZ UNEP-WCMC and FEBA 2020). Short-term indicators should be associated with specific key actions that are required for the successful implementation of EbA options (Terton and Dazé 2018). Short-term indicators should show that a particular action is completed, whereas long-term indicators show that actions have resulted in changed outcomes.

6.5.3 Investigate Future Adaptation Options and Actions

Actions that were not implemented in the first assessment of the adaptation options (Section 6.3.4) are listed to identify the reasons that implementation did not move forward. Then, shifts in vulnerabilities or exposures in the SES are analysed that could that cause a re-ordering of actions

(ICLEI 2017). A decision is made as to whether the social-ecological conditions changed enough that implementation of new adaptation actions is now possible. Finally, adaptation options and actions to address the new impacts are identified. For each action, the relevant indicators, drivers, and constraints are considered, some of which might not have been considered in the first assessment of adaptation options for mine closure design (GIZ UNEP-WCMC and FEBA 2020).

6.5.4 Communicate Accomplishments

A variety of communication methods can be employed to communicate a plan's success, including a community event, a press release, issue briefs, and reporting. It is important to gather data for monitoring and evaluation at the same time as the adaptation activities are being executed to ensure the details of changes that are occurring are recorded (GIZ UNEP-WCMC and FEBA 2020). The communication plan design should consider the following:

1. elements of the adaptation plan that need to be communicated.
2. objective of the plan.
3. social groups or individuals that would be interested in the information; and
4. communication tools to target these groups.

6.6 Climate Risk Assessment and Adaptation Framework for Mine Closure Summary

A new framework, the Climate risk assessment and adaptation framework (CRA-AF) was developed based on the natural disaster risk knowledge that has previously been applied to manage the impacts of climate events on public infrastructure. The CRA-AF was informed as well by the results of the Trend Analysis and the Delphi survey detailed in previous chapters. In the context of climate change impacts, climate risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Therefore, the CRA-AF considers the climate risk as the potential for adverse consequences for the social-ecological system that origins in the mine site. Finally, it incorporates an ecosystem-based approach for the design of adaptation strategies in the mine closure stage, with a watershed holistic perspective.

The CRA-AF provides a sequence of five steps that are intended to guide a practitioner to define the climate-related risks and their potential adaptation strategies. Step 1 – “Context definition” supports the understanding of the mine closure plans, the local area, and environmental background. It requires the user to establish the general description of the mine closure components and assemble the local climate parameters and variations on temperature and precipitation patterns. Future trends in rainfall, temperature, and climate hazards are based on the projected climate under mid-and a high-emission mitigation scenarios (4.5 and 8.5, respectively) as suggested by IPCC. At the same time, the details of the major ecosystem services in the surrounding watershed will be described. This includes the linkages with the local community livelihoods and a description of the stakeholders in the watershed that could be impacted by potential climate hazards. The primary output of this step is a list of the mine infrastructure and ecosystem services that could potentially be affected in a climate change scenario, linked by an impact-chain analysis.

Step 2 – “Assess climate risk” guides the assessment of climate-related hazards, exposure, and vulnerabilities in the social-ecological system. This process enables the practitioner to understand and analyze the interactions along with mine closure components, climate change, ecosystems, and livelihoods. This step starts identifying and defining the hazards affecting the watersheds that are generated by climate-related events on the mine closure components. The hazard related to the mine site is the product of the probability and the severity of a given climate event. At the watershed level, the vulnerability assessment is related to the main societal and ecological drivers that make up the SES that could contribute to the risk. The vulnerability rating is a function of the sensitivity and adaptive capacity of the social-ecological system. The ecosystems that provide, regulate, or support the most valuable services defined in the watershed and interact with the climate-related hazards receive an exposure value in this step. The degree of exposure can be expressed by absolute numbers, densities, or proportions of the elements at risk. The process evaluates how the ecosystem services could be adversely affected by climate hazards. Finally, once the three components of climate risk are defined, a final aggregation process is used to obtain an overall risk quantified in a single term.

Based on the previous results, Step 3 – "Adaptation plan design" will prioritize Ecosystem-based Adaptation strategies and identify activities that facilitate implementation of the EbA options. The EbA options should be actions that reduce or control climate impacts and help vulnerable populations cope with extreme weather events, harnessing the available ecosystem services. Therefore, integrating plans for mine closure will take into consideration future impacts related to climate change and actions required to reduce vulnerability and exposure, addressing mining impacts in the SES. With a multi-attribute decision process, the EbA options are rated in terms of their effectiveness for climate change adaptation.

After defining the adaptation strategies to consider in the mine closure design, Step 4 – "Implementation" provides general guidance to ensure the success of the adaptation plan. This requires establishing project timelines, roles and responsibilities, and resources relevant to the accomplishment of the objectives. In practice, such a plan would be influenced by the resources that the community members need to respond to climate risks, such as information, knowledge, and development capabilities. Therefore, the plan should be incorporated into a watershed integrated management strategy. Step 5 – "Monitoring and evaluation" supports the classification of key elements and indicators for a monitoring and evaluation process of adaptation strategies. This will be used by the practitioner to assess whether the previously defined goals have been achieved and distinguish challenges faced during execution. The decision cycle model is a tool to assist adaptive management improvement, that could cause a re-ordering of actions. This step will support the communication process with internal and external stakeholders to define the status of EbA interventions and if the objectives have been achieved.

Chapter 7: Results: Case Study Application

The CRA-AF designed in Chapter 6 was applied to the EVO mine closure plan, to test the relevance and contribution of the CRA-AF to a mine operation within a mountainous region. As detailed in Section 3.4.1, the case study design comprised a mine site visit, meetings with the management team at the mine site, and a risk assessment and adaptation workshop. The first two activities were executed according to plan, but the third activity was cancelled due the Provincial restrictions[1] to stop the spread of COVID-19. Therefore, the decision was to continue the case study with available public data related to the mine operation and the Sparwood community.

7.1 Step 1: Context Definition

7.1.1 Define Local Conditions

The EVO is located within the Elk Valley in the Kootenay mountainous region of British Columbia. Since 1970, a steel-making coal site has produced approximately 221 million tonnes from four pits (Teck Coal Limited 2017). Current annual production capacities are approximately 7 million tonnes of coal. Raw material is transported from the open pit to the plant by a 3.59-km overland conveyor belt (Teck Coal Limited 2017). The total disturbed area was 4,254.5 ha, of which 27% is already reclaimed (Teck Coal Limited 2018a). EVO's permit mine plan was amended to approve the Baldy Ridge Extension (Figure 7.1) on December 2016. The Environmental Assessment Act certificate was also issued for the expansion and is expected to extend the life of mine to 2045, with additional production of 225.3 million tonnes of coal (Teck Coal Limited 2018a).

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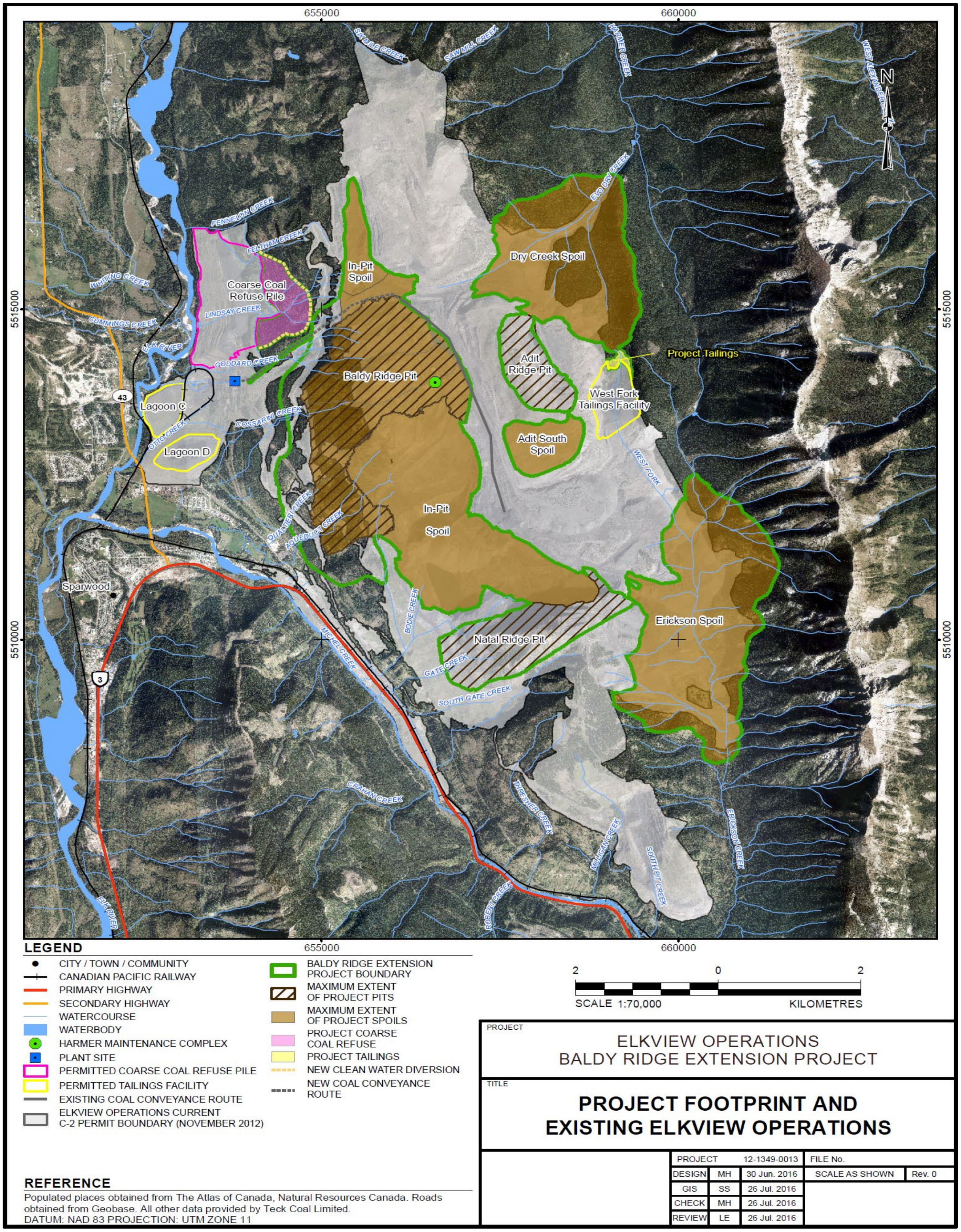
[1] https://www2.gov.bc.ca/gov/content/covid-19/info/response

Figure 7.1 Project footprint and existing Elkview Operations in British Columbia, Canada (EAO 2016)



7.1.2 Define Scope

EVO's post-mining reclamation program aims to return physical, chemical, and biological processes to pre-mining ecosystem conditions, as outlined in the Conceptual Reclamation Plan for the Elkview Coal Property (Przeczek 2003), which replaced the 20-year reclamation plan defined by the former owner, Westar Mining Ltd. (Dupley 2019). The reclamation program aimed to re-establish basic ecosystem processes and biological capabilities with a focus on restoring habitat for Rocky Mountain elk (*C. elaphus nelsoni*) and mule deer (*Odocoileus hemionus*) to enable development of self-sustaining populations (Przeczek 2003).

7.1.3 Define Execution Plan

The Conceptual Reclamation Plan for EVO proposed the following specific objectives:

1. ensure that reclaimed slopes are geologically stable;
2. reduce and control surface erosion by water and wind;
3. maintain acceptable water quality standards;
4. create acceptable habitats that, in combination with habitat adjacent to the mine property, will continue to support viable populations of elk and mule deer;
5. create conditions that will promote re-establishment of basic ecological functions (biogeochemical cycling);
6. introduce habitat elements and structure that will provide habitats for a range of wildlife species in addition to elk and mule deer;
7. create conditions that will allow for recolonisation by native plant species;
8. monitor within an adaptive management framework to ensure that reclamation treatments are effective and that program objectives are achieved; and

9. provide a framework for life of mine costing that is easily adjusted to changing mine plans (Przeczek 2003).

In March 2018, the company submitted the Annual Reclamation Report for 2017: Permit C-2 to the British Columbia Ministry of Energy, Mines and Petroleum Resources. The document contained the lawful reporting requirements and the last Five Year Mine Plan and Reclamation Plan update (Teck Coal Limited 2018b). In this update, the company noted that biodiversity is a key focus of the closure plan, with the objective to obtain a net positive impact on biodiversity in the affected areas (Teck Coal Limited 2018b). The company explained that the closure plan is based on the ecological characteristics and functions of the pre-mining landscapes. The update indicated that an ecosystem approach will be used for end-land use planning. Therefore, reclamation planning will consider all possible ecosystem components and the resulting ecosystem services in the area. The company philosophy toward landscape restoration is not limited to one designated end-land use (i.e., elk habitat), but multiple land-use objectives mentioned in the End Land Use Plan (Teck Coal Limited 2017), the Biogeoclimatic Ecosystem Classification subzones considered by the company as the ecosystem objectives for the end land use are Dry Cool Montane Spruce and Dry Cool Engelmann Spruce –Subalpine Fir. This is an important mine closure component that will be assessed against the climate change impacts with the CRA-AF. Appendix E the End Land Use Objective for EVO, with the different ecosystem categories and the correspondent land use objectives expected is shown.

7.1.3.1 Identify Infrastructure

In terms of physical and chemical function, the following mine closure infrastructure components were considered for the application of CRA-AF:

- Lagoon Tailings Area (lagoons A–D in Figure 7.2)
- West Fork Tailings Facility (WFTF)
- Saturated Rock Fill Facility

Two mine closure components were considered for biological function:

- Ecological Indicator-Based Hydrologic Model
- Wildlife Habitat Model

The Lagoon Tailings Area is located on the western perimeter of the site, immediately west of the plant. Lagoons A–D were constructed on the floodplains of the Elk River, an area that was previously covered by a glacial lake that deposited glaciolacustrine silts and clays along with areas of alluvial sediments. Most of the fine waste separated during the coal washing process was historically deposited in Lagoons A–D and is now deposited in the WFTF (Teck 2019). General information and the current configurations for these facilities are provided in Table 7.1.

Figure 7.2 Lagoon tailings area locality plan (Image from Google Earth; areas defined by the author)

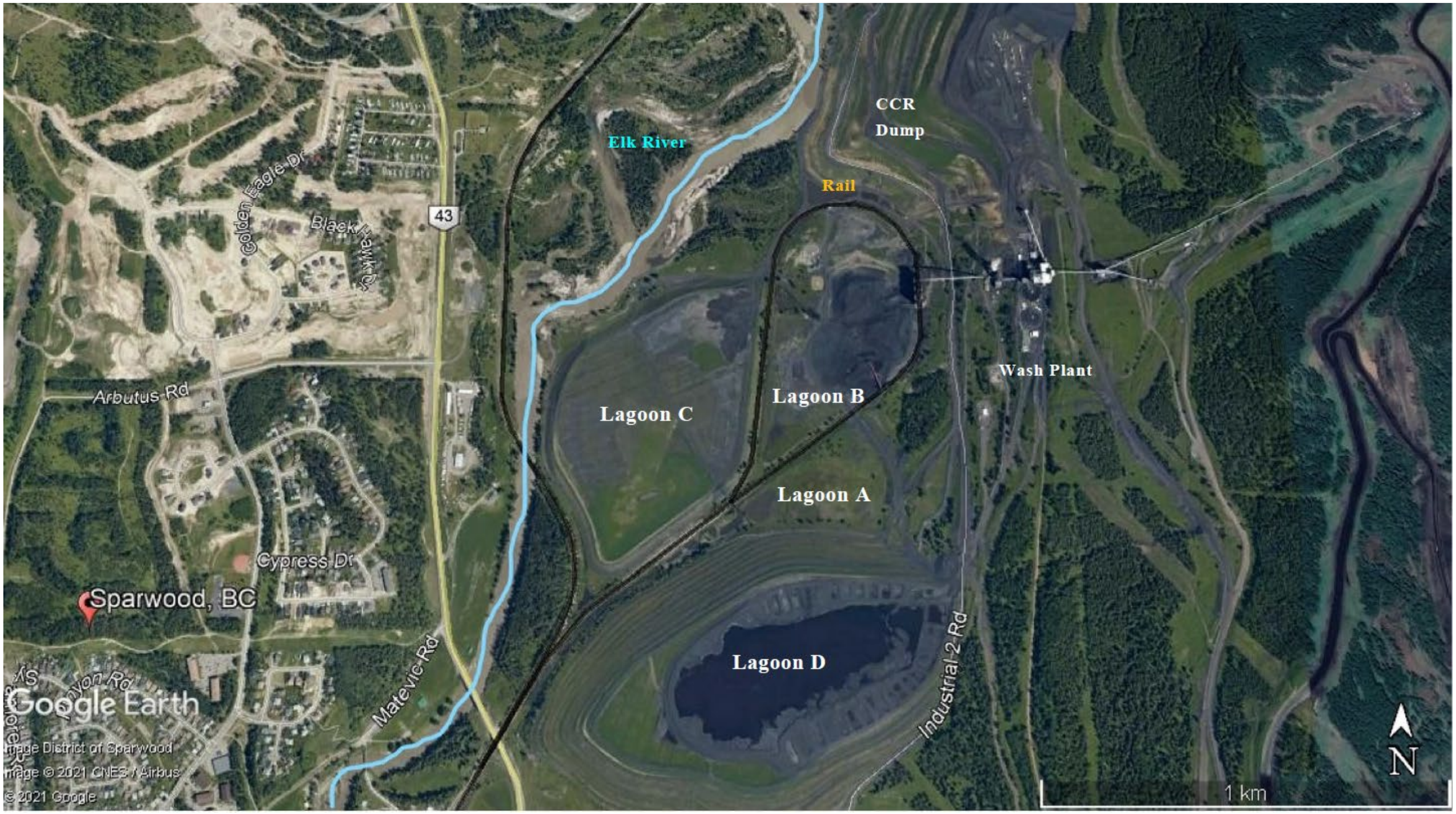


Table 7.1 West Fork Tailings Facility (WFTF) and Lagoon Tailings area: General information and configurations. Adapted from (Teck 2019; Teck Coal Limited 2017; KCB 2020)

Key parameters	WFTF	Lagoon A	Lagoon B	Lagoon C	Lagoon D
CDA consequence category	Low	Low	Low	High	Very High
Inflow design flood[1]	1:100	1:100	1:100	1/3 between 1,000 year and PMF	2/3 between 1,000 year and PMF
Min design flood	72-h PMF	24-h 1:200 year (spillway)	24-h PMF	72-h PMF	72-h PMF
EDGM	1:100	1:100	1:100	1:2,475	1/2 between 1:2,475 and 1:10,000
Min design flood	1:2,475 (PGA: 0.128 g)	1:2,475 (PGA: 0.128 g)	1:2,475 (PGA: 0.128 g)	1:2,475 (PGA: 0.128 g)	1:5,000 (PGA: 0.18 g)
Freeboard requirements	Not reported	0.33 m	0.33 m	2 m min	1.25 m min and 60 m wide beach maintained
Tailings deposition 2019	1,163,000 t	0	0	0	58,300 t
Impounded tailings volume (×1,000 m^3)	8,800	185	295	4,658.6	22,695
Max operating pond volume (m^3)		550	0	0	288,000
Approximate footprint (ha)	28.5	5.8	4.5	32.6	61
Crest length (m)	480	1,100	800	2,000	2,226
Crest width (m)	50	6	6	6	6-10
Maximum dam height (m)	35	4	4	19.5	59
Raise method	Downstream	not applicable	not applicable	East embankment: upstream Other embankments: downstream	Upstream
Downstream slope grade (H:V)	2.5:1	1.8:1	1.7:1	1.75:1	2.7:1 to 3.4:1

[1] Flood flow above which incremental increase in water surface elevation from dam failure does not pose an unacceptable threat to downstream life and property.

Lagoon A

Lagoon A was used as a tailings storage facility during the 1960s and is currently unused. The tailings are impounded by approximately 4-m high embankments on the north, west, and south perimeter. The eastern perimeter is bounded by Harmer Ridge and the Lagoon D embankment confines the southern side of Lagoon A. No construction records are available for Lagoon A, but the company indicated that the starter embankment was primarily constructed using silty sand, and sand-and-gravel glacial till (KCB 2020). The foundations comprise coarse-grained gravelly sand glacial till beneath glaciofluvial sands and sandy silts. Glaciolacustrine clay was identified under the western portion of Lagoon A (Teck 2019).

Water from Cossarini Creek flows directly through Lagoon A and discharges from a spillway at the western perimeter of the Lagoon into a series of check dam ponds. Rainfall typically infiltrates the tailings and discharges into the glacial till foundations. When it is saturated, the rain ponds on the surface of the lagoon and discharges through the spillway. The spillway was designed to accommodate a 1-in-200-year precipitation event. The water in Lagoon A is managed passively and does not require any actions from site personnel (KCB 2020).

Lagoon B

Lagoon B is an inactive tailings storage facility but was used for tailings storage in the 1960s. Like Lagoon A, the facility is impounded by 4-m high embankments, with coal stockpiles to the east and Harmer Ridge to the south. The current purpose is to receive emergency overflow process water when required. According to the Dam Inspection Report, the facility requires a storage capacity increase or construction of a spillway to meet regulatory requirements (KCB

2020). No construction records are available for Lagoon B, but site investigations indicate the starter embankment was primarily constructed using silty sand, and sand-and-gravel glacial till. The foundations comprise coarse-grained gravelly sand glacial till, underlain by glaciofluvial sands, sandy silts, and interbedded glaciolacustrine clays. Retained water within Lagoon B is left to infiltrate through the tailings into the ground (KCB 2020).

Between September 2018 and July 2019, Lagoon B was unable to store and infiltrate water from a heavy rain event. A 2019 hydrotechnical study concluded that the Lagoon B dam is unable to contain the minimum required 72-h rainfall IDF (intensity-duration-frequency). The company reported that dam infrastructure improvement is underway at the time of writing (Teck Resources Limited 2019).

Lagoon C

Lagoon C is an inactive tailings storage facility that operated from 1970 to 1996, with tailings deposition ceasing in 1987. It is presently used as a dumping location for sediments excavated from different sumps and sedimentation ponds. The facility starter dam was constructed in 1970 using sand and gravel fill. The upstream raise method was used on the eastern embankment due to site infrastructure constraints and the north, south and west embankments were raised using the downstream method. The foundation comprises coarse-grained gravelly sand glacial till underlain by interbedded glaciofluvial silty sands and glaciolacustrine clays and silts (KCB 2020)

Ponded water typically infiltrates through the tailings and discharges at ground surface level where the tailings contact glacial till foundations. Lagoon C has sufficient capacity to safely manage its Inflow Design Flood without a spillway, and ponded water infiltrates through the tailings to the natural ground. Localised changes in vegetation during a 2017 inspection on the downstream slope of Lagoon C indicate potential periodic seepage (Teck Coal Limited 2018b).

Lagoon D

Lagoon D is an active tailings storage facility with tailings deposition commencing in the early 1970s. With the WFTF in use since 2006, Lagoon D has become the secondary tailings storage location. The facility was built in 1972 with a sand and gravel starter dam, and consecutive upstream raises were constructed using clay core rockfill. The north, south, and west embankments were raised using the upstream method, and the eastern perimeter is confined by the natural hillside. Lagoon D is underlain by sand and gravel alluvial deposits overlying glaciolacustrine clays and silts (Teck Coal Limited 2017).

In 2005, the site initiated a new tailings deposit method using shallow cells on the northeastern and southeastern perimeters of the ring-dike. The cells vary in length and width; typical cell dimensions are 60 m long and 15 m wide, with cell depths ranging from 1.8 to 4.1 m. The procedure enables faster consolidation of tailings in individual cells while allowing bleed water to drain to the centre of the storage (KCB 2020).

In 2018, the crest elevation along the north and south sides of the Lagoon D dam was raised from 0 to 2 m. Lagoon D has sufficient capacity to effectively manage the pond and inflow design flood without a spillway (KCB 2020).

West Fork Tailings Facility (WFTF)

The WFTF was commissioned in 2006 to serve as the primary fine tailings storage facility. It is located on the eastern perimeter of the site, approximately 1 km from the Adit Pit and is confined by the Adit Waste Dump, West Fork Dump, Adit Ridge, and Cowboy Ridge. Fine waste material is deposited into the WFTF via six spigots along the embankment. Tailings deposition is managed to keep ponded water at the northern extent of the WFTF, away from the embankment. The Adit Toe Bern road is also progressively raised ahead of tailings deposition to minimise filtration of tailings fines into the Adit Waste Dump. The tailings surface elevation within the WFTF rises at an approximate rate of 4 m per year (Teck Coal Limited 2018b).

Rainwater falling to the surface of the lagoons usually drains to the ground surface level. The original ground comprises layers of sand and gravel glaciolacustrine clay and glacial till. The till foundations, sand end, and gravel layers at ground surface level drain water from the lagoons into the groundwater system. However, the infiltration into the groundwater system is not considered part of the monitoring protocol (KCB 2020).

Saturated Rock Fill Facility

After a series of claims related to selenium contamination on Elk Valley (Mcdonald and Strosher 2000; Linnitt 2018), the company implemented a Water Quality Plan, which included construction of the Saturated Rock Fill facility in 2018 to treat the affected water. In 2020, the company expanded the capacity and is planning additional expansion at the time of writing (Teck 2018) .

Ecological Indicator Based Hydrologic Model

According with Teck, the revegetation model focuses on assigning the proper ecosystem variant to the zone/sub zone utilizing the existing native vegetation. The goal of the model is to provide an estimate of edaphic conditions and associated ecosystem variants given information on substrate and site properties. This model supports in-field estimation of site properties for the development of revegetation treatments, advises strategies on soil placement, and provides broader landscape modeling for assessment of mitigation potential and net positive impacts on biodiversity calculations (Teck Resources Limited 2016).

Wildlife Habitat Models

Ten wildlife Habitat Suitability Index models were developed and applied to baseline conditions at all operations in Elk Valley, including EVO (Teck Coal Limited 2018b) . The models were refined in 2017 after the outputs were assessed. In addition, they were applied to the planned ecosystems on the post-mining surface to demonstrate how they changed with structural stage shifts over time within each ecosystem type targeted for reclamation. Teck continues to assess the Habitat Suitability Index models to determine the impacts of operations on wildlife and the gains from reclamation (Teck Coal Limited 2018b).

7.1.3.2 Identify ecosystem services

Not including the mining area, the largest land use types in the Sparwood Municipality Area are young forest and urban areas (Table 7.2). Agricultural fields, wetlands, logged forest areas, and residential developments are also present.

Table 7.2 Land cover types in the Sparwood municipality area (MNAI 2020)

Land use type	Area (hectares)	Portion of land (%)
Young forest	1,113.6	49
Urban development	518.5	23
Agriculture	295.4	13
Wetlands	191.4	8
Recently logged forest	75.7	3
Selectively logged forest	61.3	3
Mixed residential/agricultural	33.6	1
Total	**2289.5**	**100**

According to the Biogeoclimatic Ecosystem Classification system (MacKillop et al. 2018), the district of Sparwood is located in the Dry Cool Montane Spruce (MSdk), and Dry Cool Engelmann Spruce – Subalpine Fir (ESSFdk) zones. The former is found along lower elevations of the valley and the latter occurs at higher elevations (Elk Valley CEMF 2018). The predominant natural land cover in the area is agriculture and forests, although wetlands and mining areas also exist. These natural assets present in the area provide many services and benefits to Sparwood residents (Table 7.3).

Table 7.3 Ecosystem services provided by natural assets (MNAI 2020)

Natural asset	Ecosystem service
Forest	Water quality Stormwater management Water storage Air quality improvement Carbon sequestration Recreation
Agriculture	Water storage Crop production Carbon sequestration
Wetlands	Water quality Stormwater management Water storage Carbon sequestration Recreation
Minerals	Coal

The most important ecosystem services provided by the forests and wetlands areas are water infiltration services, which improve drinking water quality for Sparwood and towns downstream, in particular Fernie (population 5,249), Hosmer (population 115), and Elko (population 163). Due the presence of selenium in the Elk River, water quality is an important concern for inhabitants of these towns (Cope et al. 2013; Elk Valley CEMF 2018). Additional services provided by forests include managing stormwater and recharging aquifers. Wetlands reduce flooding risk. These services support the habitat for the aquatic life.

For example, westslope cutthroat trout (*Oncorhynchus clarki lewisi*) (MNAI 2020) is an indicator species for ecological, social, and economic sustainability in Elk River and its tributaries, which function as a refuge for one of the few remaining genetically pure populations in British Columbia (Walker et al. 2016). Hydrologic and habitat alterations due to mining, particularly in riparian areas, endanger cutthroat trout populations. Currently, the most threatened riparian areas are in valley bottoms and mining-affected watersheds, where sediment loading is highest. Michel Creek near EVO is considered one of the five most affected watersheds (Walker et al. 2016). Mining activities have removed cutthroat trout habitat in the upper watershed by infilling creeks with waste rock (COSEWIC 2016). Watershed habitat disconnections and degradation of streams can increase susceptibility to displacement and hybridisation, limiting recovery of the populations in the short term (COSEWIC 2016). Climate change also negatively affects recovery because warming trends in stream thermal regimes lower reproductive success and increase stress levels (MacDonald et al. 2014; Davidson et al. 2018)

7.1.3.3 Sparwood as a community of interest

The District of Sparwood had approximately 3,490 residents in 2016 (Statistics Canada 2016). The district has two principal areas, Sparwood Proper and Sparwood Heights. The former is a mixture of single and multi-family residential areas, along with business, institutional, and small manufacturing developments. The area is relatively flat (slopes typically < 2% grade) and drains toward Elk River and Michel Creek. Soils are primarily sandy loam with extensive gravel and cobblestones (District of Sparwood 2016). Sparwood Heights is located to the north of the town, across the Elk River from Sparwood Proper. Land use is predominantly single and multi-family homes with some undeveloped lots. In general, the terrain in Sparwood Heights is more elevated than Sparwood Proper, and drainage occurs from west to east toward Highway 43 and the Elk River. Soils are primarily silt-clay (District of Sparwood 2016).

The Official Community Plan for the district established a framework for the future of the district. The plan stated that "*the primary function of the District of Sparwood is that of a sub-regional centre with a diversified economic base not strictly dependent on coal mining, but* *which is able to provide services for coal mining and other industries and resources by reason of its strategic location within the Elk River Valley*" (District of Sparwood 2015). This shows the dependence of community on the mining industry and highlights the urgent need to plan for the post-closure period.

7.1.3.4 Livelihoods

Mining is the principal source of jobs in the district: 34% of the population work in coal operations. Other industries are construction, health, transport, agriculture, and commerce (Teck 2019; District of Sparwood 2019). The community considers recreation (winter sports and other outdoor activities), tourism, hunting, and fishing a strong source of financial benefits. The area received approximately 27,000 visitors in 2019, with the majority visiting in the peak fishing season between July and September. Nonetheless, in the last social analysis by Teck in 2019, 64% of the participants responded that the community does not have enough ways to make a living when the mine operations conclude (District of Sparwood 2019).

District residents have a keen interest in protecting natural assets, implementing integrated water management, and mitigating the effects of sedimentation. A dominant concern is large stormwater flows that funnel sediment and runoff into the Elk River (District of Sparwood 2015). Urban and industrial areas are expected to increase, with concomitant increases in erosion and sedimentation. Future access to drinking water is also a concern due to potential selenium contamination of wells as a result of mining activities. Among the three wells in Sparwood, one municipal well was shut down due selenium leaching from the mine (MNAI 2020).

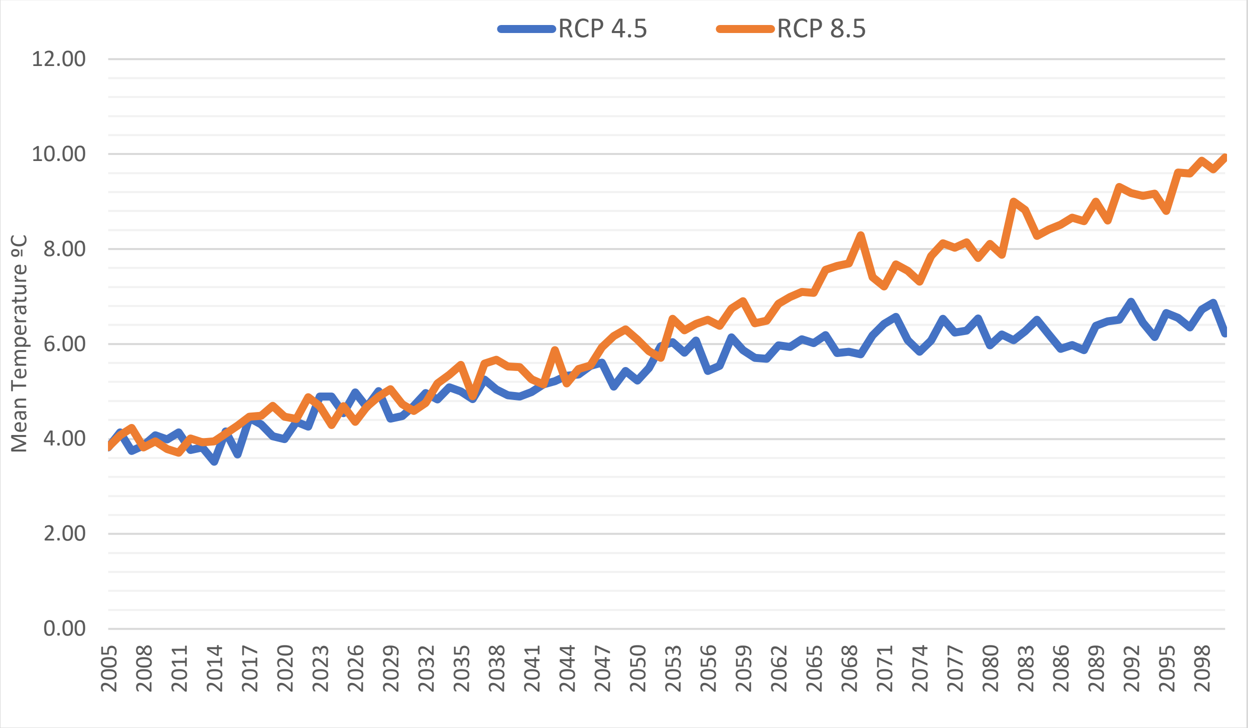
7.1.3.5 Climate Parameters for the Study Area

In the past century, the Kootenay Region of British Columbia experienced an increase of 1.6°C in the mean annual temperature (CBT 2015). In the Columbia Mountains, glacial cover has declined by 15–23% (CBT 2015). The climate records show that, compared with 1960, the area is receiving less summer rain and less winter precipitation falling as snow. At the same time, the region is undergoing longer fire seasons, intense droughts, pest outbreaks, rare flood events, and crops failures (Ministry of Environment 2016). Local precipitation and temperature patterns are variable due to the influence of elevation and mountain topography.

The region is projected to become warmer and drier in summer and warmer and wetter in all other seasons. Despite mean precipitation increases in winter, spring, and fall, warmer temperatures will increase evapotranspiration, increasing the risk of temporal droughts (Prairie Climate Centre 2019).

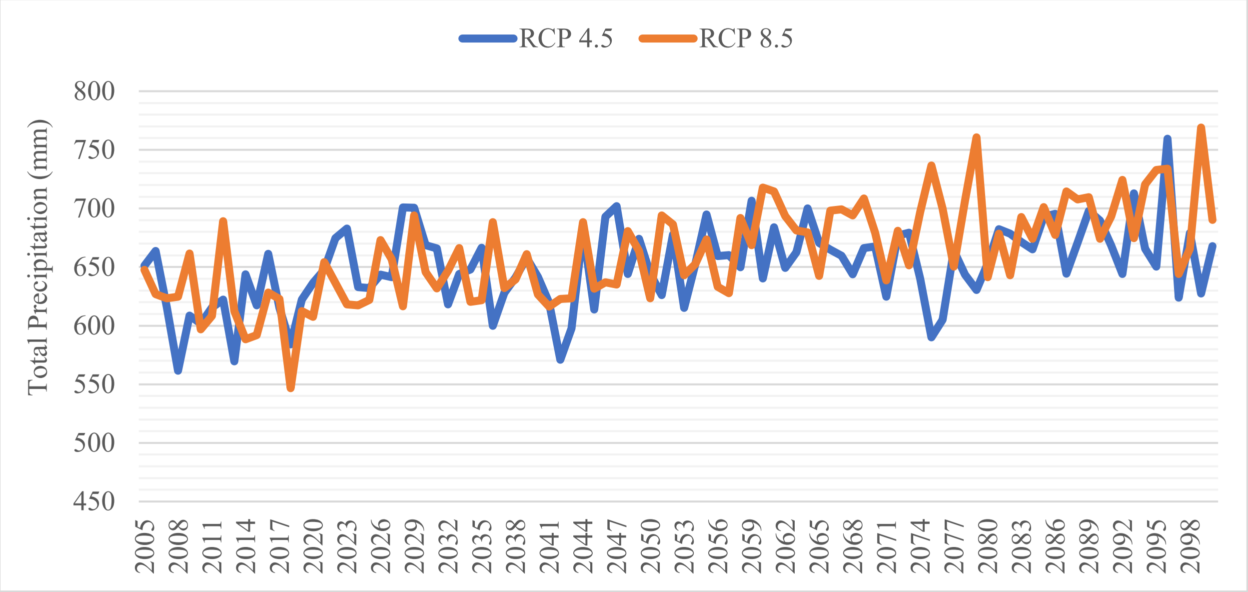
For the 1950–1980 baseline period, the mean annual temperature for Sparwood was 2.9°C; for 1981–2010 it was 3.3°C. For a high emissions scenario (RCP 8.5), mean annual temperatures are projected to be 5.2°C for 2021–2050, 7.2°C for 2051–2080, and 8.5°C for 2070–2099 (Figure 7.3). Under an intermediate emissions scenario (RCP 4.5), they are projected to be 4.9°C for 2021–2050, 6°C for 2051–2080, and 6.3°C for 2070–2099.

Figure 7.3 Mean temperature 2005–2100, Sparwood, British Columbia. Data from Climate Station 1157630 (CRIM 2019)



Total annual precipitation for 1950–1980 was 611.9 mm. Under a high emissions scenario (RCP 8.5), this is projected to be 6.9% higher for 2021–2050, 12.4% higher for 2051–2080, and 14.2% higher for 2070–2099 (Figure 7.4). Under an intermediate emissions scenario (RCP 4.5), total annual precipitation is projected to be 7.6% higher for 2021–2050, 9.4% higher for 2051–2080, and 10.2% higher for 2070–2099.

Figure 7.4 Total annual precipitation 2005–2100, Sparwood, British Columbia. Data from Climate Station 1157630 (CRIM 2019)



Baseline data (1950–1980) and incremental changes for future climate scenarios in Sparwood were applied to define variations in temperature and precipitation in three time periods 2030 (average 2021–2050), 2060 (average 2051–2080), and 2090 (2070–2099) under climate change scenarios RCP 4.5 and 8.5 described in Section 6.1.1 (Table 7.4). For instance, the historical mean minimum temperature in Sparwood is –3.10°C. The projected minimum temperature for 2070–2099 under RCP 4.5 is –0.45°C (85% higher) and under RCP 8.5 it is 2.66°C (186% higher).

Table 7.4 Climate projections under two climate change scenarios (Representative Concentration Pathways or RCP) for Sparwood, British Columbia.

Percentages are relative to baseline.

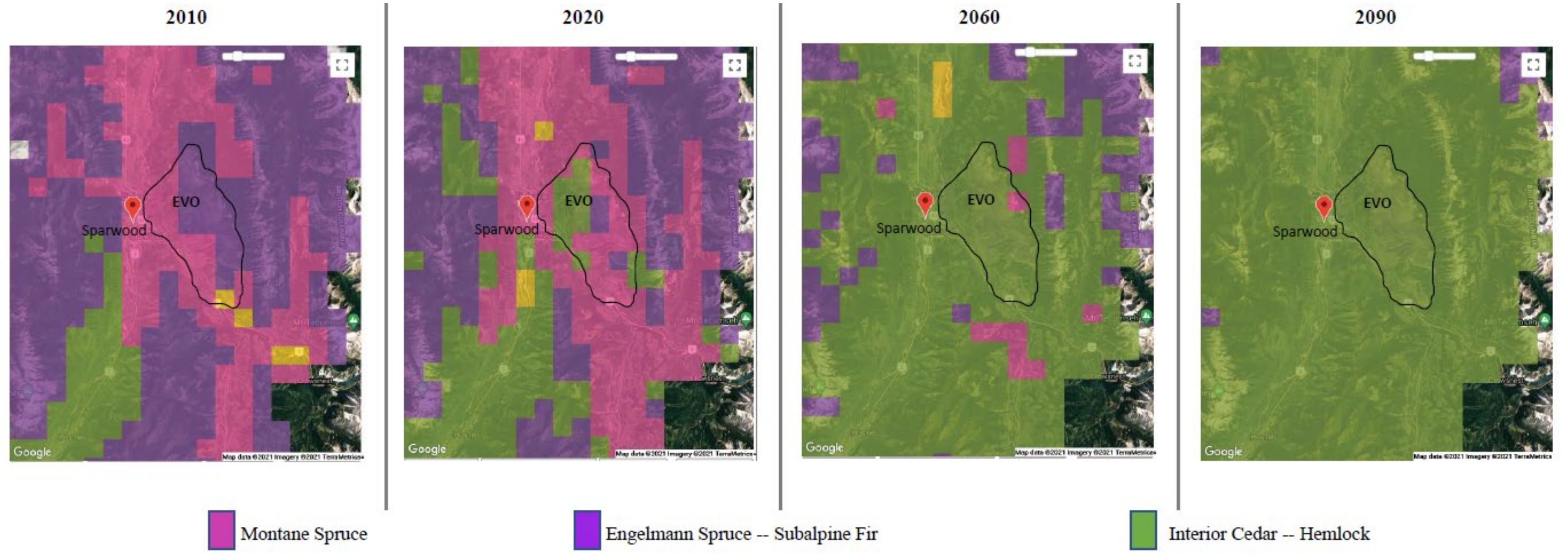
Climate parameter	**Baseline** (1950–1980)	**Change scenarios**					
		RCP 4.5			RCP 8.5		
		2030	2060	2090	2030	2060	2090
Min temperature (°C)	–3.1	–0.94 70%	–0.16 95%	–0.45 85%	–0.68 78%	1.37 144%	2.66 186%
Max temperature (°C)	8.79	10.86 24%	11.89 35%	12.19 39%	11.03 26%	13.03 48%	14.29 63%
Mean temperature (°C)	2.82	4.97 76%	6.02 113%	6.32 124%	5.15 83%	7.20 155%	8.48 201%
Coldest day temperature (°C)	–32.6	–29.4 10%	–27.2 17%	–26.9 18%	–28.6 12%	–25.0 23%	–23.1 29%
Hottest day temperature (°C)	30.2	32.8 8.6%	33.9 13%	34.5 14%	33.1 10%	35.5 18%	37.5 24%
Days with Tmax > 25°C	24	43.3 81%	53.2 122%	56 133%	45.5 90%	65 170%	79.7 232%
Days with Tmax > 30°C	2.6	11.0 323%	17.5 573%	19.8 662%	12.3 373%	26.7 927%	40.6 1462%
Growing degree days > 5°C	1044.4	374.4 64%	567.7 46%	568.9 46%	428.7 59%	837.9 20%	1149.2 10%
Total precipitation (mm)	611.9	658.4 7.6%	669.1 9.3%	674.3 10.2%	653.8 6.9%	687.7 12.4%	698.6 14.2%
Max 1-day total precipitation (mm)	28.35	31.08 10%	31.48 11%	31.87 12%	31.23 10%	33.76 19%	34.52 22%
Wet days > 20 mm	1.79	2.44 36%	2.6 45%	2.7 52%	2.4 35%	2.9 62%	3.3 83%

Climate and land-use change are expected to diminish aquatic habitat due sediment accumulation and altered thermal regimes. Future scenarios suggest an increase of average warmest-month stream temperatures of approximately 1–2°C. Thus, the native salmonid population in the Elk Valley is likely to decline in the future, threatening Indigenous cultural and recreational fishing activities (Bear, McMahon, and Zale 2007).

Climate change will alter local vegetation growing patterns and natural disturbance regimes like wildfires and insect and disease outbreaks (e.g., the mountain pine beetle, *Dendroctonus ponderosae* Hopkins). Some locations could face longer periods of climatic moisture deficit, affecting tree species that requires atmospheric humidity and a specific amount of water for seeds to germinate (Leech, Almuedo, and Neill 2011). Therefore, the vulnerability to seasonal drought will depend on the capacity of seeds of some tree species to cope with the new ecological conditions.

The Montane Spruce biogeoclimatic zone is expected to reduce in area by 2051–2080 due to the effects of climate change. According to Wang et al. (2012), the increase in temperature creates the possibility for the expansion of alpine and subalpine ecosystems. The climate is projected to be appropriate for the Interior Cedar – Hemlock zone. Based on historical data and future climate projections, Figure 7.5 shows historical, current, and projected forest ecotypes in the Sparwood District and EVO current operational footprint for 2060 and 2090 periods.

Figure 7.5 Historic, current, and projected forest ecotypes in Sparwood, British Columbia



Projected distribution of forest ecotypes in Sparwood District and Elk Vally Operational footprint for a climate change scenario of average magnitude, for historic (2010s), current (2020s), and projected (2060 and 2090). The Interior Cedar – Hemlock zone will replace the current biogeoclimatic zone. The projections were extracted from http://www.climatewna.com/ClimateBC_Map.aspx based on Wang et al. (2016).

The probable variation in biogeoclimatic zones means correlative change in plant densities and growing patterns. Thus, the availability of forage material for elk would change (MacKillop et al. 2018). At the same time, the warming climate would affect the snowpack and both summer and winter ranges. An earlier spring thaw would allow elk to remain in the area and browse during the winter, inhibiting recovery in revegetation areas (Barbour and Kueppers 2012). Furthermore, the species range could shift due climate change (Peterson et al. 2002) as elk limited by available habitat migrate, shrinking local population sizes.

7.1.4 Define the Scope

7.1.4.1 Identify Climate-Related Risk to Assess

The Sparwood District Climate Plan (Sparwood Council 2019) considered three climate impacts as most relevant to the local community:

1. warmer winter temperatures reducing snowpack;
2. higher temperatures increasing wildfire activity; and
3. extreme weather events contributing to urban and overland flooding.

These climate events would threaten the safety and livelihood of the Sparwood community by causing flooding, wildfires, water shortages, and extreme storms (Walker et al. 2016). The threats are expected to become more relevant in the future, physically endangering residents' homes and buildings and challenging the ability of the public infrastructure to serve the common interest and societal needs (Hunt and Watkiss 2011).

More frequent and intense rainfall events due to climate change will increase sediment deposition in Elk River. Large stormwater flows regularly dump sediment and other urban runoff into some stretches of the Elk River (Walker et al. 2016), reducing the provision of ecosystem services by riverine habitat and riparian areas. At the same time, temperature influences on species migration, ecosystem shifts, and disease/pests outbreaks(i.e. mountain pine beetle), would affect ecosystem services and economic activities on the community (Leech, Almuedo, and Neill 2011; Westerling 2006).

7.1.4.2 Identify Major Non-Climatic Drivers that Influence Risk in the SES

The mine closure components that would have the most influence on potential climate impacts to the watershed are the lagoons and WFTF. The Dam Safety Inspection (KCB 2020) at EVO reported the consequence categories (Table 7.5) for the facilities based on the Canadian Dam Association Guidelines (CDA 2016). The dams for the WFTF, Lagoon A, Lagoon C, and Lagoon D are all designed for a 72-hour probable maximum precipitation. An overtopping study of Lagoon B determined that it does not have adequate storage to contain the inflow design flood. Additionally, overtopping is a credible failure mode for the current lagoons A–C. Finally, internal erosion and piping are credible failure modes for Lagoon D and the WFTF (KCB 2020).

Table 7.5 Facility consequence categories for Elkview Operations. Sparwood, British Columbia (KCB 2020)

Facility	Consequence category
West Fork Tailings Facility	Low
Lagoon A	Low
Lagoon B	Low
Lagoon C	High
Lagoon D	Very high

EVO conducted a site investigation in 2019 focused on the glaciolacustrine foundation units below the lagoon dams. The information was used to inform an updated liquefaction trigger analysis as part of the initial closure planning and design for this facility. The site investigation report is being drafted at the time of writing and is not publicly available.

Soil erosion and flooding could contribute to surface and ground water selenium contamination, affecting aquatic life and diminishing economic opportunities for recreation, tourism, and fishing, which have important financial benefits in the region (Walker et al. 2016; MNAI 2020). Various reports (Kennedy et al. 2000; Cope et al. 2013; COSEWIC 2016) have noted that selenium pollution from mining in the Elk Valley is negatively impacting fish and aquatic biodiversity, including habitat for the westslope cutthroat trout (*O. clarkii lewisi*).

7.1.5 Define Execution Plan

Three meetings and one site visit were performed with the company selected as a case study. The company decided not to be directly involved in the research and suggested the use of publicly available data. Based on the importance of the site in terms of geography, ecosystem, and production, the decision made by the researcher was to perform the assessment with the public information. The protocol was validated in a workshop (see Chapter 8).

For the climate scenario timeline, climate predictions are up to the year 2100, which is deemed the maximum reasonable timeframe in which to extend predictions. Future climate change is assessed over the time periods 2030 (average 2021–2050), 2060 (average 2051–2080), and 2090

(2070–2099) under RCP scenarios 4.5 and 8.5 (see Section 6.1.1) with respect to baseline period 1950–1980.

7.2 Step 2: Assess Climate Risk

7.2.1 Identify Infrastructure Response Considerations for Mine Closure

Infrastructure response considerations for mine closure reflect how each infrastructure component responds to climate-imposed stress (Table 7.6). To evaluate the potential impacts of changing climate on the infrastructure components of interest, specific response considerations were identified and tailored to this study based on PIEVC guidelines (Engineers Canada 2016).

Table 7.6 Relevant component response considerations. Adapted from Engineers Canada (2016)

Mine closure component	**Response consideration (justification)** With respect to the mine closure component being assessed, climate-imposed stress may affect…
Structural design	Safety • load carrying capacity • overturning • sliding • fracture / collapse • fatigue • serviceability Deflection • permanent deformation • cracking and deterioration • vibration Foundation design • permafrost
Watershed, surface water, and ground water	Erosion • streams • rivers • ditches Erosion scour of associated or supporting earthworks Slope stability of embankments Sediment transport and sedimentation Channel realignment / meandering Water quality Water quantity Water resource demand • public, hydro, industrial, agricultural • groundwater recharge Runoff

Mine closure component	**Response consideration (justification)** With respect to the mine closure component being assessed, climate-imposed stress may affect…
	Thermal characteristics of the water resources
Operations, maintenance, and materials performance	Occupational Safety Access to worksite Structural integrity Equipment performance • maintenance and replacement cycles • electricity demand • fuel use Functionality and effective capacity • to provide the intended service as designed • to establish standards over the short, medium, and long term Equipment • component selection • design, process, and capacity considerations Materials performance Pavement performance Hill softening cracking from freezer ground thaw
Emergency response	Procedures and systems to address: • severe storm events • flooding • ice dams • ice accretion • water damage Emergency response needs • frequency • cost • resources required Ability of emergency responders to respond
Social effects	Accessibility to critical facilities: • hospitals • fire stations • police services Community roads, transportation of goods to a community Energy supply to a community Dislocation of affected populations Provision of basic services • potable water distribution • wastewater collection • power distribution Community business viability Destruction or damage to heritage buildings, monuments Destruction or damage to archaeological sites and objects of interest Impacts to private homeowners • home insurance cost • health impacts • ability to buy and sell homes Public perception and interaction
Environmental effects	Release of toxic or controlled substance Degradation of quality: • air • surface water • ground water • soil

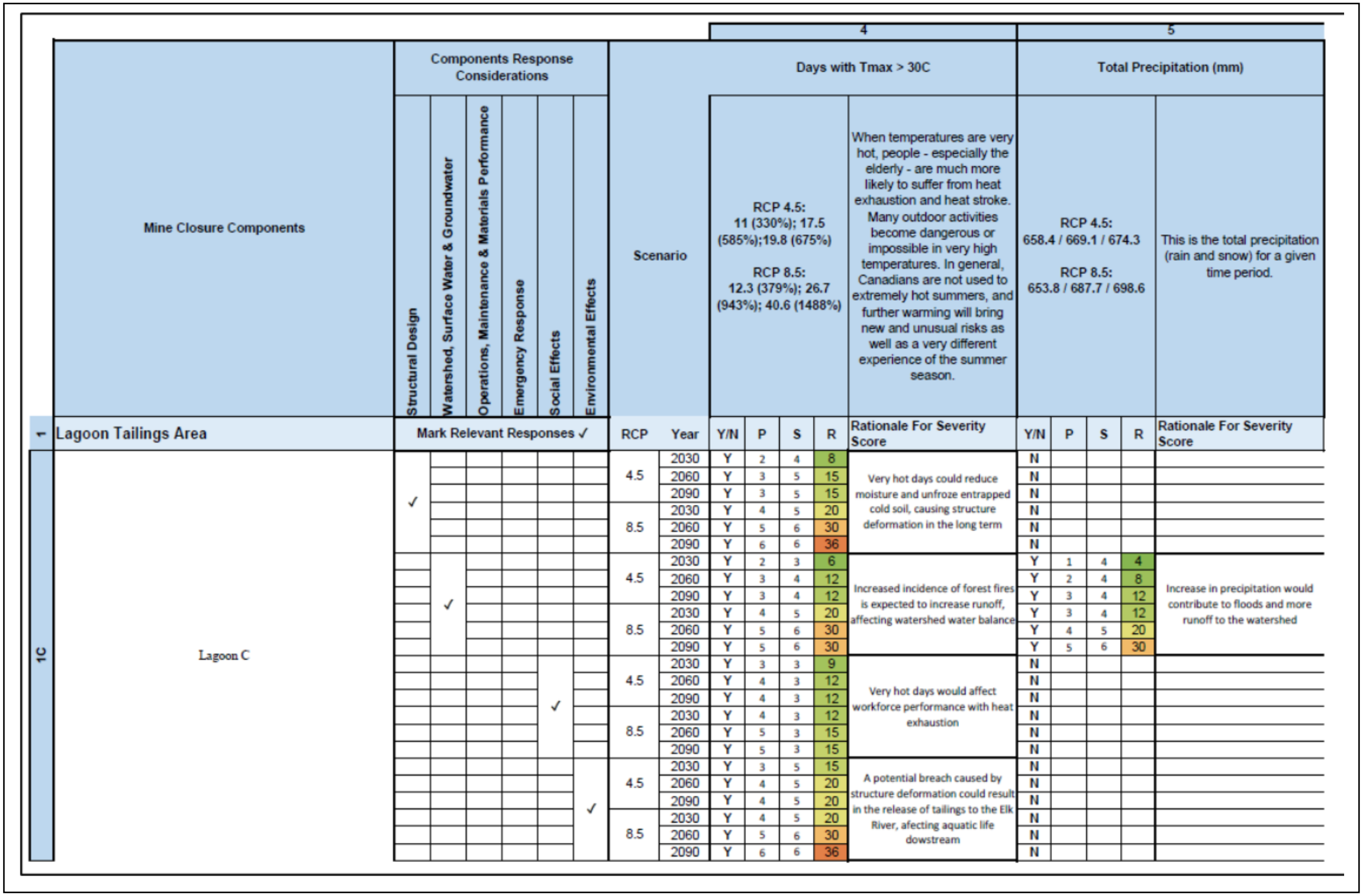
Mine closure component	**Response consideration (justification)** With respect to the mine closure component being assessed, climate-imposed stress may affect…
	Damage to sensitive ecosystems • physical harm to birds and animals Increase in greenhouse gas emissions

7.2.2 Determine Climate-Related Hazards

The mine closure components defined in Section 7.1.1 were assessed against the response considerations in Table 7.6 and the potential climate-related impacts defined in Section 7.1.1.5 using a Yes/No analysis. If climate events were considered to have a possibility of affecting the mine closure components from the perspective of the specific response consideration, then this interaction was retained for continued the study with CRA-AF. Therefore, each interaction was evaluated against the related climate parameter. Then, each interaction was scored based on a probability and severity value. One mine closure component can have different hazard or intermediate-risk scores for different interactions. For example, in the image of part of the hazard evaluation matrix showing the probability and severity scoring of interactions (Figure 7.6), when looking at the impacts of Days with Tmax > 30°C, Lagoon C has a medium-low risk score for the Social Effects consideration, but a high-risk score for the Environmental Effects response. More hazardous interactions will be considered in the next steps of the CRA-AF.

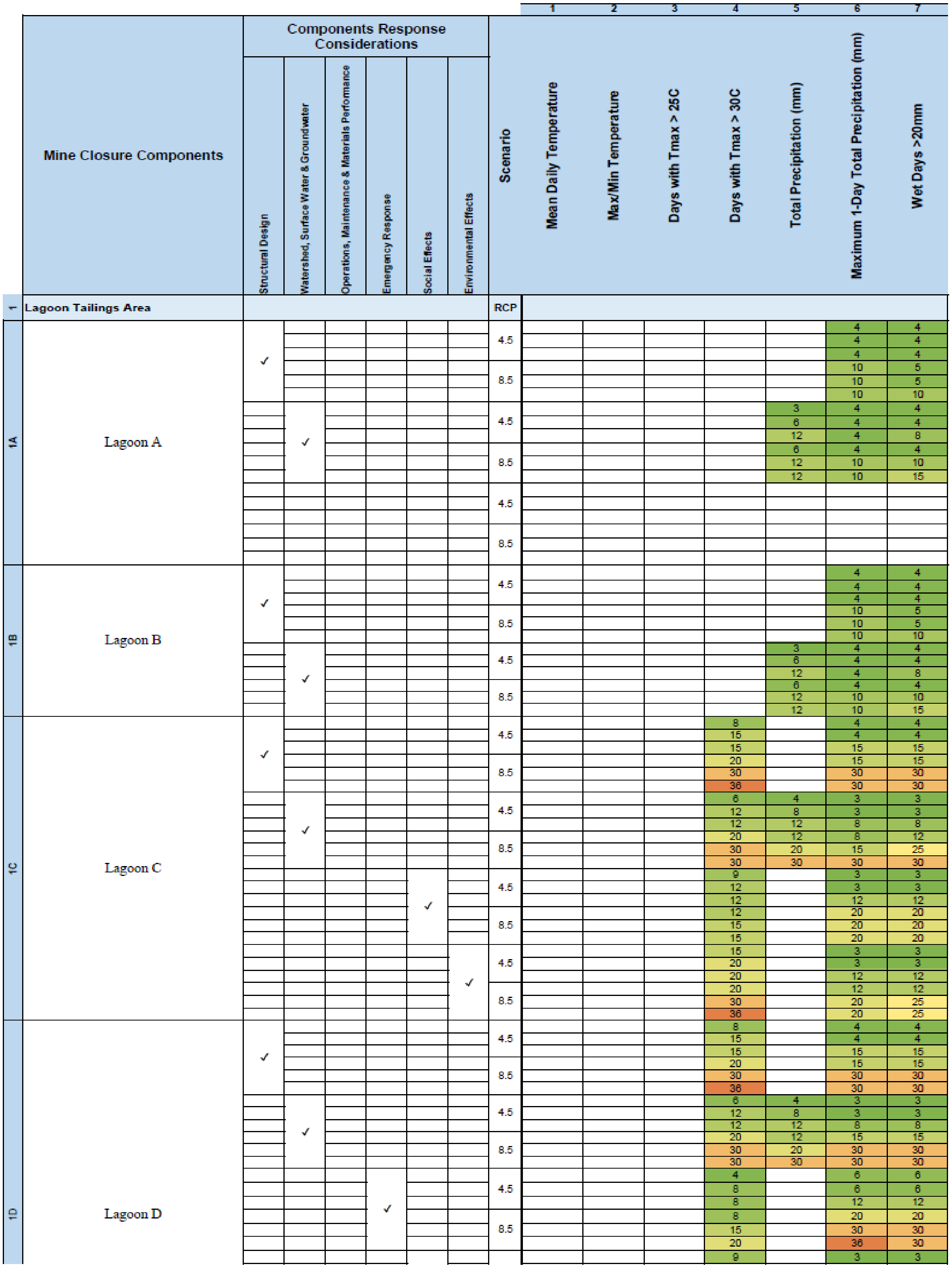
Five categories of hazard (or intermediate-risk) were used to define the hazard profile. The potential hazards were assessed for the periods 2030 (average 2021–2050), 2060 (average 2051–2080), and 2090 (2070–2099) under emission scenarios RCP 4.5 and 8.5 (see Section 6.1.1). The complete hazard assessment matrices are presented in Appendix H. A summary of the evaluation, including the hazard scores for future climate scenarios, is presented in Figure 7.7.

Figure 7.6 Hazard evaluation matrix (P: probability; S: severity; R: hazard or intermediate-risk)



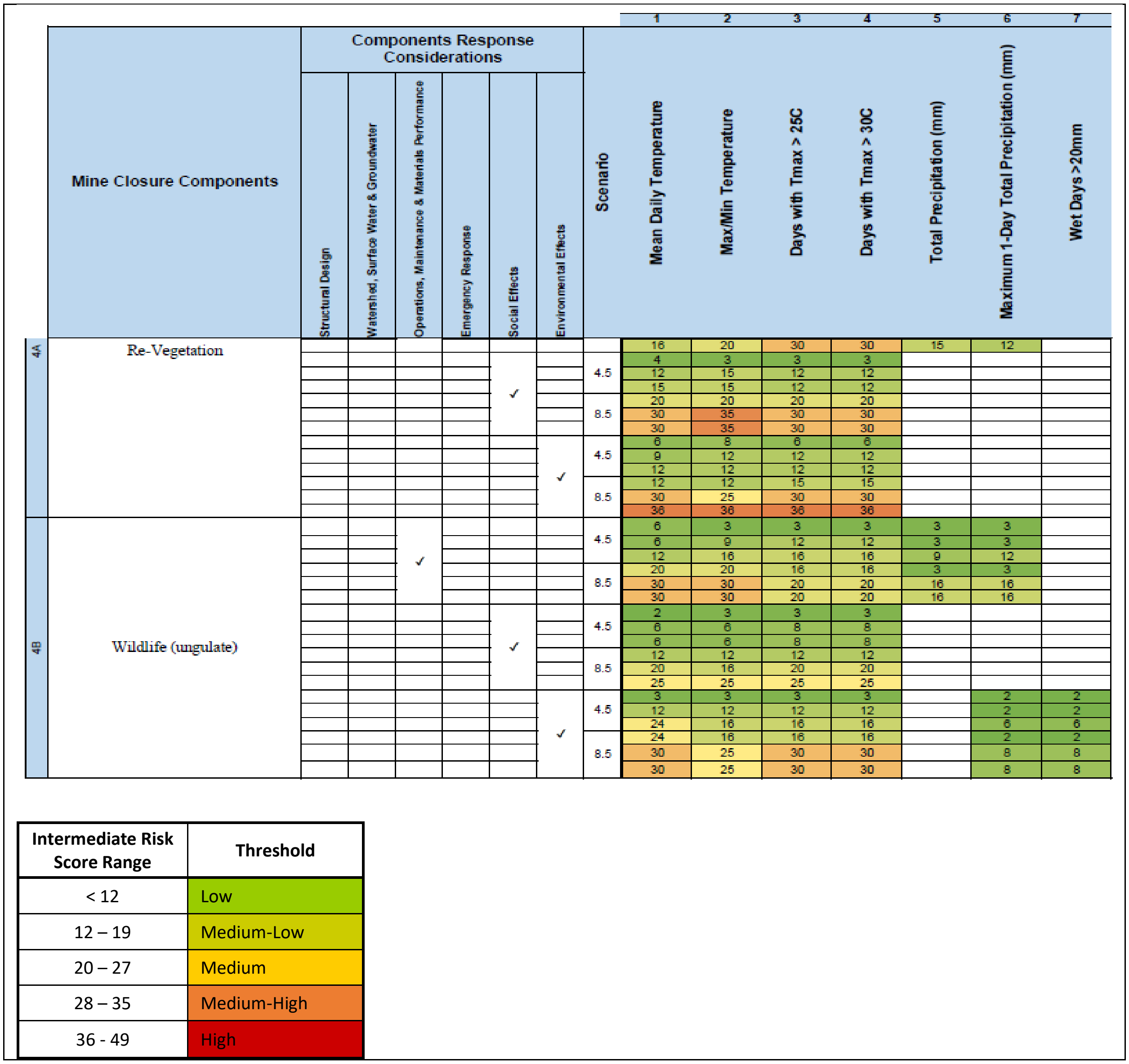
										4					5				
	Mine Closure Components	Components Response Considerations						Scenario		Days with Tmax > 30C					Total Precipitation (mm)				
		Structural Design	Watershed, Surface Water & Groundwater	Operations, Maintenance & Materials Performance	Emergency Response	Social Effects	Environmental Effects			RCP 4.5: 11 (330%); 17.5 (585%);19.8 (675%) RCP 8.5: 12.3 (379%); 26.7 (943%); 40.6 (1488%)				When temperatures are very hot, people - especially the elderly - are much more likely to suffer from heat exhaustion and heat stroke. Many outdoor activities become dangerous or impossible in very high temperatures. In general, Canadians are not used to extremely hot summers, and further warming will bring new and unusual risks as well as a very different experience of the summer season.	RCP 4.5: 658.4 / 669.1 / 674.3 RCP 8.5: 653.8 / 687.7 / 698.6				This is the total precipitation (rain and snow) for a given time period.
-	Lagoon Tailings Area	Mark Relevant Responses ✓						RCP	Year	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score
1C	Lagoon C	✓						4.5	2030	Y	2	4	8	Very hot days could reduce moisture and unfroze entrapped cold soil, causing structure deformation in the long term	N				
									2060	Y	3	5	15		N				
									2090	Y	3	5	15		N				
								8.5	2030	Y	4	5	20		N				
									2060	Y	5	6	30		N				
									2090	Y	6	6	36		N				
			✓					4.5	2030	Y	2	3	6	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	Y	1	4	4	Increase in precipitation would contribute to floods and more runoff to the watershed
									2060	Y	3	4	12		Y	2	4	8	
									2090	Y	3	4	12		Y	3	4	12	
								8.5	2030	Y	4	5	20		Y	3	4	12	
									2060	Y	5	6	30		Y	4	5	20	
									2090	Y	5	6	30		Y	5	6	30	
						✓		4.5	2030	Y	3	3	9	Very hot days would affect workforce performance with heat exhaustion	N				
									2060	Y	4	3	12		N				
									2090	Y	4	3	12		N				
								8.5	2030	Y	4	3	12		N				
									2060	Y	5	3	15		N				
									2090	Y	5	3	15		N				
							✓	4.5	2030	Y	3	5	15	A potential breach caused by structure deformation could result in the release of tailings to the Elk River, afecting aquatic life dowstream	N				
									2060	Y	4	5	20		N				
									2090	Y	4	5	20		N				
								8.5	2030	Y	4	5	20		N				
									2060	Y	5	6	30		N				
									2090	Y	6	6	36		N				

Figure 7.7 Hazard Evaluation Summary



	Mine Closure Components	Components Response Considerations						Scenario	1	2	3	4	5	6	7
		Structural Design	Watershed, Surface Water & Groundwater	Operations, Maintenance & Materials Performance	Emergency Response	Social Effects	Environmental Effects		Mean Daily Temperature	Max/Min Temperature	Days with Tmax > 25C	Days with Tmax > 30C	Total Precipitation (mm)	Maximum 1-Day Total Precipitation (mm)	Wet Days >20mm
1	Lagoon Tailings Area							RCP							
1A	Lagoon A	✓						4.5						4	4
														4	4
														4	4
								8.5						10	5
														10	5
														10	10
			✓					4.5					3	4	4
													6	4	4
													12	4	8
								8.5					6	4	4
													12	10	10
													12	10	15
								4.5							
								8.5							
1B	Lagoon B	✓						4.5						4	4
														4	4
														4	4
								8.5						10	5
														10	5
														10	10
			✓					4.5					3	4	4
													6	4	4
													12	4	8
								8.5					6	4	4
													12	10	10
													12	10	15
1C	Lagoon C	✓						4.5				8		4	4
												15		4	4
												15		15	15
								8.5				20		15	15
												30		30	30
												36		30	30
			✓					4.5				6	4	3	3
												12	8	3	3
												12	12	8	8
								8.5				20	12	8	12
												30	20	15	25
												30	30	30	30
						✓		4.5				9		3	3
												12		3	3
												12		12	12
								8.5				12		20	20
												15		20	20
												15		20	20
							✓	4.5				15		3	3
												20		3	3
												20		12	12
								8.5				20		12	12
												30		20	25
												36		20	25
1D	Lagoon D	✓						4.5				8		4	4
												15		4	4
												15		15	15
								8.5				20		15	15
												30		30	30
												36		30	30
			✓					4.5				6	4	3	3
												12	8	3	3
												12	12	8	8
								8.5				20	12	15	15
												30	20	30	30
												30	30	30	30
				✓				4.5				4		6	6
												8		6	6
												8		12	12
								8.5				8		20	20
												15		30	30
												20		36	30
												9		3	3

	Mine Closure Components	Components Response Considerations						Scenario	1	2	3	4	5	6	7
		Structural Design	Watershed, Surface Water & Groundwater	Operations, Maintenance & Materials Performance	Emergency Response	Social Effects	Environmental Effects		Mean Daily Temperature	Max/Min Temperature	Days with Tmax > 25C	Days with Tmax > 30C	Total Precipitation (mm)	Maximum 1-Day Total Precipitation (mm)	Wet Days >20mm
						✓		4.5				12		3	3
												12		12	12
								8.5				12		3	3
												15		12	12
												15		25	25
							✓	4.5				15		3	3
												20		3	3
												20		12	12
								8.5				20		3	3
												30		25	25
												36		25	25
2	**Tailing Facility**														
2A	West Fork Tailings Facility (WFTF)	✓						4.5				2		1	1
												2		1	1
												3		2	2
								8.5				2		1	1
												3		2	2
												3		3	3
						✓		4.5				9			
												12			
												12			
								8.5				12			
												15			
												15			
							✓	4.5				2			
												2			
												2			
								8.5				3			
												3			
												3			
3	**Water Treatment**														
3A	Elkview Saturated Rock Fill Water Treatment Facility		✓					4.5				4		3	3
												8		3	3
												15		8	8
								8.5				20		15	15
												20		15	15
												30		24	24
				✓				4.5				2	3		
												4	3		
												6	8		
								8.5				8	3		
												12	8		
												15	8		
						✓		4.5				3			
												9			
												16			
								8.5				16			
												16			
												30			
							✓	4.5				9		3	3
												12		3	3
												12		8	8
								8.5				20		8	8
												30		20	20
												30		30	30
4	**Biodiversity Management Plan**														
			✓					4.5			6	6		2	2
											9	9		4	4
											9	9		4	4
								8.5			16	16		4	4
											20	30		12	9
											20	30		15	9
				✓				4.5	3	3	3	3	4	3	
									9	9	12	12	4	3	
									12	9	12	12	15	12	
								8.5	12	16	20	20	4	3	
									12	16	20	20	15	12	



	Mine Closure Components	Components Response Considerations						Scenario	1	2	3	4	5	6	7
		Structural Design	Watershed, Surface Water & Groundwater	Operations, Maintenance & Materials Performance	Emergency Response	Social Effects	Environmental Effects		Mean Daily Temperature	Max/Min Temperature	Days with Tmax > 25C	Days with Tmax > 30C	Total Precipitation (mm)	Maximum 1-Day Total Precipitation (mm)	Wet Days >20mm
4A	Re-Vegetation								16	20	30	30	15	12	
						✓		4.5	4	3	3	3			
									12	15	12	12			
									15	15	12	12			
								8.5	20	20	20	20			
									30	35	30	30			
									30	35	30	30			
							✓	4.5	6	8	6	6			
									9	12	12	12			
									12	12	12	12			
								8.5	12	12	15	15			
									30	25	30	30			
									36	36	36	36			
4B	Wildlife (ungulate)			✓				4.5	6	3	3	3	3	3	
									6	9	12	12	3	3	
									12	16	16	16	9	12	
								8.5	20	20	16	16	3	3	
									30	30	20	20	16	16	
									30	30	20	20	16	16	
						✓		4.5	2	3	3	3			
									6	6	8	8			
									6	6	8	8			
								8.5	12	12	12	12			
									20	16	20	20			
									25	25	25	25			
							✓	4.5	3	3	3	3		2	2
									12	12	12	12		2	2
									24	16	16	16		6	6
								8.5	24	16	16	16		2	2
									30	25	30	30		8	8
									30	25	30	30		8	8

Intermediate Risk Score Range	Threshold
< 12	Low
12 – 19	Medium-Low
20 – 27	Medium
28 – 35	Medium-High
36 - 49	High

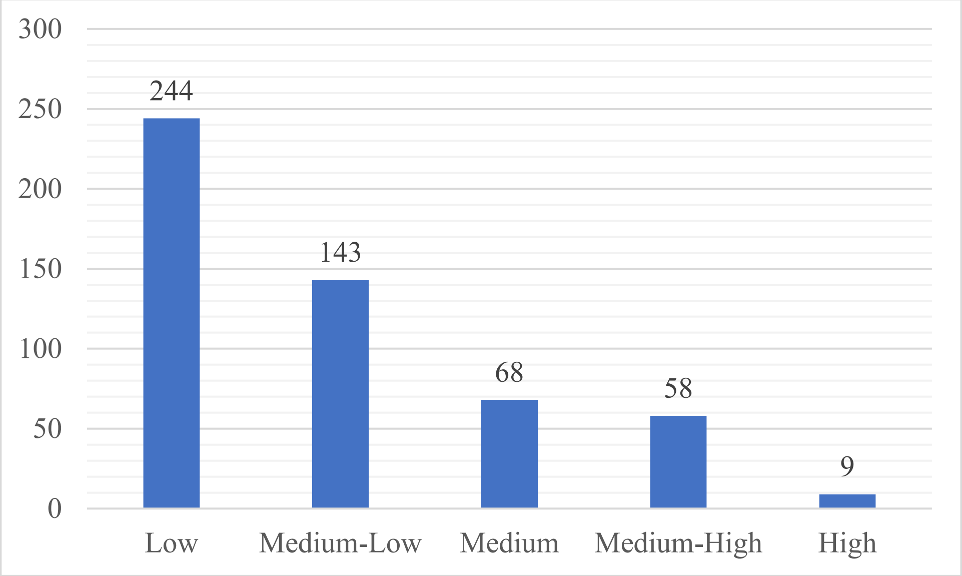
The "medium-high" and "high" level classification related to the mine closure components were considered together as the high-hazard interactions that originate at the mine site level, are of interest, and may require action to manage potential consequences. A total of 67 high-hazard interactions (defined as having an intermediate-risk score greater than 28) were identified in the hazard evaluation. These climate-related hazards that would affect the SES at the watershed level are shown in Figure 7.8.

Figure 7.8 Total high hazard interactions

Mine Closure Components	Component Response	Climate Parameter	Description	RCP	Year	Intermediate-Risk Score
Lagoon C	Structural Design	Days with Tmax > 30C	Very hot days could reduce moisture and unfroze entrapped cold soil, causing structure deformation in the long term	8.5	2060	30
					2090	36
		Maximum 1-Day Total Precipitation	Increase in total precipitation on a single day would affect the load carrying capacity	8.5	2060	30
					2090	30
		Wet Days >20mm	Increase in number of days with daily precipitation totals greater than 20mm would affect the load carrying capacity	8.5	2060	30
					2090	30
	Watershed, Surface Water & Groundwater	Days with Tmax > 30C	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	8.5	2060	30
					2090	30
		Total Precipitation (mm)	Increase in precipitation would contribute to floods and more runoff to the watershed	8.5	2090	30
		Maximum 1-Day Total Precipitation	Increase in total precipitation on a single day would produce runoff and flooding in the watershed	8.5	2090	30
		Wet Days >20mm	Increase in number of days with daily precipitation totals greater than 20mm would produce runoff and flooding in the Elk River	8.5	2090	30
	Environmental Effects	Days with Tmax > 30C	A potential breach caused by structure deformation could result in the release of tailings to the Elk River, affecting aquatic life dowstream	8.5	2060	30
					2090	36
Lagoon D	Structural Design	Days with Tmax > 30C	Very hot days could reduce moisture and unfroze entrapped cold soil, causing structure deformation in the long term	8.5	2060	30
					2090	36
		Maximum 1-Day Total Precipitation	Increase in total precipitation on a single day would affect the load carrying capacity	8.5	2060	30
					2090	30
		Wet Days >20mm	Increase in number of days with daily precipitation totals greater than 20mm would affect the load carrying capacity	8.5	2060	30
					2090	30
	Watershed, Surface Water & Groundwater	Days with Tmax > 30C	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	8.5	2060	30
					2090	30
		Total Precipitation (mm)	Increase in precipitation would contribute to floods and more runoff to the watershed	8.5	2090	30
		Maximum 1-Day Total Precipitation	Increase in total precipitation on a single day would produce runoff and flooding in the watershed	8.5	2060	30
					2090	30
		Wet Days >20mm	Increase in number of days with daily precipitation totals greater than 20mm would produce runoff and flooding in the Elk River	8.5	2060	30
					2090	30
	Emergency Response	Maximum 1-Day Total Precipitation	Increase in total precipitation on a single day would increase the required evacuation area in a breaching event	8.5	2060	30
					2090	36
		Wet Days >20mm	Increase in number of days with daily precipitation totals greater than 20mm would increase the required evacuation area in a breaching event	8.5	2060	30
					2090	30
	Environmental Effects	Days with Tmax > 30C	Very hot days cause structure deformation that could result in the release of tailings to the Elk River, affecting aquatic life dowstream	8.5	2060	30
					2090	36
Elkview Saturated Rock Fill Water Treatment Facility	Watershed, Surface Water & Groundwater	Days with Tmax > 30C	Very hot days would increase the algal growth in surface water	8.5	2090	30
	Social Effects	Days with Tmax > 30C	Very hot days would increase the water temperature discharged	8.5	2090	30
	Environmental Effects	Days with Tmax > 30C	Very hot days would affect the system operability, reducing the removement of contaminants in the discharged water	8.5	2060	30
					2090	30
		Maximum 1-Day Total Precipitation	Increase in total precipitation on a single day would affect the quality and quantity of discharged water	8.5	2090	30
		Wet Days >20mm	Increase in number of days with daily precipitation totals greater than 20mm would affect the quality and quantity of discharged water	8.5	2090	30
Re-Vegetation	Watershed, Surface Water & Groundwater	Days with Tmax > 30C	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	8.5	2060	30
					2090	30
	Operations, Maintenance & Materials Performance	Days with Tmax > 25C	Temperature increase modify growing patterns of trees and grass of previousl	8.5	2090	30
		Days with Tmax > 30C	Temperature increase modify growing patterns of trees and grass of previousl	8.5	2090	30
	Social Effects	Mean Daily Temperature	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems	8.5	2060	30
					2090	30
		Max/Min Temperature	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems	8.5	2060	35
					2090	35
		Days with Tmax > 25C	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems	8.5	2060	30
					2090	30
		Days with Tmax > 30C	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems	8.5	2060	30
					2090	30
	Environmental Effects	Mean Daily Temperature	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal	8.5	2060	30
					2090	36
		Max/Min Temperature	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal	8.5	2090	36
		Days with Tmax > 25C	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal	8.5	2060	30
					2090	36
		Days with Tmax > 30C	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal	8.5	2060	30
					2090	36
Wildlife (ungulate)	Operations, Maintenance & Materials Performance	Mean Daily Temperature	Temperature increase modify wildlife distribution patterns	8.5	2060	30
					2090	30
		Max/Min Temperature	Change in seasons Temperature modify wildlife distribution patterns and carr	8.5	2060	30
					2090	30
	Environmental Effects	Mean Daily Temperature	Temperature increase modify wildlife population due reduction of winter range habitat	8.5	2060	30
					2090	30
		Days with Tmax > 25C	Temperature increase modify wildlife population due reduction of winter range habitat	8.5	2060	30
					2090	30
		Days with Tmax > 30C	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal	8.5	2060	30
					2090	30

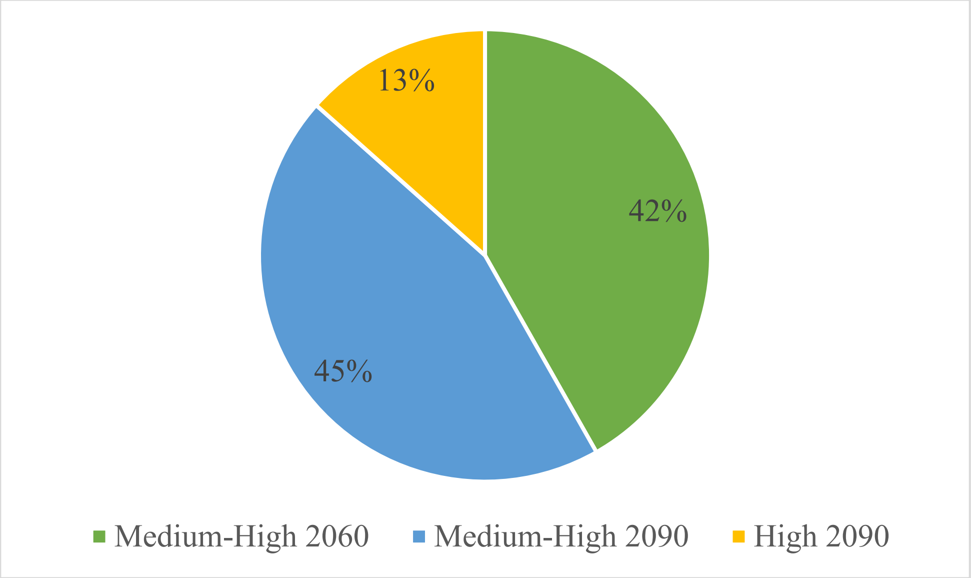
Nine hazard interactions with score greater than 36 were identified in the evaluation. Most interactions fell under low and medium-low hazard categories, for which no action is essential. Medium interactions must be reassessed in the next climate risk analysis as part of the monitoring process. The distribution of hazards scores is shown in Figure 7.9.

Figure 7.9 Distribution of hazard scores



Medium-high and high-hazards are present only for scenario RCP 8.5, with 2090 having 58% (39) of the hazard interactions (Figure 7.10). For 2051–2080, 28 climate interactions represent 42% of the total of hazards. This illustrates that the changing climate in a high emission scenario increases the hazard level from the mine closure components by the end of the century because the mine closure components were not designed to withstand them. These climate-related physical events may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.

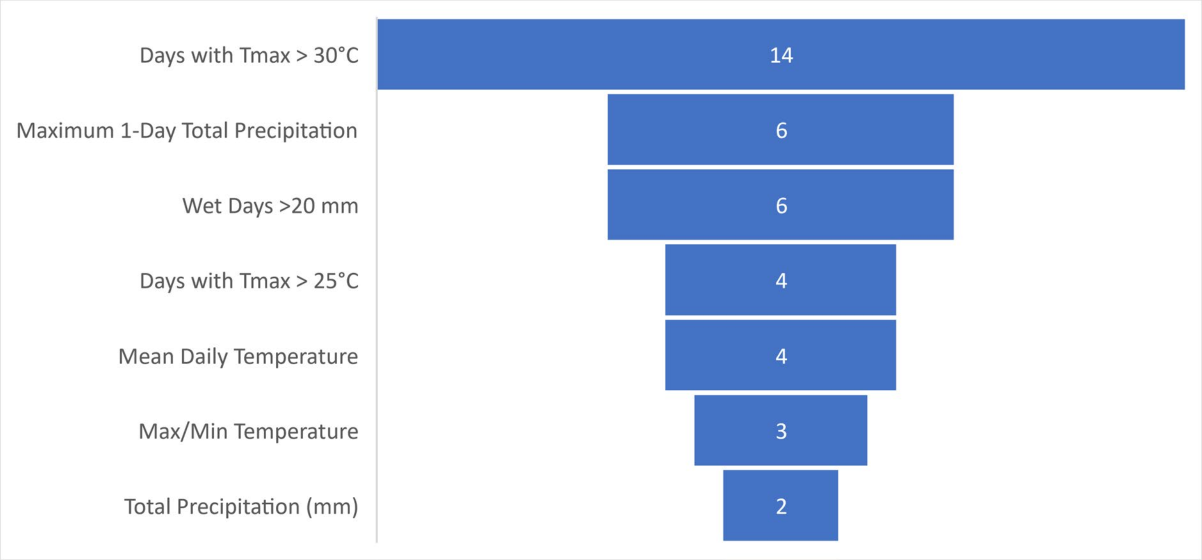
Figure 7.10 Potential hazardous period



7.2.2.1 Climate Parameters of Interest

The high hazards interactions were related by climate parameter threatening the site, indicating that some climate parameters posed varying degrees of climate hazard related to mine closure components (Figure 7.11). The three principal climate parameters are explained below in decreasing order of concern.

Figure 7.11 Distribution of climate parameters associated with the highest hazard scores



1) Days with Tmax > 30°C

A "very hot day" is a day with a maximum temperature (Tmax) greater than or equal to 30°C. These days are an indicator of summer heat. Under emission scenario RCP 4.5, 19.8 very hot days, or an increase of 662% compared with the baseline period, is projected for 2090 (Table 7.4). Under RCP 8.5, very hot days are projected to increase 1462% (40.6 days) compared with the baseline period.

This increase in very hot days could reduce moisture and thaw entrapped cold soil, causing structural deformation in the long term for Lagoons C and D. A potential breach caused by structural deformation could result in the release of tailings to the Elk River, affecting aquatic life downstream. Very hot days would increase algal growth in surface waters, affecting the system operability of the Saturated Rock Fill (SRF) Water Treatment Facility. Without effective water treatment to reduce the levels of contaminants in the discharged water, negative effects on the watershed and the environment could occur.

An increase in the number of very hot days is associated with increased incidence of droughts and forest fires that will alter the revegetation plan and reduce erosion-protecting cover vegetation. As a consequence, it is expected to increase runoff that could modify the watershed water balance and result in soil degradation and removal. High temperatures can also lead to more thunderstorms, which means increased risks of flash flooding, lightning, and hail. At the same time, high temperatures will modify growing patterns of native tree and grass of previously selected seeds (native species) for revegetation. These changes will likely decrease wildlife populations due to reduction of winter range habitat and food. In general, the increase of temperature will alter the Biogeoclimatic ecosystem locally.

The number of very hot days will determine practicability of outdoor activities, influence how infrastructure is designed, and markedly affect energy use. When temperatures are very hot, humans, especially the elderly, are much more likely to suffer from heat exhaustion and heat stroke. Many outdoor activities could become dangerous or impossible. For those who are not used to extremely hot summers, warming days will bring new and unusual risks.

2) Maximum 1-Day Total Precipitation

This metric of the most total precipitation on a single day for a specific period of time is the sum of the total rainfall and snow water equivalent (mm) falling in 24 hours. These data are among the most important and readily available measures of extreme rainfall potential and are used frequently in flood risk assessments. These data are also used to aid design of structures for long-term water retention.

Under emission scenario RCP 4.5, by 2090, the maximum 1-day total precipitation is expected to be 31.87 mm, an increase of 12% over the baseline period (Table 7.4). Under emission scenario RCP 8.5, this value could be as high 34.52 mm, an increase of 22% relative to historical climate data.

For lagoons C and D, the increase in total precipitation on a single day would affect their load-carrying capacities. If overtopping occurs, runoff and flooding would affect ecosystem health and aquatic life in the watershed. An increase in total precipitation on a single day could diminish the functionality of the SRF Water Treatment Facility, affecting the quality and quantity of discharged water to the environment.

3) Wet Days > 20 mm

Very high precipitation creates many challenges, like overwhelmed storm drains and flash flooding in residential areas. Under an RCP 4.5, the days with total precipitation amounts greater than 20 mm is expected to rise by 52% (2.7 days) by the end of the century compared with the baseline period (Table 7.4). An increase of 83% (3.3 days) over historical climate data would take place under RCP 8.5.

For lagoons C and D, an increase in the number of high-precipitation days would affect their load carrying capacities, creating the possibility of runoff and flooding in the Elk River. More high-precipitation days could lead to structural failures that may require an emergency preparedness and response plan review undertaken in consultation with the community.

A high number of days with daily precipitation totals greater than 20 mm is important to consider for land restoration, because it can cause sinking revegetation areas, seed washout, topsoil erosion, and soil structure damage. If they exceed load capacity, heavy rainfall and snowfall events could disrupt infrastructure, like tailings and water treatment facilities, roads, and bridges.

7.2.3 Social-Ecological System Vulnerability Assessment

The CRA-AF continues by assessing the main societal and ecological drivers that are potentially vulnerable to climate-related hazards. The three principal climate parameters described in Section 7.2.2 were selected for the SES vulnerability assessment, with an academic aim. As mentioned in Section 6.2.4, the vulnerability rating is a function of the sensitivity and the adaptive capacity of the system.

7.2.3.1 Sensitivity

If the functionality of a service area is likely to be affected because of the projected climate change scenarios, it should be considered sensitive to climate change. A sensitivity assessment determined if changing climate conditions will significantly affect the functionality of a particular service area in the Sparwood community. The results of the sensitivity assessment are presented in Appendix G.

The functionality of the water supply utility would be affected by the expected warmer temperatures and the shift of precipitation patterns in 2060 and 2090. Ground water contamination with selenium is already affecting one water well, and future disruptions could occur in community drinking water sources. Warmer summer temperatures increase evaporation rates and residential demand for water, risking the functionality and water supply system.

Future urban interfaces with parks and natural areas will experience increased incidence of droughts and forest fires due to the increase in very hot days. In the RCP 8.5 emission scenario, the increase in wildfire incidence will decrease the land available for future urban development areas in the three time periods assessed.

Similar effects would generate the increase in precipitation and temperature that would contribute to the soil degradation, floods, and contaminated runoff (i.e., selenium) to the Elk River, harming the aquatic ecosystem and consequently, the tourism and recreational fishing industries. In a high emission scenario for 2060 and 2090, after mine closure, the functionality of these services will cease. Therefore, Sparwood residents who economically depend on these activities will be impacted.

7.2.3.2 Adaptive Capacity

Appendix G contains the assessment regarding the ability of the service areas to accommodate to climate variability with little or no cost.

Future development of the community will place additional demands on the water supply system, requiring component and capacity upgrades. The maintenance activities for infiltration detection and renovation program of the current distribution were estimated to cost C$150,000/year (Sparwood Council 2019). In the scenarios that predict water shortages during hot summers, or if the water quality in one of the two wells is compromised by selenium contamination, the necessary service adjustment will require substantial additional cost.

The Sparwood Municipality has a long-term planning wildfire management practice, including harvesting trees, improving access, increasing water availability, and reducing the number of ignition sources. These activities will require some cost and staff intervention, with more demand in 2060 and 2090 periods.

To be able to adjust to projected hazards to tourism and recreational fishing industries, substantial effort is required. For instance, the selenium concentration in the Elk River, which affects westslope cutthroat trout, must be reduced. Water quality management must be consistently applied during the closure stage. Other adjustments are required for riparian zones and natural instream cover. All these activities will require substantial cost and staff intervention during the three future time periods assessed.

With both sensitivity and adaptive capacity assessments complete, the vulnerability of each service area can be established (Table 7.7). Those service areas with high sensitivity and low adaptive capacity are highly vulnerable; those with low sensitivity and high adaptive capacity have low vulnerability; and those service areas that have both high sensitivity and high adaptive capacity have a medium vulnerability.

Table 7.7 Vulnerability rating for each service area

Climate event	Factor	RCP	Period	Vulnerability	
Days with Tmax > 30°C	Parks and natural areas	8.5	2030	V3	Medium
			2060	V4	Medium-high
			2090	V4	Medium-high
Days with Tmax > 30°C Maximum 1-day total precipitation	Road maintenance	8.5	2030	V3	Medium
			2060	V4	Medium-high
			2090	V4	Medium-high
Maximum 1-day total precipitation	Economic development: fishing and tourism	8.5	2030	V4	Medium-high
			2060	V5	High
			2090	V5	High
Wet days >20 mm	Resident age	8.5	2030	V2	Medium-low
			2060	V3	Medium
			2090	V3	Medium
Maximum 1-day total precipitation	Wastewater Treatment Plant	8.5	2030	V3	Medium
			2060	V4	Medium-high
			2090	V4	Medium-high
Maximum 1-day total precipitation Days with Tmax > 30°C	Drinking water plant	8.5	2030	V5	High
			2060	V5	High
			2090	V5	High

7.2.4 Elements Exposed to Climate Change within the social-ecological system

Exposure of relevant elements of Sparwood's SES to the climate hazards was evaluated. All biogeoclimatic zones are expected to continue moving farther north. Since the baseline period, approximately 20% of land in British Columbia has shifted to climates characteristic of different biogeoclimatic zones (Wang et al. 2012). Based in the climate data analysed in Section 7.1.1.5, the Montane Spruce zone will be drastically reduced in 2051–2080 and extirpated from the area by the end of the century. This suggests that it and the Dry Cool Engelmann Spruce – Subalpine Fir subzone will have high exposure to the increment in temperature by the end of the century.

In terms of vegetation, some ecosystems may undergo regime shifts. For instance, changes from forest to shrubs or to grassland would be observed. These shifts will initially benefit some species, although the new habitats may be affected by forage reduction due to overgrazing (McCain, King, and Szewczyk 2021). Habitat for some species will alter in distribution and abundance. For instance, elk habitat will be negatively impacted by increasing fire activity in addition to reduced winter range. Overall, the total habitat area will be reduced in the mountains, affecting the animal populations in the District of Sparwood.

The increase of warmer days and the mean annual temperature will increase the incidence of mountain pine beetle outbreaks, a species that has been associated with the destruction of a large percentage of coniferous trees in forests throughout western Canada (Bentz et al. 2010). Warmer winter temperatures means that insect winter mortality rates will decline, allowing populations to reach epidemic levels (Buotte et al. 2016). Given that trees are a key component of watershed hydrology, high tree mortality will mean lower evapotranspiration rates and increased runoff from rain and snowmelt. These will combine with projected watershed hydrology effects of warmer temperatures such as significantly elevated snow melt rates and increased streamflow magnitude as response to storms (Walker et al. 2016).

Table 7.8 Exposure level of ecosystem services to climate change effects in Sparwood, British Columbia under Representative Concentration Pathway model 8.5

Climate event	Ecosystem service	RCP	Period	Exposure
Maximum 1-day total precipitation Min/max temperature	Aquatic organisms	8.5	2030	0.3
			2060	0.6
			2090	0.8
Min/max temperature Days with Tmax > 30°C	Forest biogeoclimatic zone	8.5	2030	0.4
			2060	0.8
			2090	1.0
Min/max temperature	Wildlife	8.5	2030	0.4
			2060	0.8
			2090	1.0
Days with Tmax > 30°C Min/max temperature	Forest	8.5	2030	0.64
			2060	0.64
			2090	0.64
Maximum 1-day total precipitation	Riparian zone	8.5	2030	0.22
			2060	0.22
			2090	0.22
Min/max temperature Days with Tmax > 30°C	Stream temperature	8.5	2030	0.3
			2060	0.6
			2090	0.8

7.2.5 Analyse Climate Risk Scores

Based on the available information on the EVO and District of Sparwood, hazard, vulnerability, and exposure ratings were combined into risk values by arithmetic aggregation to define a single risk component to support decision making in relation to mine closure design. In Table 7.9 are shown the results of risk scoring process for each mine closure component and the related climate impact. Factors associated with SES sensitivity and capacity can be used as a starting point to identify adaptation strategies for the EVO and community. With the climate risk in the SES identified and the cause-effect relationships between the mine site and its surroundings defined, the adaptation strategies will provide a measure of risk management at the mine closure stage.

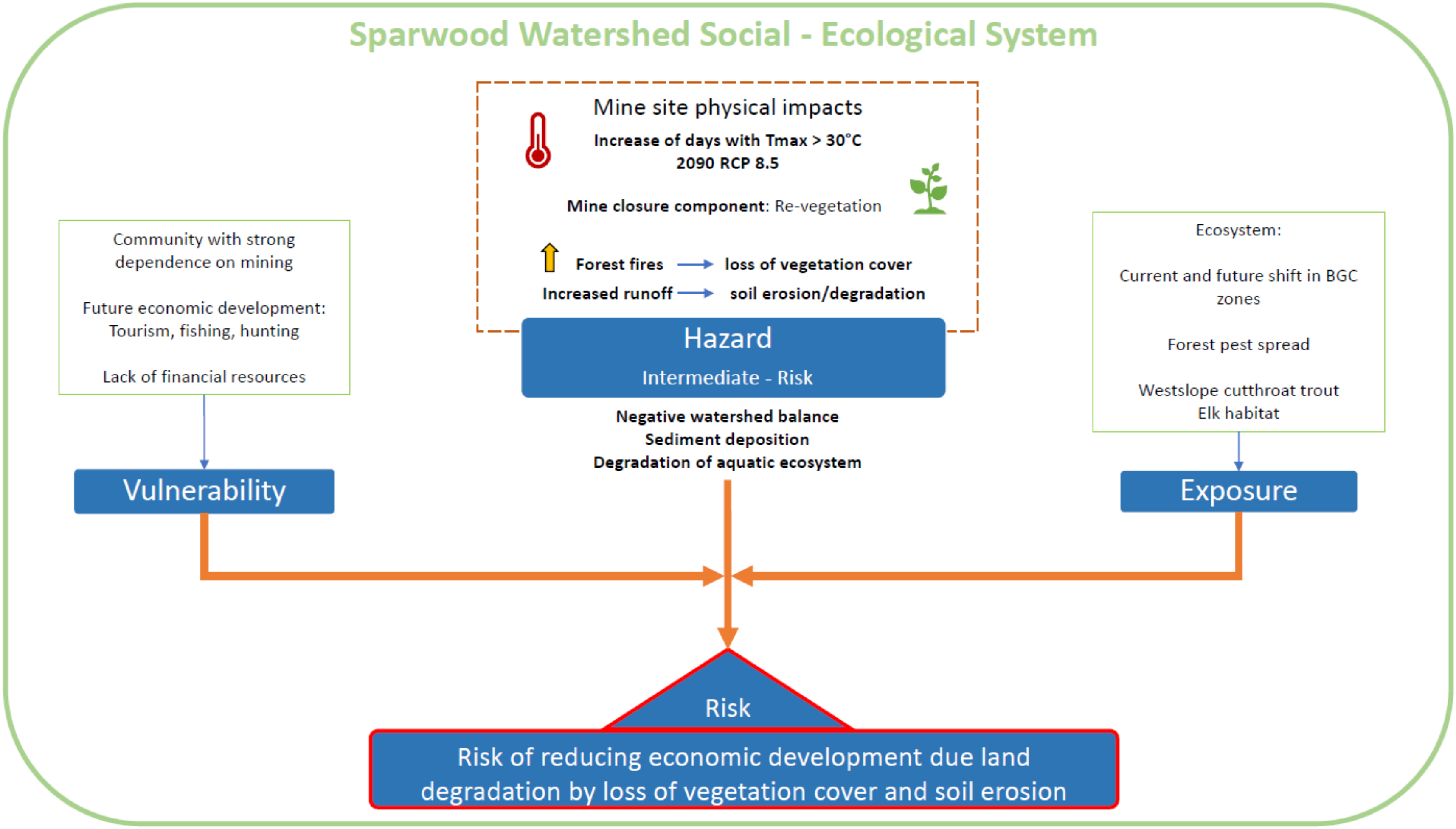
Table 7.9 Aggregated indicators and risk scores for each mine closure component and the related climate impact

Climate event combination	Infrastructure / mine closure element	Period	Hazard	Vulnerability	Exposure	Risk	Risk level	SES risk description
Days with Tmax > 30°C Maximum 1-day total precipitation	Lagoon C	2030	0.45	0.75	0.3	0.50	Intermediate	Loss of livelihood diversification due to aquatic life degradation by river contamination
		2060	0.7	0.9	0.6	0.73	High	
		2090	0.8	0.9	0.8	0.83	Very high	
Total precipitation (mm) Days with Tmax > 30°C	Lagoon D	2030	0.45	0.75	0.3	0.50	Intermediate	Loss of livelihood diversification due aquatic life degradation by river contamination
		2060	0.7	0.9	0.6	0.73	High	
		2090	0.8	0.9	0.8	0.83	Very high	
Maximum 1-day total precipitation Wet days >20 mm	Lagoon D	2030	0.45	0.3	0.22	0.32	Low	Property damage and loss of life due to fast-moving flood after lagoon breaching event
		2060	0.7	0.4	0.22	0.44	Intermediate	
		2090	0.8	0.4	0.22	0.47	Intermediate	
Maximum 1-day total precipitation Total precipitation (mm)	Lagoon D	2030	0.2	0.9	0.22	0.44	Intermediate	Loss of drinking water supply due runoff erosion and water source contamination
		2060	0.4	0.95	0.22	0.52	Intermediate	
		2090	0.7	1	0.22	0.64	High	
Days with Tmax > 30°C	Elkview SRF	2030	0.4	0.9	0.64	0.65	High	Loss of drinking water due to function reduction on SRF after wildfires and erosion
		2060	0.7	0.95	0.64	0.76	High	
		2090	0.8	1	0.64	0.81	Very high	
Days with Tmax > 30°C	Revegetation	2030	0.3	0.55	0.64	0.50	Intermediate	Property damage and loss of life due to wildfire in urban areas
		2060	0.7	0.7	0.64	0.68	High	
		2090	0.8	0.75	0.64	0.73	High	
Days with Tmax > 30°C Days with Tmax > 25°C	Revegetation	2030	0.3	0.75	0.4	0.48	Intermediate	Lower economic development due land degradation by loss of vegetation cover and soil erosion
		2060	0.7	0.9	0.8	0.80	High	
		2090	0.8	0.9	1	0.90	Very high	
Days with Tmax > 25°C	Wildlife (ungulates)	2030	0.3	0.75	0.4	0.48	Intermediate	Loss of livelihood diversification due biogeoclimatic shift affecting elk habitat
		2060	0.7	0.9	0.8	0.80	High	
		2090	0.7	0.9	1	0.87	Very high	

The climate risk scores indicate that the projected increase in temperature in the District of Sparwood would threaten the livelihood, sustainability, and safety of the community. The scenario analysis approach, with three periods for each scenario, is useful to understand the potential climate risk range of the mine closure implementation plan. Thus, some threats like wildfires, flooding, water pollution, and loss of biodiversity could become more pronounced if the Elkview Operation mine closure plan does not incorporate adaption strategies.

There is a very high risk of reducing economic development in Sparwood due to land degradation by loss of vegetation cover and soil erosion caused by the warming temperatures projected to occur by 2090 in a high-emission scenario (Figure 7.12). With the number of days over 30°C rising by almost sixteen-fold over the baseline period, the incidence of droughts and forest fires is expected to reduce erosion-protecting vegetative cover. At the same time, the increase in temperature will dramatically affect the distribution of biogeoclimatic zones, decreasing the dominance of native species in favour of more drought-tolerant plants. Thus, the revegetation closure plan suggesting use of pre-mining forest species could be unsuccessful. Also, when vegetation cover is reduced, more plentiful precipitation would contribute to soil degradation and promote runoff with contaminants such as selenium to the Elk River. Therefore, after the mine closure, the Sparwood community will be more vulnerable to aquatic ecosystem disturbance because it will affect recreation, tourism, and fisheries activities, which would have important economic benefits ensuring the livelihood of the community.

Figure 7.12 Climate risk in the social-ecological system



Similar levels of warming can be expected to change wildlife (e.g., elk, mule deet) biodiversity in the area, with the very high risk of loss of diversification due to biogeoclimatic zone shift. By the periods 2060s and 2090s, wildlife populations would be altered due reduction of winter range habitats. In emission scenario RCP 8.5, some forest may transform into shrubs or grassland. Regardless, it will be exposed to increases in invasive noxious species that may reduce forage potential in new habitats. The reduction of available habitat area will contribute to the decline in the local elk population. Therefore, local inhabitants will be affected by reduced access to ecosystem services the elk provide (e.g., tourism, hunting). Community members who strongly depended on mining activities for economic benefits will be more vulnerable after mine closure. At the same time, habitat reduction will challenge the mine closure's biodiversity objective related to the elk population's natural recovery.

The combination of climate events could increase hazards from the mine site, affecting the SES. As temperature and precipitation patterns change in season and in scale, more natural disturbances would be observed such as wildfire, pest outbreaks, changes to the water cycle, and water availability. The risk of loss of drinking water utility in the town would increase because the function of the SRF would be compromised by wildfire and erosion. For instance, very hot days would affect SRF operability, inhibiting removal of mineral contaminants in the water discharged to the Elk River. The frequency of wildfires is projected to increase by 30%, and wildfire severity is projected to increase 40% in spring, 95% in summer, and 30% in fall by the period 2060s and 2090s. Runoff and soil erosion will increase in exposed burned areas during the rainy season, which could overload the SRF filtration capacity. Thus, high selenium concentrations in the Elk River and Michel Creek could affect the vulnerability of water wells and drinking water quality in the town.

Another combination of climate events could threaten the infrastructure of Lagoons C and D, with the risk of loss of livelihood diversification due aquatic life degradation by river contamination. The projected very hot days could reduce moisture and thaw entrapped cold soil, causing structure deformation in the long term. Additionally, the increase in total precipitation on a single day would affect the load carrying capacity, contributing to floods and more runoff from the watershed. Therefore, this combination would increase aquatic life exposure and consequently, the vulnerable residents who depend on it. For instance, westslope cutthroat trout has economic and social importance to the Ktunaxa Nation, Sparwood residents, and visitors to the Elk Valley.

Additional risks are important to consider, such as the high risk of property damage and loss of life due to wildfires in urban areas and intermediate risk of damage of property and loss of life due to a fast-moving flood in a Lagoon D breaching event. The former risk is a result of the high vulnerability to wildfires and insect outbreaks in future urban development areas by the period years 2060’s and 2090s. The latter risk is a result of high precipitation that would contribute to floods and more runoff to the watershed, increasing potential overtopping by the periods 2060s and 2090s. The Elk River is exposed to frequent riparian disturbance, thus, in an eventual failure of Lagoon D, the sediment control function of the riparian zone will be reduced, which would have negative consequences for vulnerable individuals and local infrastructure, threatening the people health and lifestyles, specifically elderly and young children.

7.3 Step 3: Adaptation Plan Design

After the identification of hazard, vulnerability, and exposure factors to define the climate risk, EbA measures were assessed and prioritised to establish strategies to support the land restoration process, while simultaneously reducing or controlling climate change impacts.

7.3.1 Establish Adaptation Objectives

This section integrates conditions that could reduce the impacts of climate risk in the watershed with the mine closure plan, aiming to reduce vulnerability and exposure in the SES. The relationship between local climate risk and specific climate-related events was reviewed to define the actions required to manage hazards from the mine site and define measures that will help decrease vulnerability and exposure (Table 7.10).

Table 7.10 Adaptation objectives required to address the potential climate risk

Climate-related Event	Climate risk	Objectives	
		Action	Measures
Days with Tmax > 30°C Maximum 1-day total precipitation Total precipitation (mm)	Loss of livelihood diversification due aquatic life degradation by river contamination	Reduce / control water erosion from lagoons C and D	Establish restoration plan for westslope cutthroat trout Increase local capacity in tourism industry
Maximum 1-day total precipitation Wet days >20 mm	Property damage and loss of life due to fast-moving flood caused by a lagoon breaching event	Review stability analysis. Update OMS Manual, for erosion areas Update Emergency Preparedness Plan & Emergency Response Plan considering future urban development	Enhance riparian habitat
Maximum 1-day total precipitation Total precipitation (mm)	Loss of drinking water service due to runoff erosion and water source contamination	Reduce / control water erosion from Lagoon C and D	Enhance water quality source Build new water pond Establish wetlands
Days with Tmax > 30°C	Loss of drinking water service due to reduced function of Saturated Rock Fill (SRF) Water Treatment Facility after wildfire and erosion	Expand SRF capacity	Assess optimal temperature for bacteria Integrate wildfire management plan into mine closure plan Minimise sediment loading to streams Expand SRF capacity Establish wetlands
Days with Tmax > 30°C	Property damage and loss of life due to wildfire in urban areas	Reduce wildfire threat	Integrate fire management plan into mine closure plan, considering urban interface Support future community planning and design
Days with Tmax > 30°C Days with Tmax > 25°C	Lower economic development due to land degradation by loss of vegetation cover and soil erosion	Protect land	Integrate wildfire management plan into mine closure plan Review selection of species that are suited to the site ecosystem and future climate to strengthen alternative economic activities
Days with Tmax > 25°C	Loss of livelihood diversification due to biogeoclimatic zone shift affecting elk habitat	Restore wildlife habitat	Review selection of adequate seed species Establish prescribed fire program Species that are suited to the site ecosystem and future climate

7.3.2 Identify Adaptation Outcomes for Vulnerable Livelihood Strategies

Adaptation outcomes were identified along with the assessment of the cause-effect components of climate risk. Table 7.11 shows adaptation outcomes that might improve SES capacity through conservation, management, or restoration practices.

Table 7.11 Adaptation outcomes for vulnerable livelihood strategies

Climate risk	Adaptation outcomes
Loss of livelihood diversification due to aquatic life degradation by river contamination	Restored river habitat increases aquatic species diversity and abundance and provides opportunities to develop alternatives eco-business livelihood
Property damage and loss of life due to fast-moving flood after lagoon breaching event	Restored riparian habitat slows flood flows and erosion Implement a flood warning protocol to alert residents
Loss of drinking water supply due to runoff erosion and water source contamination	Manage harmful pollutants from water by trapping metals and organic materials
Loss of drinking water due to function reduction on Saturated Rock Fill Water Treatment Facility after wildfires and erosion	Manage harmful pollutants from water by trapping metals and organic materials Identify ‘no-development’ zones
Property damage and loss of life due to wildfire in urban areas	Forest management using adapted tree seed species with prescribed fire program
Lower economic development due to land degradation by loss of vegetation cover and soil erosion	Forest management using adapted tree seed species with prescribed fire program.
Loss of livelihood diversification due to biogeoclimatic zone shift affecting elk habitat	Restoration of mountain ecosystem

7.3.3 Identify EbA Options for Vulnerable Livelihood Strategies

The EbA options were proposed with the aim to reduce or control the climate risk defined in Section 7.2.5 and obtain the desired adaptation outcomes. These EbA options (Table 7.12) manage extreme events while supporting vulnerable groups in the SES.

Table 7.12 Ecosystem-based Adaptation (EbA) options identified for each climate risk

Climate risk	EbA Options
Loss of livelihood diversification due to aquatic life degradation by river contamination	Establish wetlands Control erosion of riverbanks with vegetation Enhance riparian habitat Establish riparian buffer strips Establish natural ponds
Property damage and loss of life due to fast-moving flood after lagoon breaching event	Establish wetlands Control erosion of riverbanks with vegetation Enhance riparian habitat
Loss of drinking water supply due to runoff erosion and water source contamination	Establish wetlands Enhance riparian habitat Establish riparian buffer strips
Loss of drinking water due to function reduction on Saturated Rock Fill Water Treatment Facility after wildfires and erosion	Establish wetlands Collect rainwater from ground surfaces—small reservoirs and micro-catchments Establish riparian buffer strips
Property damage and loss of life due to wildfire in urban areas	Use adapted tree species for seed bank Prescribed burning
Lower economic development due to land degradation by loss of vegetation cover and soil erosion	Use adapted tree species for seed bank Prescribed burning Fisheries management plans Establish riparian buffer strips
Loss of livelihood diversification due to biogeoclimatic zone shift affecting elk habitat	Manage grasslands and adapted tree species to prevent erosion and habitat loss

7.3.4 Prioritise and List Effective EbA Options for Vulnerable Livelihood Strategies

A multi-criteria analysis determined how effectively each EbA option contributed to the Sparwood SES based on five criteria (Table 7.13; see Section 6.3.4). The EbA options assessed in the decision matrix with a score 10 or more were highlighted as the most effective EbA options to provide the required results.

Table 7.13 Ecosystem-based Adaptation (EbA) options assessed using decision matrix

Adaptation outcome	Potential EbA options	Ability to reduce current and future climate risks	Ability to generate social benefits for vulnerable social groups	Ability to restore, maintain, or improve ecosystem health	Enhance sustainable use of biodiversity and ecosystem services at local level	Build integrated management of ecosystem services with multi-sector approach	EbA Score
Forest management using adapted tree species with prescribed fire program	Manage adapted tree seed species	High	High	High	Medium	High	14
	Prescribed fire	High	Medium	High	Medium	High	13
	Develop fisheries plans	Medium	High	High	High	Medium	13
	Establish buffer strips	Medium	Low	Medium	Low	High	9
Restoration of mountain ecosystem	Manage adapted tree species	High	High	High	Medium	High	14
	Manage adapted grassland species	High	High	Medium	High	High	14
Manage harmful pollutants from water by trapping metals and organic materials	Establish wetlands	High	High	High	High	High	15
	Collect rainwater from ground surfaces in small reservoirs	Medium	Medium	Low	Medium	Low	8
	Establish buffer strips, micro-catchments	High	High	High	High	High	15
Restoration of river habitat, increase aquatic species diversity and abundance and provide opportunities to develop alternative eco-business livelihood	Establish wetlands	High	High	High	High	High	15
	Control erosion of riverbanks with vegetation	Medium	Medium	Medium	Medium	Medium	10
	Enhance riparian habitat	High	High	Medium	High	Medium	13
	Establish buffer strips	High	Medium	High	Medium	Medium	12
	Natural water ponds	Medium	Low	High	Low	Low	8

To manage the risk of property damage and loss of life due to wildfires encroaching on urban areas, the EbA option recommended to be included in the mine closure plan is to establish a reforestation management plan using adapted tree and seed species alongside a prescribed fire program.

The risk of loss of livelihood diversification due to biogeoclimatic zone shift affecting elk habitat would be reduced with a mountain ecosystem restoration plan that includes managing grasslands and planting adapted tree species to prevent erosion and habitat loss.

After a wildfire, provision of safe drinking water by the SRF Water Treatment Facility would be reduced. Erosion and water source contamination would also occur. These consequences could be ameliorated by trapping metals and organic materials by establishing and/or restoring wetlands. At the same time, the riparian buffer strips would slow runoff and water infiltration.

The risk of floods and river contamination affecting aquatic life could be ameliorated by restoring riverine habitat suitable for aquatic species and provide opportunities to develop alternative eco-business livelihoods. These objectives will be achieved by incorporating wetland restoration, controlling erosion on riverbanks with natural vegetation, enhancing riparian habitat, and installing buffer strips.

7.3.4.1 Identify actions required to implement priority EbA options

The EbA options selected have the greatest potential to be included in the EVO mine closure plan to reduce the potential negative impacts of the climate change. Table 7.14 lists the key actions required in the mine closure plan to implement the prioritised EbA options.

Table 7.14 Key actions for EbA implementation

EbA options selected	Actions suggested
Establish wetlands	Define type, location, substrate, vegetation, and cover area
Buffer strips, micro-catchments	Define sedimentation erosion rates, nutrient inputs, stream temperature, and movement of wildlife populations
Manage adapted tree seed species	Define species range expansion rates, tree growth rates, and soil requirements
Manage adapted grassland species	Define species range expansion rates, interspecific interaction, vegetation growth rates, and soil requirements
Prescribed fire program	Plan vegetation composition, structure, integrity, and distribution
Fisheries development plans	Define habitat characteristics, fish and fish forage populations, and riparian reserve zone; design business plan
Enhance riparian habitat	Define vegetation, base flow, hydrology, downstream flooding

7.4 Step 4: Implementation

Based on the EbA options selected and the actions suggested by the CRA-AF, a formal action plan needs to be established. This required defining an execution timeline, roles and responsibilities of those involved in implementation, as well as financial resources. In this case study application, the implementation section was considered only as a general overview because any adaptation strategies for mine closure planning, as a response to local climate risk, will require a previous decision from EVO about the actions to implement. Nonetheless, the following sections suggest actions based on publicly available information, with an academic rationale.

7.4.1 Identify roles and responsibilities for priority EbA options

Table 7.15 lists the actors who should be involved in the planning, design, and implementation of each EbA option defined in the climate risk assessment. The list includes not only the mining company employees, but stakeholders in the community of the SES. The information related to the actors was collected from District of Sparwood publicly available data for the case study, but in a real situation, potential participants should be defined by their roles and responsibilities in plan implementation.

Table 7.15 Implementation roles and responsibilities

EbA options selected	Elkview Operations	Sparwood community
Establish wetlands	Environment area Define specific characteristics and location to set up wetlands	Manager of Planning Define bylaws, resolutions and other measures that support the activity
Establish buffer strips, micro-catchments	Hydrology and Environment areas Define sedimentation and erosion rates, nutrient inputs, stream temperatures, and movement of wildlife populations	Director Parks, Recreation and Culture Define bylaws, resolutions and other measures that support the activity
Manage adapted tree seed species	Environment area Define species range expansion rates, vegetation growth rates, and soil requirements	Socio-Community Advisory Committee Define bylaws, resolutions and other measures that support the activity
Manage adapted grassland species	Environment area Define species range expansion rates, interspecific interaction, vegetation growth rates, and soil requirements	Socio-Community Advisory Committee Define bylaws, resolutions and other measures that support the activity
Prescribed fire	Safety, Environment and Social areas Define vegetation composition, structure, integrity, and distribution	Manager of Planning Define bylaws, resolutions and other measures that support the activity
Develop fisheries	Social and Environment areas Define habitat characteristics, fish populations, riparian reserve zone, design business plan	Director Parks, Recreation and Culture Define bylaws, resolutions and other measures that support the activity
Enhance riparian habitat	Hydrology and Environment areas Define vegetation, base flow, hydrology, downstream flooding	Director Parks, Recreation and Culture

The process should continue with identification of factors that positively influence and facilitate implementation of each EbA option. This will include considering local actors and resource opportunities that support integrated watershed management.

7.5 Step 5: Monitoring and Evaluation

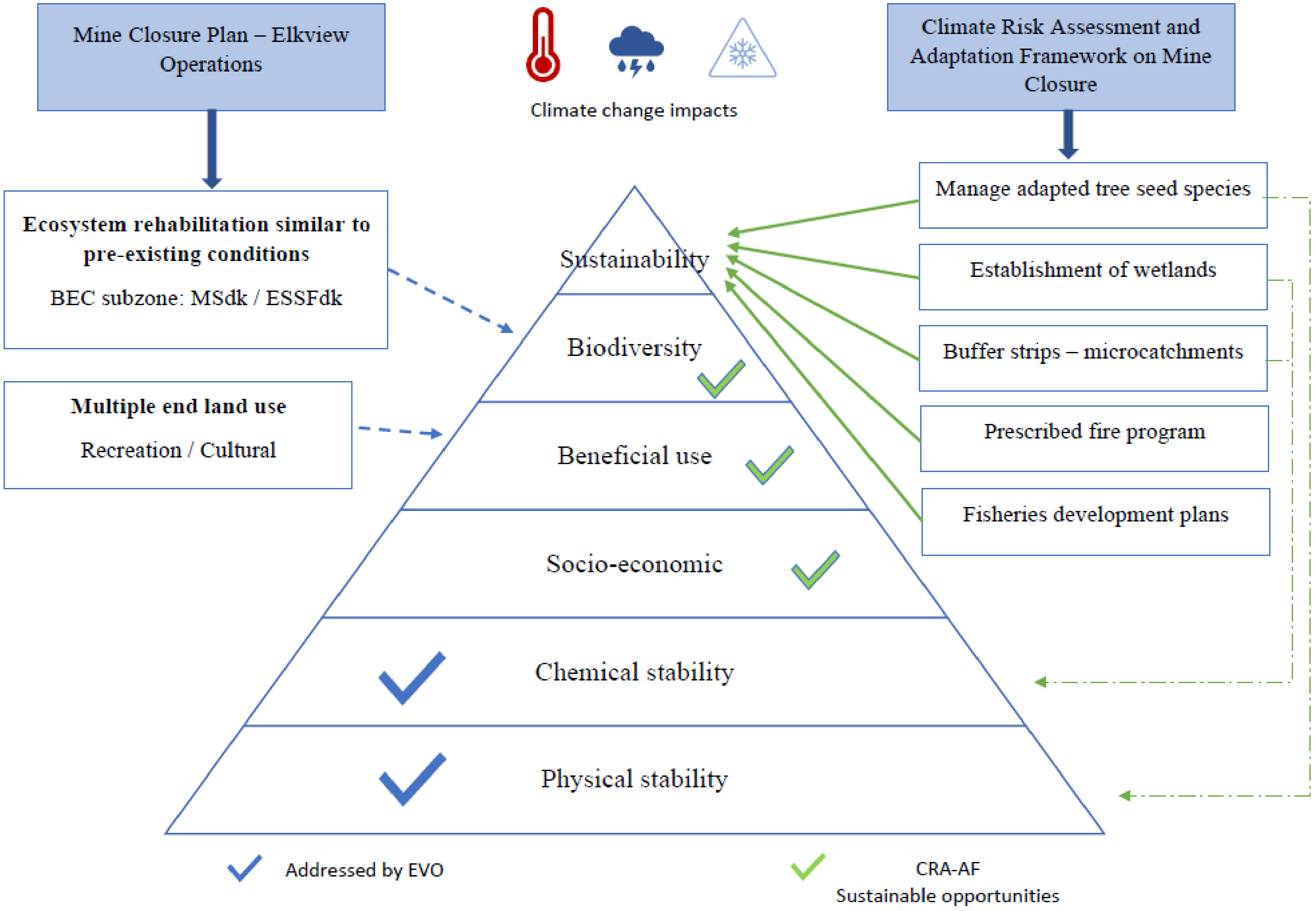
Similar to Section 7.4, for the case study, monitoring and evaluation were considered with a broad perspective as part of the mine closure plan to quantify the effectiveness of mine closure design strategies. Thus, this section establishes the framework to assess adjustments in the EbA strategy. Furthermore, it is important to highlight that climate risk scenarios should be periodically reassessed when new climate data are available at the watershed level. This step will help communicate actions and results with internal and external stakeholders.

At the same time, construction of a set of indicators will facilitate understanding how climate change is affecting the ecosystem and ecosystem services as well as the adaptation capacity of the community. For instance, establishing a long-term monitoring strategy for westslope cutthroat trout habitat and populations in the Elk River would contribute to the fisheries development plan defined as an adaptation strategy. Another example is monitoring wetlands as part of land restoration, with specific indicators related to hydrological effects, water retention, and fragmentation of wildlife habitat.

7.6 Comparison of Mine Closure Objectives

Results from the CRA-AF applied in the case study are compared with current EVO mine closure objectives and the reclamation plan for end land use. This process underscores gaps in the mine closure plan and sustainable opportunities provided by the CRA-AF. The hierarchy of mine closure needs in Figure 7.13 shows the elements that would be achieved by the closure plan defined by the case study and the potential updates based on the CRA-AF in mine closure framework designed. EbA strategies are prioritised that could contribute to improving design and management during closure and reclamation.

Figure 7.13 Comparison of mine closure objectives and design opportunities: EVO vs CRA-AF



The general approach to reclamation in the current plan is appropriate because it aims to establish desirable physical, chemical, and biological processes. However, design of an intervention for the socio-economic transition is less clear. This process would be facilitated by communication, economic development, worker relocation, and other projects. Furthermore, knowing whether physical and chemical processes are stable would require updated analysis of climate change and extreme weather events. For instance, glaciolacustrine foundation analysis in lagoons C and D was underway at the time of writing. Interpretation of the stability analyses data would be stronger with the climate risk information based on the climate scenario analysis.

Analysis of potential climate change impacts suggests that the current plan for mine closure and end land use is not satisfactory and would unlikely achieve the ideal goal of sustainable development. In terms of revegetation to support biodiversity, the current plan considers the Dry Cool Montane Spruce and Dry Cool Engelmann Spruce – Subalpine Fir biogeoclimatic subzones. However, this study found that temperature increases and precipitation decreases will dramatically change the distribution of biogeoclimatic zones. Drier conditions would favour more drought-tolerant species that are characteristic of the Interior Cedar – Hemlock zone (Wang et al. 2012). Therefore, as suggested in the EbA option selection, the plan will require establishing better adapted genotypes over large areas of disturbance, like cedar, hemlock, and douglas fir (CBT 2020).

Increases in drought and wildfire intensity and frequency would reduce vegetation cover, which protects the soil from erosion. Lower evapotranspiration would reduce the soil structure too. More soil movement and sediment transport during the rainy season would affect drinking water quality and quantity and would be exacerbated by extreme precipitation events. Therefore, the mine closure plan will be improved with the establishment of wetlands in key areas, riparian buffer strips, and micro-catchments in waterways.

At the same time, the potential increase in frequency and severity of wildfires in restored areas will increase the risk of urban fires in the community. The vegetation distribution, structure, and composition will influence fire behaviour, which could have detrimental impacts in the residential structures. Thus, prescribed fire programs are required to reduce the wildland-urban interface risk (District of Sparwood 2006). Furthermore, the mine closure plan should avoid narrow reliance on historical disturbance patterns. The climate risk analysis will provide information to guide decision makers to define the diverse plant species required when revegetating, where the selection of seed adapted to the altered climates in the next decades will play a critical role (Haughian et al. 2012).

Finally, the transition when the mine life comes to an end can be challenging in terms of local economic development. One exposed group is community residents and mine workers whose livelihoods rely on the outdoor business activities (i.e., tourism, hunting, and fishing). The effects of extreme precipitation events on restored areas could adversely affect natural and human systems with contaminated water. Selenium currently affects aquatic biodiversity and habitat for westslope cutthroat trout (Cope et al. 2013), and the CRA-AF also indicates a risk of loss of livelihood diversification due to contamination-related aquatic life degradation. Therefore, the mine closure plan should incorporate economic development plans that contribute to the region’s economic base like fishing opportunities on the Elk River.

7.7 Contribution to closure maturity by closure element

As an evolving activity, innovative mine closure will seek to obtain a self-sustaining ecosystem, supporting the development goals of the region. These aspirations could be achieved by careful planning in the initial stages before operations begin. Most regulations on mine closure and land restoration underline the requirement of restoring the mined landscape to pre-mining conditions and use. However, the results presented here suggest that climate change will alter historical temperature and precipitation patterns, and as a consequence, change local environmental conditions. Therefore, the CRA-AF will provide information and enhance knowledge to improve decisions on mine closure design.

The International Council on Mining and Metals published the Closure Maturity Framework Tool (ICMM 2020) to help mining company members and the mining industry in general to assess the performance of closure management, progressive activities, and closure practices. At the same time, the ICMM's Integrated Mine Closure Good Practice Guide (ICMM 2019b) provides guidance on closure planning and implementation for the mining industry. In these guides, climate change is addressed with a qualitative risk analysis (likelihood and consequences) approach, with climate projections analysis to understand potential impacts on mine closure design. In addition, climate change is only addressed at the mine site level and not with a SES perspective that considers exposures and vulnerabilities at the watershed level. In contrast, this dissertation moves beyond qualitative, mine-level assessments to understand climate risk in the SES with a holistic perspective. The research findings will provide mine closure strategies that support sustainable development in the watershed.

Therefore, this section intends to suggest the contributions by the CRA-AF to inform the closure elements considered in the ICMM tools. This will support decision-makers in applying the CRA-AF to define adaptation strategies in mine closure design. The closure vision and post-closure land use will consider the information developed by the climate risk assessment with an SES perspective. Table 7.16 lists the interactions between the five steps of the CRA-AF and the closure elements suggested in the ICCM tools. See Appendix G for additional detail on the proposed contributions.

Table 7.16 CRA-AF Contribution to Closure Maturity

CRAAF steps **ICMM closure elements**	**Context definition**	**Assess climate risk**	**Adaptation plan design**	**Implementation**	**Monitoring and evaluation of adaptation**
Integration into life of asset planning	✓	✓	✓	✓	
Knowledge base	✓	✓			✓
Closure vision, principles, and objectives	✓		✓	✓	
Post-closure land use	✓		✓	✓	
Engagement for closure	✓			✓	✓
Threats and opportunities including temporary or sudden closure	✓	✓	✓	✓	✓
Closure activities		✓		✓	
Success / closure / design criteria	✓	✓	✓		✓
Progressive closure	✓	✓		✓	✓
Social and economic transition	✓		✓	✓	✓
Closure costs		✓		✓	✓
Closure execution plan	✓	✓			✓
Monitoring, maintenance, and management		✓		✓	✓
Relinquishment / successful transition				✓	✓

Chapter 8: Results: Validation of the Climate Risk Assessment and Adaptation on Mine Closure Framework

After the design of the CRA-AF and its application in the case study (Chapters 6 and 7, respectively), the next step was to assess and receive feedback regarding the proposed framework. To execute this activity, an online workshop and survey was conducted with experts on December 16, 2020, using Zoom. Expert panel members were from the private sector, development institutions, academia, consulting firms, and government (Table 8.1). All experts had experience in one or more of the fields of the mining industry, land restoration, and climate change and are recognised for expertise in mine closure, land restoration, environmental management, and natural resources management. They were selected based on interactions the PhD candidate was able to establish through conferences or webinars. The experts were invited by email. Those who confirmed their participation received a summary of the CRA-AF one week before workshop. From the 20 online invitations sent out, 15 people confirmed their participation, and 5 were unable to attend due to conflicts in their schedule. From the total of 15 people confirmed, 12 attended the online workshop and responded the survey (Table 8.1).

Table 8.1 Group of categories of experts who were invited to and participate in the feedback workshop

Category / Group	Government	Mining industry	Development institution	Academia	Consulting firm
# Invitations	4	4	4	4	4
# Participants	2	3	3	1	3

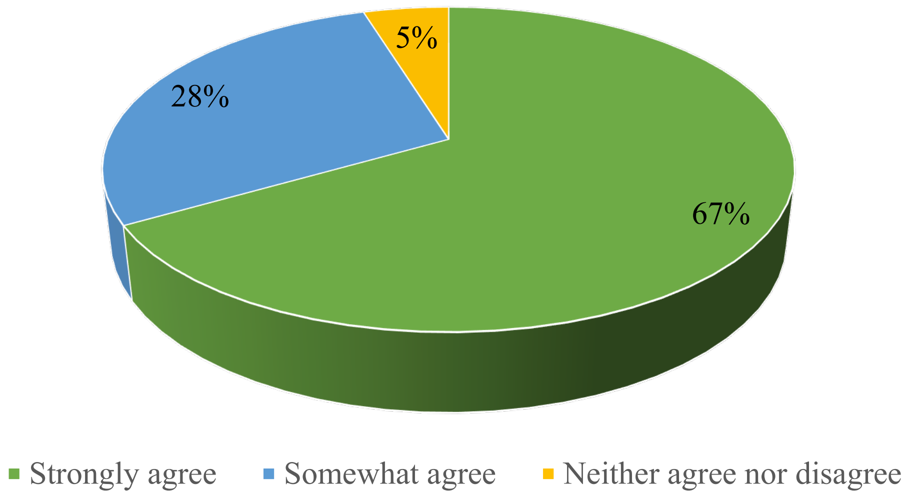
The online workshop comprised a Microsoft PowerPoint presentation describing the CRA-AF and explaining the results of the CRA-AF application in the Case Study. The format followed the online Focus Group qualitative method, including a quantitative online survey throughout the presentation

The two objectives were to: 1) solicit feedback and comments on the overall protocol; and 2) assess perceptions of the methodology and effectiveness of the CRA-AF. To achieve these objectives, participants were verbally asked to select their degree of agreement with statements regarding the CRA-AF. Each participant had 60 seconds to review alternatives and select one anonymously. The following sections present the statements and corresponding answers.

8.1 Scenario analysis

"Is important to consider two RCP scenarios with three specific periods (i.e., 2030, 2060, 2090) to provide accurate risk analysis at local level" A total of 95% of the participants agreed (67% strongly agreed and 28% somewhat agreed) that it is important to use two RCP scenarios with three time periods in the climate risk analysis (Figure 8.1).

Figure 8.1 Degree of agreement on the use of two RCP scenarios for climate risk analysis



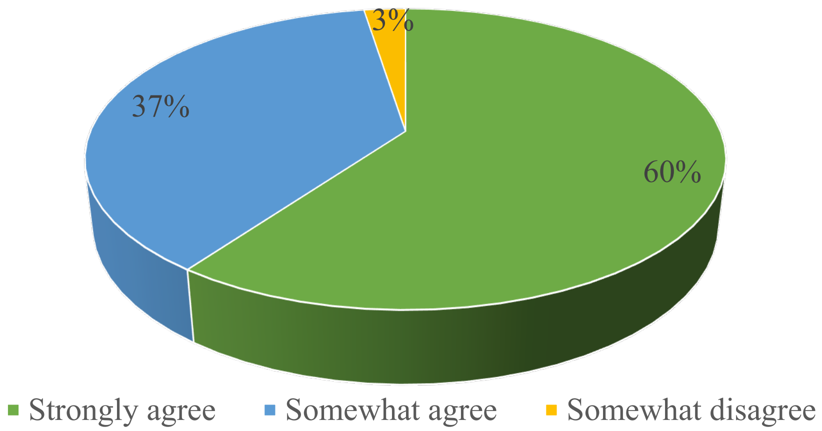
One respondent from the Mining Industry group underlined the importance of the hazard, vulnerability, and exposure concepts to assess climate risk and added that it is sometimes very difficult to quantify the final risk. The participant stressed that "*the important thing with creating risk scenarios is to get to deal with uncertainty.*" The participant also mentioned that "*just doing that, just creating credible risk scenarios takes us 80% of the way to generating our strategies for managing those risks.*" The participant stated, "*I really don't worry too much about getting the numbers right*" in relation to the risk factor. In terms of the importance of the CRA-AF and scenarios to support policymakers and mine managers, the participant stated, "*…what could go wrong and what strategies do you need to deal with*". Therefore, the methodology of the proposed CRA-AF would provide a system to analyse increasing levels of knowledge about climate risk and provide scenarios to decision-makers to begin developing a response.

A participant from the Academia group considered the use of climate scenarios and different time periods in the climate risk assessment to be favorable for understanding soil erosion and sediment deposition for land restoration in mountainous regions. The participant mentioned that "*changes in snow and rain patterns under the different climate scenarios could affect the soil erosion processes*." This is an important idea already considered in the framework that will help understand potential shifts in seasonal patterns through time. The seasonal changes in temperature and precipitation affect soil moisture, river flows, sediment accumulation, evaporation rates, snow cover, water storage level, and other factors.

8.2 Social – Ecological system approach

"Adopting a Social-Ecological Systems approach offers an effective approach for understanding climate risks at the watershed level." 97% of the participants agreed (60% strongly agreed and 37% somewhat agreed) with the effectiveness in applying an SES approach to understand climate risks throughout the watershed (Figure 8.2).

Figure 8.2 Degree of agreement on social-ecological system approach for understand climate risk



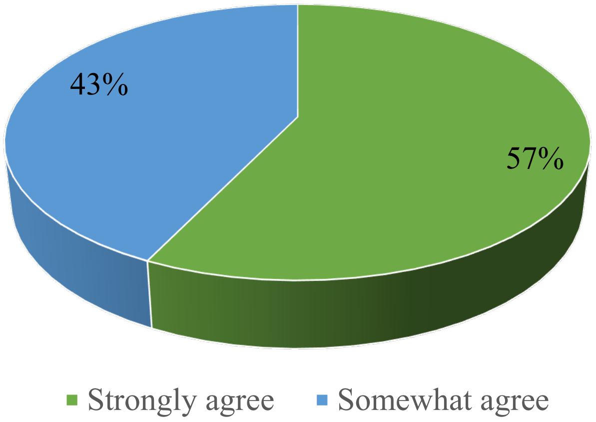
The participant who opposed the idea of adopting an SES approach to understand climate risk at watershed level, considered that "*that sort of mental framework…already exists in the mining industry, the status quo approach for risk in mining sector, which does tend to be probability times consequences*." The participant, from the category of "Consulting firm", considered that the current concepts in the mining industry about risk might be a barrier to adopting a new framework. This is interesting to note, because it would help design future research related to communication strategies and perception analysis within the mining industry.

Another participant from the same category considered that the challenge will be convincing miners and consultants to choose an alternative risk concept: "*the discussion on terms of risk within the mining industry is often brought into cost and capital investment*."

8.3 Assessment of extreme events

"Climate Risk and Adaptation Protocol support the assessment of extreme events affecting the land restoration process". All participants strongly (57%) or somewhat agreed (43%) with this statement (Figure 8.3).

Figure 8.3 Degree of agreement on extreme events assessment support



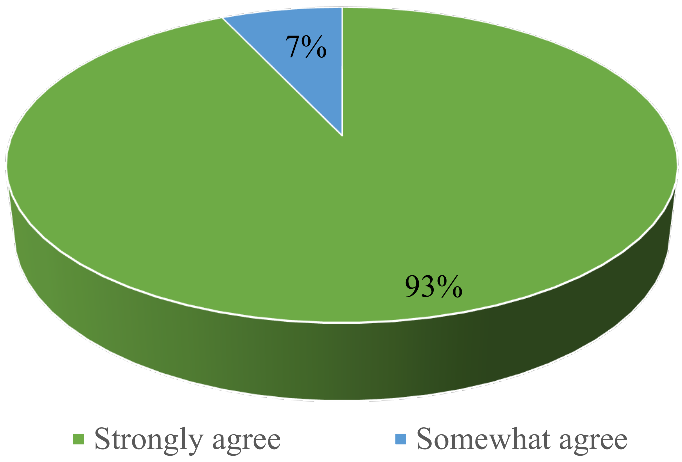
A variety of comments were made about future extreme events in mountainous terrain and changes in precipitation patterns that could be captured by the CRA-AF in support of land restoration design. One participant noted the opportunity to apply the proposed framework to understand potential risks and impacts on permafrost. This is important because temperature changes would increase the permafrost thaw rates and pose a risk to infrastructure in tundra and arctic environments in Europe and northern Canada.

A participant from the group Academia emphasised the interesting approach of the framework to land restoration, because "*extreme climate events would produce soil erosion and sediment deposits in mountainous regions*." Thus, the framework would favor the "*understanding of the relationship between soil properties and different climate scenarios*."

8.4 Climate risk at the mine site and beyond

"For a Mine Closure design with a sustainable perspective, it is important to consider both the climate risk affecting the site and climate risk outside the site." All participants agreed (93% strongly agreed and 7% somewhat agreed) that it is crucial to contemplate the climate risks in the mine site, as well as it is beyond the borders of the operation or area of mining property (Figure 8.4). Thus, this process would provide information to the decision makers for a mine closure design in conjunction with a sustainable perspective.

Figure 8.4 Degree of agreement on considering climate risk in inside and outside the mine site



A participant from the consultancy category noted that, in terms of mine closure facilities management, "*we do not speak any more about probability in risk. So, we do speak about consequential risks*." The participant highlighted the concept of consequence of failure defined in the Dam Safety Regulations and Canadian Dam Association Guidelines, with the importance of considering potential impacts upstream or downstream of a dam as a result of failure. The participant considered that the use of probability on risk for mine closure "*could be said that it's an easier way of dealing with it but is very difficult to have consistency in the analysis*." At the same time, the participant referred to the concept of exposure, "*it is exactly the key aspect that when it came to consequential risk, because that will be the consequences of any failure*." The participant concluded that the definition of risk proposed in this framework is acceptable.

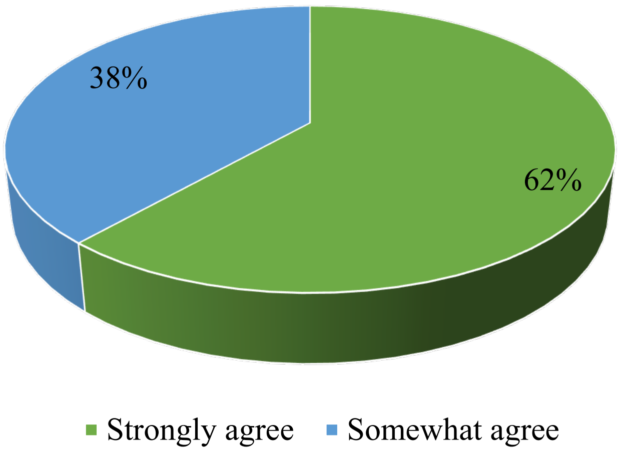
A participant from the group Government emphasised the importance of the proposed framework in terms of analysing climate risk outside the mining operation. The holistic perspective was considered significant because "*indigenous knowledge would be integrated into the risk assessment*" in the vulnerability and exposure assessment.

8.5 Contribution of adaptation plan for mine closure design

"The Adaptation Plan procedure contribute to inform the mine closure and land restoration design". All participants agreed (62% strongly agreed and 38% somewhat agreed) with this statement (Figure 8.5). This demonstrates again that all the participants (100%) agreed on the contribution of the adaptation strategies to the design for mine closure.

During the discussion, a participant from of the category "Development Institution", emphasised that "*is very important to understand what the risks and potential impacts are going to be, and* *then, from there, work towards finding the EbA strategies that would address the specific risks.*" This comment validates the process already established in the CRA-AF, that prioritises a holistic comprehension of the risk because that would determine what the adaptation strategies would be.

Figure 8.5 Degree of agreement on contribution for mine closure design



Another participant from the same category, considered the proposed framework ideal because it offers a "*perspective of an effective intervention by the use of social-ecological systems in the context of mining operations.*" The participant highlighted that the impacts of climate change in mountains would affect social groups and the ecological system. Nonetheless, he expressed the concern based in personal experience that "*mining companies are very focused in itself*" and when social factors need to be managed "*people begin receiving money from mining for a specific period of time.*" This practice is evidence of short-term planning for closure in terms of sustainability.

8.6 Validation Process Summary

A panel of 15 experts was invited to evaluate the applicability of the CRA-AF, based on the case study results and their own experience, through providing independent feedback. All of the participating experts have experience in one or more of the fields of mining industry, land restoration, and climate change and are recognized for expertise in mine closure, land restoration, environmental management, and natural resources management. They were able to express their views and provide argumentation of their opinion related to potential benefits associated with the newly developed CRA-AF. The validation was performed through an online focus group discussion and completing a subsequent questionnaire.

After the presentation of the framework and group discussion, the experts were asked to select their degree of agreement with statements regarding the CRA-AF. Each participant had 60 seconds to review alternatives and select one anonymously. The process led to identifying feedback and comments on the overall framework and assess perceptions of the methodology and effectiveness.

The validation step emphasized the importance of considering two RCP scenarios with three specific periods to assess the local climate risk. This procedure supports dealing with the associated uncertainty of magnitude and likelihood that may change in the future due to changes in the social-ecological system. Therefore, CRA-AF would provide a system to analyze the evolving knowledge and developments related to the mining industry and climate changes, such as the potential shifts in seasonal patterns through time. This offers information to decision-makers to begin developing adaptation responses.

The use of a social-ecological system approach was considered effective to understand climate risks throughout the watershed. All the experts supported the concept to contemplate the climate risk in the mine site and outside the mining property. In this way, the framework provides information for a mine closure design in conjunction with a sustainable perspective. Nonetheless, some questions were raised regarding the potential adoption by the mining industry of this new method, due to the status quo approach for risk management (which only looks at likelihood/consequence). Therefore, a key contribution of the CRA-AF to the mining industry is the definition of climate risk applying the hazards, vulnerabilities, and exposure factors based in IPCC. Moreover, the challenge to move the climate risk beyond cost and capital investment makes an interesting potential future research on risk perception analysis within the mining industry.

The experts discussed the importance of considering potential climate change impacts upstream or downstream the watersheds, mentioned that CRA-AF holistic approach will support this value. Emphasis was received for the exposure concept that is already considered in the CRA-AF. The exposure analysis is a key characteristic to understand the consequence of any potential failure due to extreme climate events in the social-ecological system. Additionally, the holistic perspective was deemed significant due to the integration of the local community's knowledge in the adaptation strategies decision process.

Besides the application of the CRA-AF in support of land restoration design in mountainous regions, the experts identified an opportunity to use the framework to increase the knowledge on potential risks and impacts on permafrost areas. This is an interesting point due to projected increases in permafrost thaw rates, which could result a risk to mine infrastructure in the tundra and arctic environments. Thawing will not only lead to risk in the design and construction but in the operation with potential mine infrastructure instabilities.

The validation contributed towards a better understanding of the climate risks associated with mine closure design through a review and judgment process by an expert panel in mine closure and ecosystem adaptation strategies. The participants highlighted that the impacts of climate change in mountains would affect social groups and the ecological system, and that the proposed framework provides a potential solution to improve the identification and adaptation of these associated risks.

Chapter 9: Conclusions, Contributions, and Future Work

9.1 Discussion

Climate change is an inherently complex problem with a wide range of factors affecting the ecosystem and human society at different spatial and temporal scales and magnitudes. The mining sector plays an important role in mitigation efforts because it provides the minerals for green energy and global decarbonisation demand. However, the local effects of extreme climate events, such as flooding, drought, and wildfires, are also beginning to directly influence the activities of mining operations worldwide. These effects have implications across the entire mining life cycle; however, in this dissertation, it has been argued that the mine closure stage has not yet received adequate attention regarding the potential impacts of climate extremes and their possible management alternatives. The dissertation demonstrates that the CRA-AF may be appropriate to address this gap and contribute to improved design and management throughout the land restoration process.

This thesis topic was triggered from many years of applied practical experience within the extractives industry. After 18 years of working within the sector, I decided to resign from a management position in a large mining company and embark on my PhD. As mentioned in Chapter 2, I made this decision because I felt that the mining industry is not giving adequate attention to the full extent of risks posed by climate change and the impact that these would have on the mine closure process. Moreover, when developing plans for mine closure and reclamation, I had observed that many mining companies based their planning on general concepts and would not compromise beyond what was required by government regulations and other standards (e.g., investor requirements, expectations from industry associations). When I questioned this approach, the perception among colleagues at the operational level was that it was not necessary to do an in-depth analysis. Rather, it was sufficient to define a budget for future closure management because the corporate level did not require further details. My objectives in embarking on this PhD were to provide empirical data regarding the importance of climate risk, reasons why it should be explicitly considered during mine closure design, and an understanding of the mechanisms to adapt land restoration processes to potential impacts of extreme weather.

The mine closure and land restoration process from mining activities exposed to climate risk in mountainous regions was selected as the focus of this dissertation because of the strong presence of mining activities and the vulnerability of social and ecosystem groups in these areas. Moreover, mountains are considered “water towers,” from which most of the world’s rivers and freshwater systems originate. Thus, the fragile connection between headwater regions and downstream communities and ecosystems makes the research topic one of great interest for the mining industry in terms of sustainable development support beyond the life of mine. Despite their importance, mountainous watersheds are among the least studied regions in relation to climate adaptation (Björnsen Gurung et al. 2012).

The 2016 Paris Agreement committed signatories to reduce global CO2 emissions. In the same way, various industries globally have expressed the urgency of reducing GHG emissions and being able to contribute to mitigation processes. The mining industry also commented on the CO2 mitigation plans and in general, indicated that they would support this process. However, there was no clear position in the mining industry as to specific details on what the contribution or management would be. It was only in 2016 that the Church of England began the process of asking companies (e.g., Anglo American, Rio Tinto, Glencore) where their funds were and what actions they were taking to reduce GHG emissions (The Church of England 2016). Similarly, several investors in the extractive industry have begun to ask companies to reveal information about the work they are doing to contribute to the Paris Agreement commitment.

Among the stages of the mine life cycle, mine closure has always been considered less relevant to corporate management, primarily because it does not generate a direct financial return. As mentioned in Chapter 2, many companies focus only on aspects of regulatory or corporate compliance such as ensuring physical and chemical stability and generating a general socio-economic plan for end land use. Opportunities to restore the soil so that it continues to promote sustainable development of the human population and ecosystem are not routinely considered (Worrall et al. 2009). It is therefore not surprising that the mine closure stage is not evaluated against the potential risks of climate change. This issue is even more critical when mining occurs in extremely fragile terrain, such as mountainous systems. When land has not been restored, it will lose its capabilities to generate benefits to the ecosystem. Poorly managed soil restoration and watershed management can have catastrophic consequences for the environment and society.

This dissertation presented a top-down and bottom-up approach to comprehend how climate risk affects the mining sector. The top-down analysis presented in Chapter 4 investigates the current global approach of mining companies and corporate strategies for climate risk analysis and management. The trend analysis in this chapter provided evidence that, from a corporate perspective, the mining industry is mainly focussed on climate mitigation, strategies for GHG reduction, and pathways for transitioning energy systems towards renewable technologies.

Chapter 5 highlighted the main climate-related risks faced by the mining sector and potential adaptation strategies for land restoration processes. The bottom-up analysis was performed at the local level with the CRA-AF introduced in Chapter 6. Application to a mine site as a case study (Chapter 7) provided evidence on how the local climate risk and extreme events would affect the mine closure design. This evidence suggested that climate change and consequent impacts are not considered in for mine closure design. The novel proposed framework provides the opportunity to adapt the mine closure design and plan accordingly to reduce the potential negative effects of climate change (e.g., more frequent and more severe wildfires, habitat shifts, water pollution, and biodiversity reductions).

Chapter 2 suggested that international guidelines and industry standards for mine closure mention the climate change risk from a general perspective, without suggesting best practices or applicable methodologies. The unique risks from climate change impacts are not necessarily given sufficient focus in current guidelines. The trend analysis in Chapter 4 showed that most of the top 10 mining companies studied recognised that climate change would affect their industry in all stages, and it is a risk that is currently highly relevant. Nonetheless, the companies noted that there is still uncertainty surrounding the impact levels and how they will affect different regions in the long term. Given a lack of concrete guidelines for climate change management in the sector, there is an urgent need to incorporate climate risk assessment practices and adaptation strategies that can support an approach to design sustainable mine closure plans. Therefore, as mentioned in Chapter 4, these challenges would require transformation of business strategies, investment in new technologies, and more support for research.

This study found that, while some companies began to assess climate risks and establish internal policies for managing GHG more than 10 years ago, this is not a common practice, and the majority of companies are just beginning down this path. Moreover, the current trend is for mining companies to manage climate risk from a financial risk perspective, based on climate physical impacts, climate policies, carbon taxes, and new technologies. The mining sector is still in the process of reviewing and learning how to adapt to climate change impacts. Importantly, a notable gap was identified in the analysis of the mine closure stage and of the possible risks generated from climate change.

A common thread in the research completed through this dissertation, including the literature review, company benchmarking, the expert survey, and the case study, is that the mining industry faces a serious risk from global climate change as it relates to the hydrological cycle and water resource access. The analysis in Chapter 4 provide additional supporting evidence that water is the most significant resource for operations and in the watershed because water availability changes with the seasons and seasonal patterns are projected to change (e.g., earlier spring with more rain than snow in the mountains). In line with this result, more than 67% of the risks reported by mining companies involved water-related infrastructure. For example, tailings ponds and dams were key concerns because initial designs often did not consider the potential risks of future climate variability. Furthermore, the analysis of future climate scenarios for the case study in Chapter 7 illustrates the significance of potential consequences throughout the watershed and the associated implications for land restoration after the life of mine.

The panel of experts analysed in Chapter 5 considered that the extreme climate events would produce very significant impacts on the watershed ecosystem in the mine closure stage if an infrastructure related with water management were to fail. Similar with the findings in Chapter 4, the largest impacts would be on water management infrastructure, tailing management facilities, and drainage channels. These risks will be associated with the potential increase in precipitation and modification of the landscape structure in the sites. Therefore, water-related structures may need to be redesigned to manage more water during the mine closure stage.

Changes in hydrological systems have the potential to increase social conflicts between companies and communities due to water quality and quantity diminution. The situation has the potential to be exacerbated with mining expansion, abandoned and legacy sites that continue to pollute water systems, cumulative negative effects along the watershed, transboundary water impacts, shrinking habitat for aquatic life, and impacts in the biodiversity and on the livelihood of people living in mountainous regions. Improved understanding of potential climate risks at a local level is therefore important to support decision-makers to incorporate adaptation strategies in the mine closure plan, and in turn, contribute to the long-term development of societies in these regions and associated SESs.

The results in Chapter 5 suggested that the kinds of practices that could facilitate adaptation to climate change risk in mountainous watersheds during the mine closure stage and reduce adverse effects for land restoration require the development of an integrated watershed management approach that considers long-term adaptation plans. This highlights the importance of understanding cumulative effects and implementing future land uses that can withstand extreme weather events as an adaptation strategy. As noted by Schreier (2017), integrated watershed management is not yet applied worldwide. Thus, the opportunity for the mining industry to promote use of this strategy will increase water stewardship benefits while incorporating local knowledge for adaptation.

The Delphi survey results suggested that areas with drought risk and long dry periods would limit vegetation growth in restored areas. Vegetation patterns and growth rates and the soil moisture regime would also be affected. The removal and disturbance of topsoil during mine development results in loss of organic content and water retention capacity. These findings were confirmed in the case study in Chapter 7, where the use of current native species for revegetation would not support the expected restored habitat. Instead, understanding the shift in biogeoclimatic zones due to climate change will help determine the species of vegetation that should be used to restore a specific area. This determination is critical: the time required for forested habitat restoration is approximately 60 years after seeding (District of Sparwood 2006). Therefore, the selection of plants and seeds species for revegetation should be done considering the future change of climate, rather than choosing species based on historical presence in the area of interest.

To achieve long-term, sustainable land restoration, including revegetation and habitat restoration, a robust and informed planning process is required that includes local climate risk management strategies. Currently, the general practice is to consider the detailed closure plan as something that will be defined later, near the end of the life of mine. The evidence in Chapter 4 suggests that corporations and mine sites lack the capacity to identify climate hazards and to define management strategies because the decision team is not interdisciplinary, or the corporate management team does not consider the entire risk comprehensively. Moreover, the knowledge of experts at the mining sites and operations is not always heard or put into practice at the corporate level. Corporate decisions are focused on market requirements in a reactive way. In other words, the actions that take place stem from external pressure, not from an internal proposal for change. Decision making in the mining sector is very slow, and most of the changes occur after negative impacts have been generated.

At the same time, this study suggests potential opportunities for climate change adaptation strategies for closure of mines located in mountainous regions. These relate to the development of proactive strategies to address vulnerabilities and enhance ecosystem services for the benefit of communities surrounding the operations and downstream. Strategies could include infrastructure to manage water supply, habitat management, and restoration of aquatic species to improve biodiversity capacity. Therefore, mountain landscape restoration strategies have a significant role to play, facilitating the management of degraded land and reducing the potential risk of natural disasters. Prioritizing EbA strategies with the use of ecosystem services can boost watershed health, improve mine closure design, and contribute to reclamation management, causing a transformative change towards sustainable pathways.

Chapter 6 presented the CRA-AF, which was designed based on 1) natural disaster risk protocols applied by various cities worldwide to understand the impacts of climate events on public infrastructure and 2) results of the Delphi survey with the expert panel. In the last decade, cities worldwide have established climate change management plans and protocols to assess their risks.

These were designed in response to natural disasters (e.g., cyclones, wildfires, landslides) that caused property damage, morbidity, and mortality. The protocols focus on the capacity of infrastructure to cope with the extreme events; thus, infrastructure is a good starting point to evaluate similar situations for mining infrastructure. Learning from municipalities and public infrastructure management, would provide the mining industry the knowledge to plan for future land uses while considering local society development goals. The mine closure stage requires going beyond infrastructure to consider land, waterways, natural habitats, and socio-economic perspectives. This is especially important because mining operations are often located in vulnerable ecosystems, and an infrastructure failure will have far-reaching downstream effects (Concha et al. 2017). Therefore, CRA-AF will contribute to assessing mine closure component responses to impacts of climate change by incorporating a social and ecological perspective with EbA strategies.

As stated in Chapter 3, the disaster risk assessment methodology applied to public infrastructure and municipal services is convenient for understanding the impacts of natural hazards on the serviceability and functionality of the public system. In Chapter 6, these concepts were applied to the structural and operational features of the closure components at the mine site level to assess hazards that originate in the mine site as a result of the climate extreme events. These hazards are defined by the combination of the probability of occurrence for a climate event and the severity or expected consequence of the mine closure component response when a climate event occurs. In the impact analysis, the cities protocol does not necessarily consider SESs that are outside the municipal area. However, these areas are highly relevant for mining operations, which affect areas beyond the mine site. The proposed framework takes the SES as the basis to analyse potential impacts of climate change related to the mine closure design. Therefore, the climate risk understanding included the impact analysis of the hazards from the mine site to the collective vulnerabilities and the exposure on the ecosystems in the watershed. This approach to climate risk assessment blends engineering and social and environmental science, resulting in a resilient design for mine closure.

The case study presented in Chapter 7 suggested that climate change will intensify local weather extremes (e.g., droughts, wildfires, floods) and affect mine closure components. However, it is important to consider that the type, magnitude, and frequency of extreme events will be related to the local geography for each mine site. For instance, the potential climate extreme events will differ between a mine located in the Canadian Rocky Mountains one in the Andes Mountains. The former is wet and cold year-round, and the latter is dry and hot. In addition, exposures and vulnerabilities will differ among watersheds surrounding mine sites because each social – ecological system is unique. The case study results illustrate how a restoration program on mountainous land could be designed from a holistic perspective that provides an understanding of all watershed components. This point of view will provide adaptation strategies for specific local characteristics of extreme climate events. Moreover, resources use would be very efficient through the integration of water and soil conservation, local capacity building, and economic diversification. For instance, watershed management to improve water quality requires collaboration between mining companies, community members, local businesses, local and national government agencies, and other actors in the watershed.

When assessing how an EbA approach could contribute to mine closure practices at the watershed scale, this dissertation found evidence that the climate risk management strategy based on the use of ecosystem services has social and ecological foundations that requires understanding of the local context. Moreover, the knowledge should not be based on history, but on the future potential paths the SESs would have, including a growing population, urban development, livelihood strategies, and habitat shifts. While observed historical data can be used to investigate trends, global climate models are most often used to predict future impacts of climate change. Thus, interactions between hazard, vulnerability, and exposure elements should be assessed with different GHG concentration trajectory scenarios and their local climate effects.

As presented in Chapter 7, the regulatory functions of ecosystem services are particularly critical to protect downstream areas in the watershed, where the effects of potential hazards are often greatest when they come from modified land upstream. The risk could increase when these changes result from mining activities, and management strategies are not in place. For instance, acid rock drainage or mine leaching from waste rock dumps that has accumulated in creeks could be washed into main watercourses by heavy rain, with negative consequences for aquatic life on the river. Careful planning that considers the ecosystem services provided by vegetation would reduce runoff, control sediments, and improve water quality.

The relationship between mine closure and EbA strategies to reduce the impacts of climate change has received little attention by researchers, as has the use of ecosystem services to define adaptation strategies to consider in mine closure. This is because conventional approaches to mine closure usually involved decommissioning the remaining infrastructure and defining actions to safeguard insecure areas of the former operations. Nonetheless, the mining industry's commitment to supporting sustainable development creates an opportunity to work towards the use of techniques to enhance ecosystem services in the SES.

Chapter 7 suggested that application of the CRA-AF is useful to define strategic updates for current mine closure plans in the case study. The results recommended actions to reduce the impacts of extreme events and climate change, while enhancing the use of ecosystem services. These actions will support the goal of sustainable development, allowing resources to be allocated where needed. This is in line with the argument from Pearce et al. (2009) that the long-term success of mining companies will be related to their ability to manage climate change. For instance, tree species selected for the projected biogeoclimatic zone will be able to grow locally, while provide forest habitat, shade, and cooling effect; restored grasslands on slopes would enhance water quality for drinking water supplies and prevent floods and droughts due to water infiltration; wetlands would reduce surface runoff, filter contaminants from runoff, and provide habitat for a variety of wildlife species.

The case study confirmed that climate change will alter seasonal temperatures (i.e., early spring) with the possibility to affect surface and ground water volume. This seasonal shift would increase competition for water among economic sectors (i.e., mining vs agriculture) and stakeholders in the watershed (i.e., drinking water). The climate risk analysis supported by RCP scenarios provide projections on water availability for different time periods that are very useful for decision-makers during mine closure design. Similarly, the CRA-AF supports an effective long-term design and provides understanding for planning essential activities. In accordance with comments in the validation workshop presented in Chapter 8, learning how climate change effects develop and how risk can be reduced is sometimes more important than the quantitative results of an assessment.

As mentioned in Chapter 7, community knowledge and participation in mine closure design and monitoring will help sustain restoration activities. Local knowledge is based on deep experience, cultural values, and direct interactions with the ecosystem over several, and historic data that is shared verbally among generations. Community involvement supports climate risk assessment with a holistic perspective on the SES. Moreover, the flow of information supports land restoration with adaptive management, promoting communication and exchange of knowledge from local to national authorities, thereby improving policy design.

As noted in Chapter 3, the isolation measures imposed partway through the research schedule due to COVID-19 prevented field activities. The collaborating company suggested the use of publicly available information: this alternative was chosen along with online meetings, surveys, and synchronous online interviews. This change was managed as an opportunity to learn more about research methodologies. For instance, the final validation workshop presented in Chapter 8 was executed online with a panel of experts on mine closure and climate change adaptation. The use of audio-visual interactivity and textual synchronicity allowed the researcher to seek clarification and follow the ideas of discussions among participants. Online interviews also allowed participation from a wide geographic range, avoiding the time and cost of travel. Compared with past personal experience leading in-person workshops or focus groups, a disadvantage of the online meetings is the limited number of participants. Defining a small group to avoid distractions and maintain participant attention is recommended.

Finally, assessment of the climate risk for mine closure design requires looking beyond the mine site boundaries to consider SES frontiers. The CRA-AF improved our understanding of the SES interactions to define HOW and WHY something changed. This perspective will provide a genuine analysis to identify the path of risk from an extreme event within the context of hazards that originate in the former mining operation. The risks of extreme climate impacts are the consequence of interactions between a hazardous event and the vulnerable community and ecosystem exposed in a given watershed area. It is important to reflect that vulnerability should understood within the social context, rather than being focused on the physical effects of mine infrastructure. The dissertation demonstrated that the application of EbA strategies would contribute to a sustainable approach to mine closure and land restoration. Consideration of ecosystem services in mine closure design will contribute to a healthy ecosystem in mountain watersheds with the resilience to adapt to climate change impacts. Further, it will improve soil restoration practices and build local capacity to understand and manage climate risk.

9.2 Conclusions

Global environmental crises require transformative approaches to risk management. Combining climate risk assessment practices with ecosystem-based adaptation strategies will support an approach to designing sustainable mine operations with a focus on closure and land restoration plans. Mine closure designs must consider the potential future impacts of climate change at the mine site and surrounding watershed and communities. The design criteria must reference the most recent climate risk assessment to provide updated information and early indicators of remedial work needed to maintain the closure plan. The dissertation confirmed that when the mine closure plan aims at ecosystem health, it contributes to protecting against natural hazards and the impacts of extreme events, particularly hydrological events such as floods and droughts. The novel CRA-AF tool supports and informs mine closure design with a sustainable development perspective. The dissertation highlights the following:

- In recent years, concerns related to climate risk and potential impacts on the mining industry have increased at the management level based on shareholder concerns, rather than internal strategic planning goals. Therefore, it is critical for site management to proactively incorporate analysis of potential future climate risk impacts in sustainable business development plans.
- Current climate risk management primarily focuses in GHG reduction and mitigation actions associated with potential financial and investment impacts. Adaptation strategies have received limited attention. Therefore, a clear understanding of climate risk management requires incorporating adaptation strategies in the design of operations and mine closure.
- There is a consensus between experts that water is the most critical resource that will be affected by climate change. Thus, water strategies and water infrastructure should be reviewed to design mine closure from an integrated watershed management perspective.
- Climate risk needs to be understood at the watershed level with a holistic perspective that incorporates SES vulnerabilities and exposure to climate hazards affecting the mine site. Therefore, a climate risk chain will support analysis of cause-effect of the extreme events in communities and ecosystems related to mine, help elucidate interactions, and facilitate identifying adaptation measures.

- The novel CRA-AF will help mine closure practitioners understand the gaps and potential local climate risks associated with land restoration. This will allow decision-makers define adaptation strategies to support climate risk management.
- The elements that constitute climate risk are beyond traditional concepts of likelihood and consequence. Mine closure design requires incorporating a holistic understanding of climate risk as the convergence of local hazards, vulnerabilities, and exposure elements. This understanding will support a sustainable design for land restoration.
- The increased frequency and severity of extreme events will affect key aspects of the restoration process like biodiversity, revegetation patterns, and water access. Analysis of future climate scenarios will define potential effects of land restoration during the long term.
- The use of local ecosystem services will support the adaptation strategies to cope with climate change risk, supporting the livelihood of local human and natural communities.
- Many mining companies erroneously view the consequences of climate change as far in the future and irrelevant to the mine closure decisions in the present day. The use of climate scenario analysis is highly recommended: it can project data to investigate climate change impacts at various time scales into the future.

9.3 Contributions

This study is relevant to advancing our understanding of climate risk analysis and extreme event management for land restoration in the mining industry and to supporting the selection of EbA strategies for mine closure design.

There is a deficit in the academic literature, including mining journals, in terms of what is known about climate change impacts and possible adaptive responses for mine closure design in mountainous regions. This study opens a dialogue to consider climate risk assessment beyond mine infrastructure impacts to encompass impacts on communities and ecosystems in the watershed. At the same time, it encourages the academic conversation related to the importance of the inter-disciplinary studies to provide solutions and alternatives in the mining industry, with a common sustainability objective.

The proposed novel framework assesses climate risk in mine closure design by the interrelationship between hazard, vulnerability, and exposure through a SES perspective, with the aim to pursue sustainable development. This will help the mining industry revise current mine closure plans and define adaptation strategies for climate risk. At the same time, effective understanding of the risks that climate change poses for mining operations and their mine closure stage supports decision making by regulatory agencies. This would provide criteria and a holistic perspective for the development of policies related to mine closure.

9.4 Recommendations for Future Work

Based on this study, the following areas are suggested for future research:

1. The proposed CRA-AF was applied in a case study where the mine operation has a direct relationship with one community in the watershed. Potential cumulative effects from other economic activities in the watershed should be studied in the context of extreme events and natural hazards.

2. Analysis of local vulnerabilities and exposures in relation to hazards from the mine provides important landscape data at both temporal and spatial scales, which could be subjected to geospatial data analysis to produce practical, visual representations of the data. This would help to bridge the gap in technical science knowledge among stakeholders and enhance their ability to contribute to integrated watershed management.

3. Reducing the uncertainty of local climate change risks requires continuous monitoring to support projection analysis at the watershed scale. For mining operations located in remote mountain locations, monitoring programs are logistically challenging, and the lack of data could threaten this process. It is recommended that future research uses telemetric sensors combined with publicly available satellite imagery and machine learning protocols to monitor the quality and quantity of ecosystem services. Predicting the occurrence of risks in advance will help mining companies prepare responses to hazards and support adaptation strategies within the SES.

4. The dissertation demonstrated that applying EbA strategies can contribute to sustainable mine closure and land restoration design. This alternative approach uses natural solutions instead of traditional infrastructure. It is recommended that additional research assess the economic costs and financial benefits of the EbA approach for mine closure to the entire SES, rather than just to the mine company.

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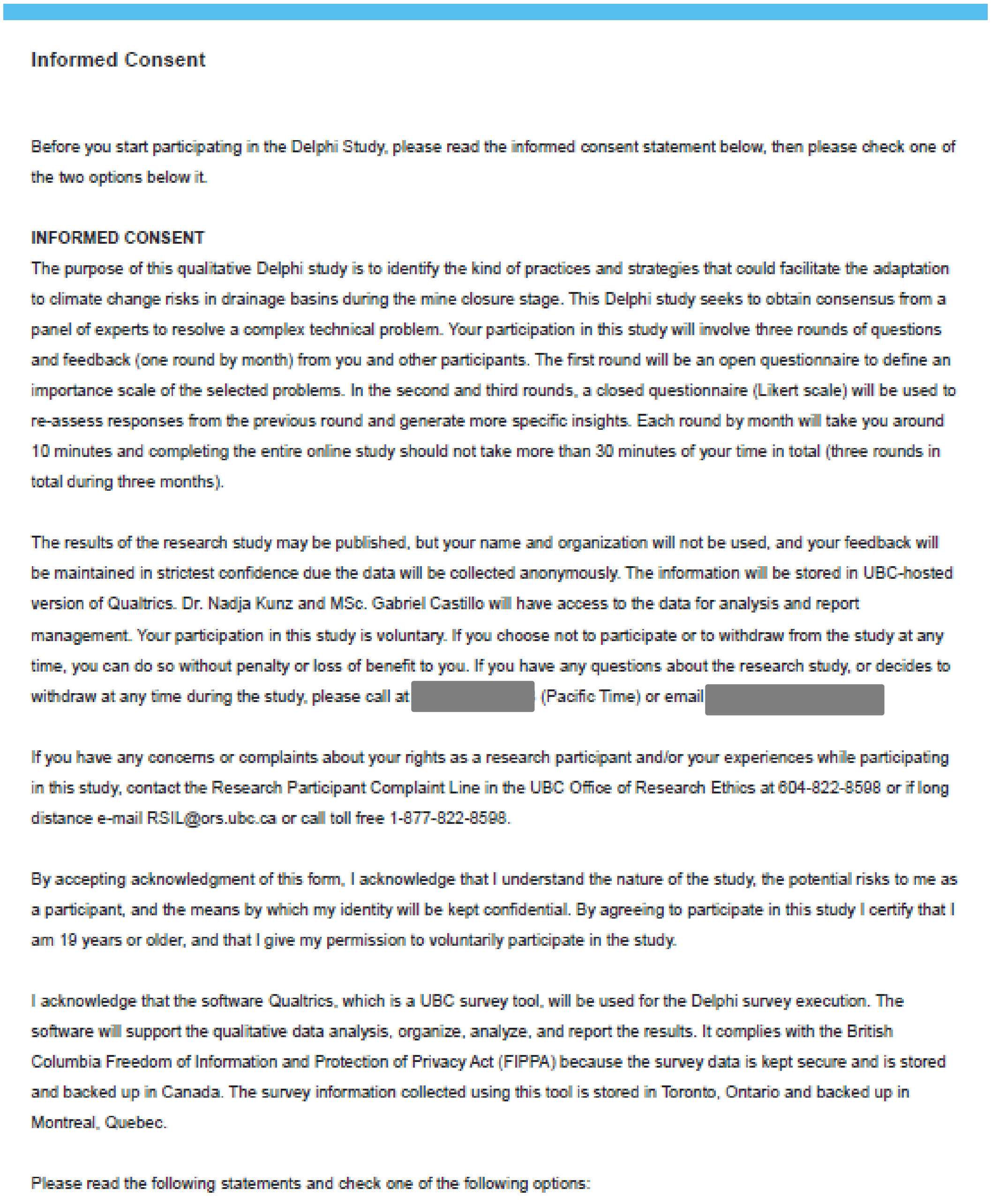
Appendices

Appendix A - Delphi Survey

A.1 First Round Questionnaire



Informed Consent

Before you start participating in the Delphi Study, please read the informed consent statement below, then please check one of the two options below it.

INFORMED CONSENT
The purpose of this qualitative Delphi study is to identify the kind of practices and strategies that could facilitate the adaptation to climate change risks in drainage basins during the mine closure stage. This Delphi study seeks to obtain consensus from a panel of experts to resolve a complex technical problem. Your participation in this study will involve three rounds of questions and feedback (one round by month) from you and other participants. The first round will be an open questionnaire to define an importance scale of the selected problems. In the second and third rounds, a closed questionnaire (Likert scale) will be used to re-assess responses from the previous round and generate more specific insights. Each round by month will take you around 10 minutes and completing the entire online study should not take more than 30 minutes of your time in total (three rounds in total during three months).

The results of the research study may be published, but your name and organization will not be used, and your feedback will be maintained in strictest confidence due the data will be collected anonymously. The information will be stored in UBC-hosted version of Qualtrics. Dr. Nadja Kunz and MSc. Gabriel Castillo will have access to the data for analysis and report management. Your participation in this study is voluntary. If you choose not to participate or to withdraw from the study at any time, you can do so without penalty or loss of benefit to you. If you have any questions about the research study, or decides to withdraw at any time during the study, please call at [redacted] (Pacific Time) or email [redacted]

If you have any concerns or complaints about your rights as a research participant and/or your experiences while participating in this study, contact the Research Participant Complaint Line in the UBC Office of Research Ethics at 604-822-8598 or if long distance e-mail RSIL@ors.ubc.ca or call toll free 1-877-822-8598.

By accepting acknowledgment of this form, I acknowledge that I understand the nature of the study, the potential risks to me as a participant, and the means by which my identity will be kept confidential. By agreeing to participate in this study I certify that I am 19 years or older, and that I give my permission to voluntarily participate in the study.

I acknowledge that the software Qualtrics, which is a UBC survey tool, will be used for the Delphi survey execution. The software will support the qualitative data analysis, organize, analyze, and report the results. It complies with the British Columbia Freedom of Information and Protection of Privacy Act (FIPPA) because the survey data is kept secure and is stored and backed up in Canada. The survey information collected using this tool is stored in Toronto, Ontario and backed up in Montreal, Quebec.

Please read the following statements and check one of the following options:

- If you select the first option, you will participate in the survey.
- If you select the second option, you will NOT participate in the survey.

Informed Consent (Select One):

○ I understand the above statement and GIVE AUTHORIZATION for my responses to the Delphi panel to be used in this research study.

○ I understand the above statement and DO NOT GIVE PERMISSION for my responses to the Delphi panel to be used in this research study.

Not take survey

We are sorry you decided not to be part of this survey in Climate Change Adaptation Strategies. If you change your decision, please let us know as soon as possible at Gabriel.Castillo@ubc.ca
Thank you.

Section I - Demographic Information (Please select one of the options)

Section I - Demographic Information (Please select one of the options)

1. Participant Location

○ North America
○ South America
○ Europe
○ Asia Pacific
○ Africa

2. What is your gender?

○ Male
○ Female

3. In what type of field/organization are you working?

○ Academia
○ Mining industry/ Association

○ Institution/ Organization

○ Other (specify) ☐

4. Years of experience in climate change or related to the field?

○ 7 - 10 years

○ 10 - 20 years

○ 20 - 30 years

○ 30 - more years

5. What is your current position? (select the option that best show your current position)

○ Full professor

○ Assistant professor

○ VP - Director

○ Senior Manager

○ Manager - Head of Area

○ Superintendent – Officer

○ Other (specify) ☐

Section II - Research General Questions

Section II - Research General Questions

Please answer the following question based on your opinion and expertise concerning climate change adaptation strategies, focusing on watersheds in mountainous regions during the mine closure or land restoration process. **Please keep in mind that we will develop a list of common responses and send these to you for a second survey where we will ask you to rank these based on their likelihood.**

a. What *effects* might climate change pose to watersheds in mountainous regions?

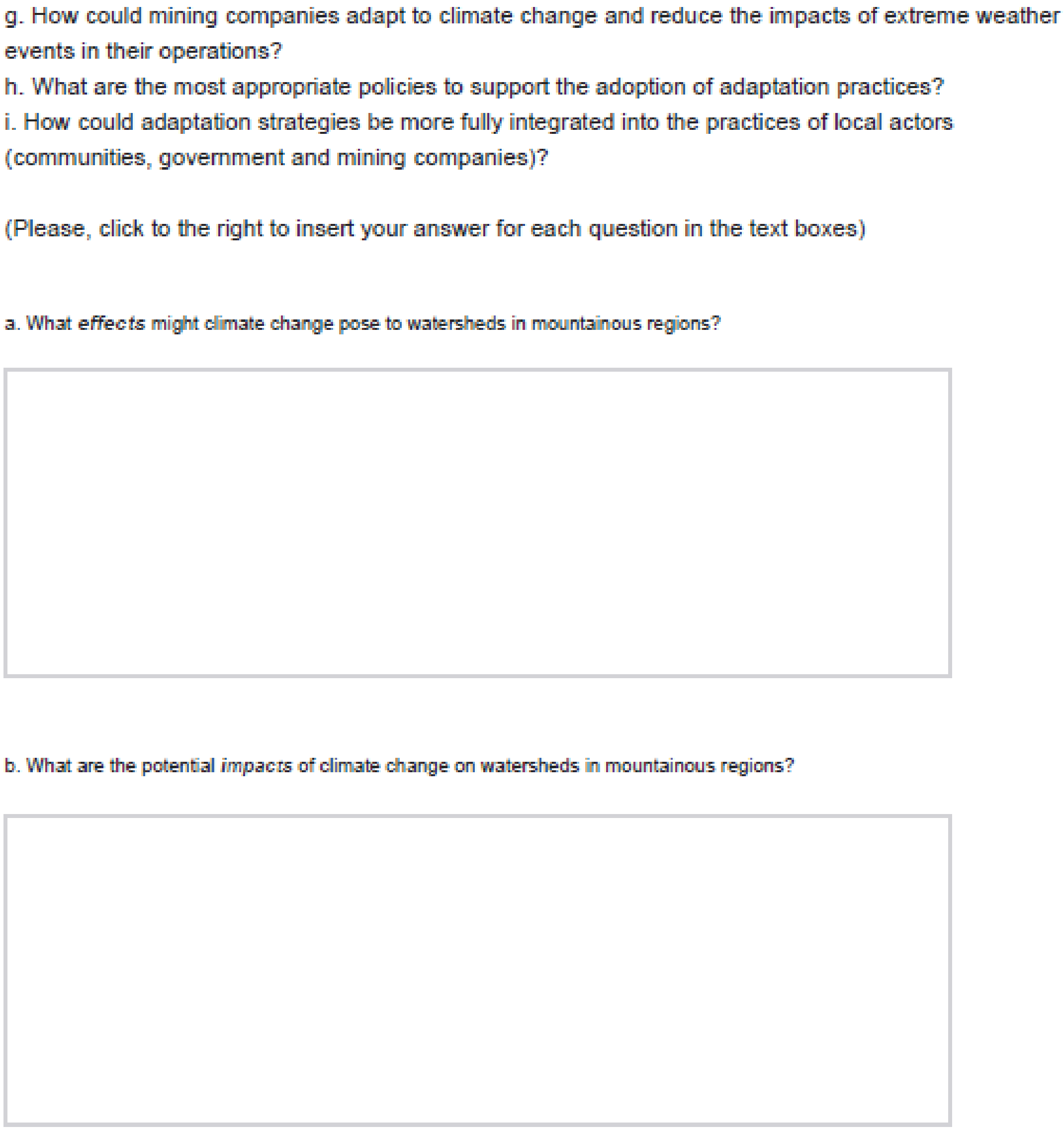
b. What are the potential *impacts* of climate change on watersheds in mountainous regions?

c. Which type of infrastructure in the mining operations might be impacted by these climate changes?

d. How could climate changes affect mine closure stage or land restoration process?

e. What general *Adaptation Strategies* are needed to adapt to overall climate changes in mountainous regions watersheds?

f. How could local communities in mountainous regions adapt to climate change and reduce the impacts of extreme weather events in the watersheds?



g. How could mining companies adapt to climate change and reduce the impacts of extreme weather events in their operations?

h. What are the most appropriate policies to support the adoption of adaptation practices?

i. How could adaptation strategies be more fully integrated into the practices of local actors (communities, government and mining companies)?

(Please, click to the right to insert your answer for each question in the text boxes)

a. What *effects* might climate change pose to watersheds in mountainous regions?

b. What are the potential *impacts* of climate change on watersheds in mountainous regions?

c. Which type of infrastructure in the mining operations might be impacted by these climate changes?

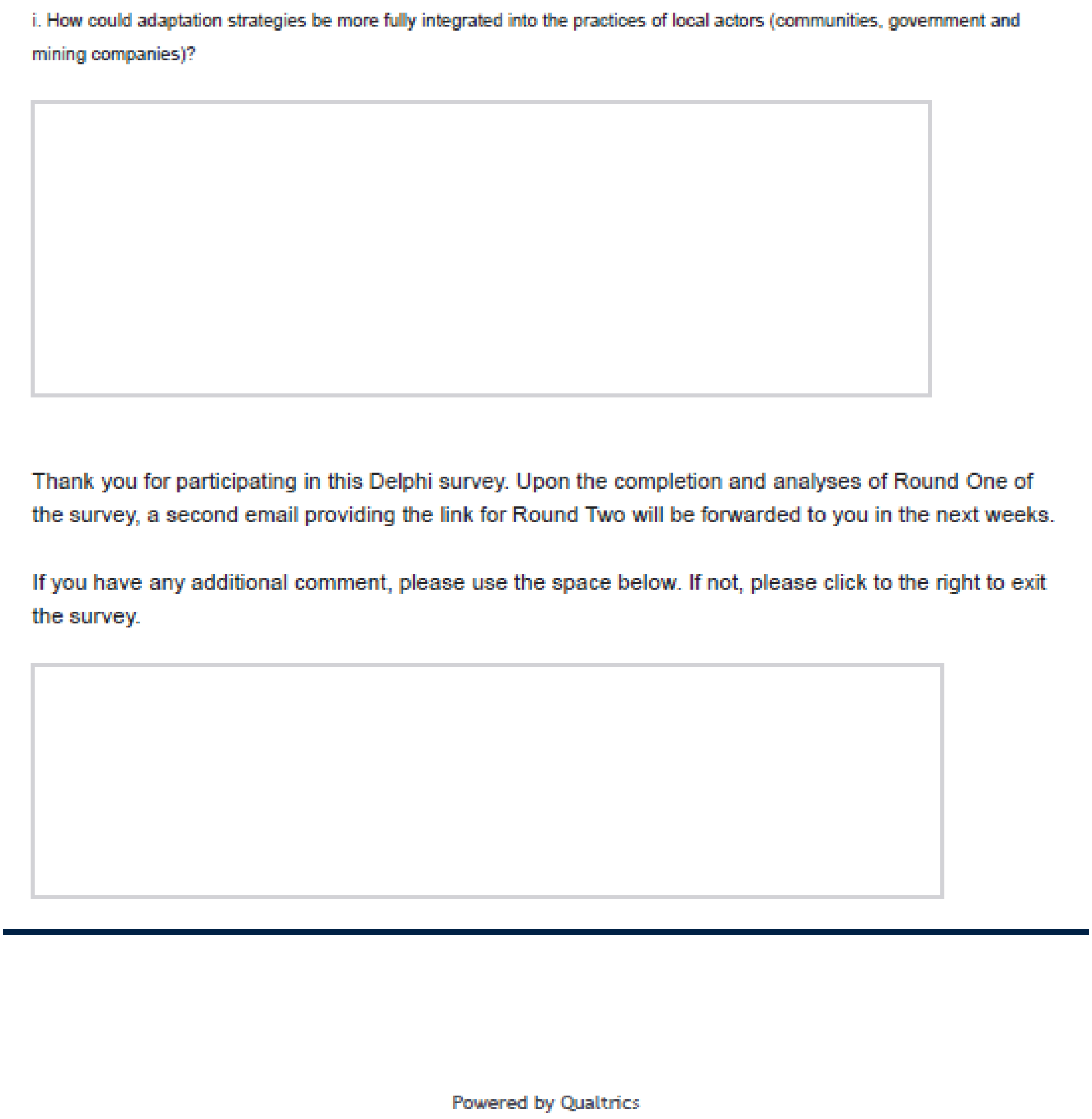
d. How could climate changes affect mine closure stage or land restoration process?

e. What general *Adaptation Strategies* are needed to adapt to overall climate changes in mountainous regions watersheds?

f. How could local communities in mountainous regions adapt to climate change and reduce the impacts of extreme weather events in the watersheds?

g. How could mining companies adapt to climate change and reduce the impacts of extreme weather events in their operations?

h. What are the most appropriate policies to support the adoption of adaptation practices?

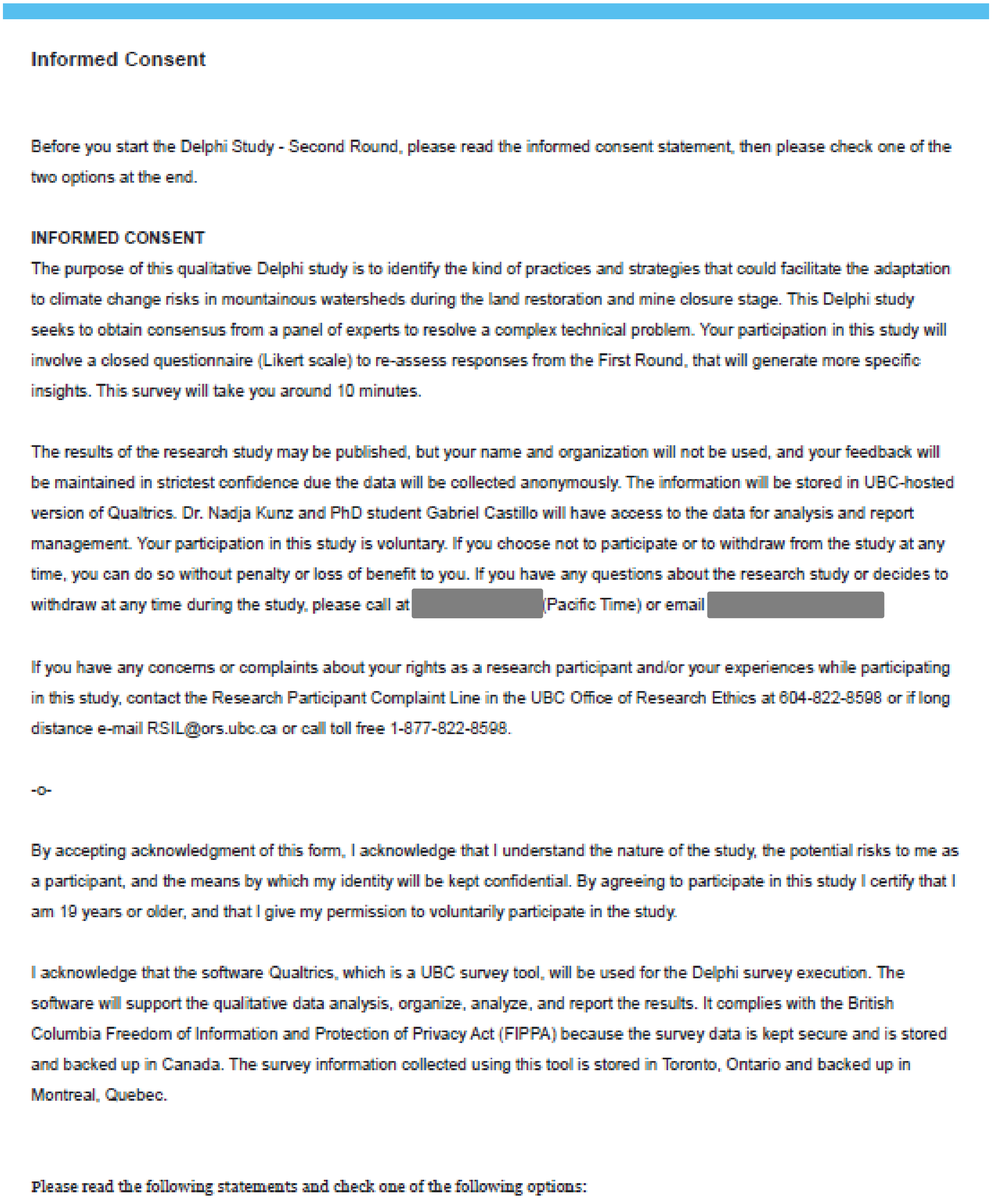


i. How could adaptation strategies be more fully integrated into the practices of local actors (communities, government and mining companies)?

Thank you for participating in this Delphi survey. Upon the completion and analyses of Round One of the survey, a second email providing the link for Round Two will be forwarded to you in the next weeks.

If you have any additional comment, please use the space below. If not, please click to the right to exit the survey.

A.2 Second Round Questionnaire



Informed Consent

Before you start the Delphi Study - Second Round, please read the informed consent statement, then please check one of the two options at the end.

INFORMED CONSENT

The purpose of this qualitative Delphi study is to identify the kind of practices and strategies that could facilitate the adaptation to climate change risks in mountainous watersheds during the land restoration and mine closure stage. This Delphi study seeks to obtain consensus from a panel of experts to resolve a complex technical problem. Your participation in this study will involve a closed questionnaire (Likert scale) to re-assess responses from the First Round, that will generate more specific insights. This survey will take you around 10 minutes.

The results of the research study may be published, but your name and organization will not be used, and your feedback will be maintained in strictest confidence due the data will be collected anonymously. The information will be stored in UBC-hosted version of Qualtrics. Dr. Nadja Kunz and PhD student Gabriel Castillo will have access to the data for analysis and report management. Your participation in this study is voluntary. If you choose not to participate or to withdraw from the study at any time, you can do so without penalty or loss of benefit to you. If you have any questions about the research study or decides to withdraw at any time during the study, please call at [redacted] (Pacific Time) or email [redacted]

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Thank you.

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Section I - Demographic Information (Please select one of the options)

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○ North America
○ South America
○ Europe
○ Asia Pacific

2. What is your gender?

○ Male
○ Female

3. In what type of field/organization are you working?

○ Academia
○ Mining industry/ Association

○ Institution/ Organization
○ Other (specify) ☐

4. Years of experience in climate change or related to the field?

○ 7 - 10 years
○ 10 - 20 years
○ 20 - 30 years
○ 30 - more years

5. What is your current position? (select the option that best show your current position)

○ Full professor
○ Assistant professor
○ VP - Director
○ Senior Manager
○ Manager - Head of Area
○ Superintendent – Officer
○ Other (specify) ☐

Section II - Questionnaire

Section II - Questionnaire (1/5)

1. Based on your knowledge of Climate Change impacts, define your **degree of Agreement** with respect to the potential occurrence of the following effects on mountainous watersheds.

	Disagree	Neither agree nor disagree	Agree
Increment of flooding events	○	○	○
Decrease of stream flow level during summer for early spring melt	○	○	○
Increased risk of landslides	○	○	○

	Disagree	Neither agree nor disagree	Agree
Intensity of precipitation may result in higher erosion of sediments	○	○	○
Changes in aquatic life ecosystems	○	○	○
Failure of infrastructure due lack of design for extreme events	○	○	○
Changes in species (flora/fauna) ranges, with the increase risk of invasive species	○	○	○
Changes in the hydrological cycles, that could produce changes to water availability downstream	○	○	○

Section II - Questionnaire (2/5)

2. To fully understand the potential impacts of climate change on the following mine infrastructure, define the **Significance** an infrastructure failure could generate on the watershed ecosystem. Consider the extreme climate events for: precipitation, wind, periods of heat, flooding, warmer average temperatures (seasonal, annual), warm winter days (temperature > 0°C), drought, and any examples of cumulative hazards.

	No Significant	Moderately Significant	Very Significant
Waste rock dumps	○	○	○
Tailing Management Facilities	○	○	○
Roads (Paved / Unpaved)	○	○	○
Drainage channels	○	○	○
Heap leaching Pads	○	○	○

	No Significant	Moderately Significant	Very Significant
Water management structures	○	○	○
Train rails	○	○	○
Power lines	○	○	○
Pipelines	○	○	○

Section II - Questionnaire (3/5)

3. Based on your knowledge, define your **degree of Agreement** with the following statements in respect to the impacts of climate change in the process of land restoration or mine closure activities.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Establishment of vegetation to stabilize disturbed areas may be slower	○	○	○	○	○
Water disposal and treatment will be more difficult	○	○	○	○	○
Long dry periods can limit vegetation growth	○	○	○	○	○
Hydraulic structures may need to be increased in design to manage more water	○	○	○	○	○
Increased rain fall can promote Acid Rock Drainage (ARD)	○	○	○	○	○
Tipping points will affect species ranges and ecosystem resilience	○	○	○	○	○
The selection of plants species for revegetation should be considering future change of climate, more than choosing	○	○	○	○	○

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
species based on historical presence in the area of interest.					
Wetter conditions will affect covers and revegetation stability	○	○	○	○	○

Section II - Questionnaire (4/5)

4. Based on your knowledge, what is your opinion of the **degree of Importance** for the following adaptation strategies, in reducing the adverse effects of climate change in mountainous watersheds?

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Wetlands management, conservation and restoration	○	○	○	○	○
Integrated management of the watershed and long-term plans	○	○	○	○	○
Design infrastructure based in risk assessment for future climate scenarios and extreme weather events	○	○	○	○	○
Develop climate scenarios with local expert-based narratives	○	○	○	○	○
Improved management and conservation of ecosystems	○	○	○	○	○
Execute climate risk assessment of physical and biological systems at watershed level	○	○	○	○	○

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Design emergency response and evacuation plans	○	○	○	○	○
Design and implement future land uses that can withstand extreme weather events	○	○	○	○	○

Section II - Questionnaire (5/5)

5. Based on your experience, define the **degree of Usefulness** of the following public administration strategies for enhancing the acceptance of climate change adaptation actions in watersheds areas.

	Not at all useful	Moderately useful	Very useful
Encourage cooperation amongst all organizations and local actors	○	○	○
Promote local understanding of needs, problems and solutions	○	○	○
Promote the usage of climate change prediction models in environmental & social impact assessment	○	○	○
Establish participatory planning process for future land use, based in local risk and vulnerabilities	○	○	○
Empower watershed organizations	○	○	○
Increase the consultation to local actors during the process of designing policies	○	○	○

Comments

Do you have any additional comments or concerns you would like to share? Please use the text box in this section.

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Appendix B - Climate change effects in cities

Climate change effect	Local climate change impact	Exposure	Consequence / impact	Vulnerability
Sea level rise (virtually certain)	Inundation or long-term waterline change resulting in flooding or long-term erosion, up-river migration of salt wedge	1. Residential, commercial, and industrial property and buildings 2. Transportation infrastructure (roads, rail, ports, airports) 3. Recreational areas 4. Municipal infrastructure (sanitary and storm sewers, dykes, seawalls, sidewalks, trails, electricity grid) 5. Agricultural areas 6. Aquifers 7. First Nations sites (harvesting, archeological) 8. Important ecological areas (salmon and forage fish habitat)	Medium to long-term: Loss of and damage to property and infrastructure Reduced agricultural viability Reduced ecosystem services First Nations food and cultural impacts	All areas below the new local projected high water mark not protected by, or unable to be protected by, dyke infrastructure All ecological areas on the seaward side of dykes or in areas where shoreline translation is impeded (e.g., by development or natural rocky structures)
	Extreme high tide / storm surges and event-based erosion	1. Residential, commercial, and industrial property and buildings 2. Transportation infrastructure (roads, rail, ports, airports) 3. Recreational areas 4. Municipal infrastructure (sanitary and storm sewers, dykes, seawalls, sidewalks, trails, electricity grid) 5. Agricultural areas 6. Aquifers 7. First Nations sites (harvesting, archeological) 8. Important ecological areas (salmon and forage fish habitat)	Sudden and disruptive loss or interruption of assets and services (as above) In addition to event-based nature of storm surges, their impact is much higher due to high water levels and wave power	All areas as above in addition to all assets and services within a floodplain
Increased temperature	Increased frequency of hot spells / heat waves	Energy system distribution	Energy shocks and disruptions due to increased demand	Areas where peak energy demand approaches peak distribution capacity
	Warmer with fewer cold days and nights, more hot days and nights (virtually certain)	1. Roads, bridge, and tunnels 2. Housing 3. Industry	Exacerbated air pollution Road surface deterioration caused by high surface temperatures, damage to expansion joints	Areas with older infrastructure, high-cost infrastructure, high traffic
		1. Energy system distribution 2. Public health	Heat-related illness and death	Elderly, particularly when these do not have access to air conditioning

Climate change effect	**Local climate change impact**	**Exposure**	**Consequence / impact**	**Vulnerability**
			Increased demand for cooling in occupied buildings, putting more pressure on local electricity supply Strains on power supply	Energy infrastructure, in areas where peak demand approaches capacity
Increased temperature	Melting glaciers Reduced snowmelt runoff	1. Domestic water 2. Hydropower generation 3. Agricultural water	Reduced energy production Reduced crop production Seasonally reduced water availability.	Areas dependent on supply from reservoirs fed by nivial and mixed nivial/pluvial watersheds Risk to pluvial watersheds depending on projected local rainfall changes
Changed temperature patterns	Wildfire	1. Housing damage 2. Rural roads 3. Municipal infrastructure (General)	High severity wildfires that spread rapidly increase in burned area Landslides	Communities with a large urban-forest interface
	Invasive organisms	1. Public health 2. Crop production	Higher rate of pathogen transmission and altered disease patterns More pest degree-days	Risk for new zoonotic disease in humans and more pests in crops
Changed precipitation patterns	Increased frequency of heavy precipitation events (very likely)	1. Rural roads 2. Fuel pipelines	Landslides and debris flows Pipelines and other transportation infrastructure used for fuel affected by landslides and erosion	Unsealed roads
		1. Public health	Contaminated waters and spread of disease in stagnant waters	Drainage systems, reservoirs
		1. Transportation system (roads and rail)	Disrupted transport, commerce, and economic activity due to road flooding	# Routes and passengers passing through potentially affected areas and the capacity for re-routing

Climate change effect	Local climate change impact	Exposure	Consequence / impact	Vulnerability
		1. Solid waste infrastructure 2. Storm management infrastructure along creeks	Soil and sediment erosion with increased flooding Leaching of contaminants from closed landfills and industrial sites	Lack of stormwater infrastructure and/or infrastructure capacity
		1. Housing	Urban floods	Insufficient river dykes, bottlenecks in drainage infrastructure
Changed precipitation patterns	Areas affected by increased drought (likely)	1. Water supply system: potable water, irrigation, wastewater	Seasonally reduced water supply exacerbates water scarcity and competition Intensified droughts, resulting in disruptions to water supply, even in humid areas	Province-wide users of public water systems
		1.Hydropower generation 2. Domestic water supply and storage infrastructure	Change in volume and timing of stream flows, reduced snowpack	Capacity of hydroelectric system to produce, store and import power.

Appendix C - Suggested Climate Threshold Parameters

Climate Parameter	Infrastructure threshold parameter
Temperature	Rate of change Mean values Extremes o High summer o Low winter
Precipitation as rain	Frequency (One-Day, Short Duration Less than 24 hours, Multi-Day) Total annual/seasonal precipitation and rain Intensity of rain events (One-Day, Short Duration Less than 24 hours) Proportion of annual and seasonal precipitation as rainfall Drought conditions
Precipitation as snow	Frequency Total annual/seasonal precipitation and snow Magnitude of snow events Proportion of annual and seasonal precipitation as snowfall Frequency and intensity of rapid snow melt events Rain on snow events
Wind speed	Mean values (1-hour mean winds) o Monthly o Seasonal o Annual Extremes/gusts Thunderstorm winds General wind patterns/gradients Changes in hurricane and/or tornado frequency/intensity
Ice	River or lake ice build-up Sea ice build-up
Hail	Frequency of events Magnitude of events
Frost	Freeze thaw cycles Change in frost season
Ice Accretion	Change in frequency/intensity of ice storm events Ice build-up on infrastructure components
Other	Other climate factors as relevant to infrastructure under consideration

Appendix D - Normalisation Methods

D.1 Min-Max Method

"*The min-max normalisation methodology converts all values to scores ranging from 0 to 1 by subtracting the minimum score and dividing it by the range of the indicator values*" (Fritzsche et al. 2014). This method was applied to metric indicator values as follows:

$$X_{i,0\ to\ 1} = \frac{X_i - X_{Min}}{X_{Max} - X_{Min}}$$

Where:

Xi,0 to 1 is the normalised data point in range of 0 to 1; Xi is the individual data point to be transformed; XMin is the lowest value for that indicator; and XMax is the highest value for that indicator.

In this methodology, previously defined thresholds must be converted.

D.2 Five-Class Evaluation Scheme

The five-class evaluation scheme (Table D.1) uses a qualitative positive-to-negative scale to define classes 1 through 5 (Fritzsche et al. 2014). This method is used with categorical values. In the five-class system, the most positive conditions are represented by the lowest class and the most negative conditions are represented by the highest class.

Table D.1 Five-Class Evaluation Scheme (Fritzsche et al. 2014)

Class number	Description
1	Optimal (no improvement required)
2	Rather positive
3	Neutral
4	Rather negative
5	Critical (could lead to severe consequences)

With this method, the measurement scale changes from nominal to ordinal, then the indicator values are converted to a metric class value of 0 to 1 (Table D.2).

Table D.2 Class values and descriptions (Fritzsche et al. 2014)

Categorical class value from 1 to 5	Metric class value from 0 to 1	Description
1	0–0.2	Optimal (no improvement required)
2	> 0.2–0.4	Rather positive
3	> 0.4–0.6	Neutral
4	> 0.6–0.8	Rather negative
5	> 0.8–1	Critical (could lead to severe consequences)

Appendix E - Elkview Operation Mine Closure End-Land-Use Objective (Teck Coal Limited 2017)

	TEM/BEC Site Series	Structural Stage 1 - 3 (Sparse - Shrub/Herb)	Structural Stage 4 - 5 (Young Forest)	Structural Stage 6 (Mature Forest)	Structural Stage 7 (Old Growth Forest)
Alpine	ESSFdk1/Ag	Recreation FN Cultural Use Wildlife Winter Range (Sheep Focus) Wildlife Habitat (Birds, Small Mammals) Rare and Listed Plant Habitat High Biodiversity Value	n/a		
	ESSFdk1/Am				
	ESSFdkp/Ag				
	ESSFdkw/Af				
	ESSFdkw/Ag				
	ESSFdkw/Am				
	ESSFdkp/Sk11		Recreation FN Cultural Use Wildlife Habitat (Birds, Small Mammals) Rare and Listed Plant Habitat High Biodiversity Value		
	ESSFdkp/Sk24				
	ESSFdkw/Sk				
Grassland Brushland	ESSFdk1/Gb	Recreation FN Cultural Use Wildlife Winter Range (Ungulate Focus) Wildlife Habitat (Birds, Small Mammals) Wildlife Habitat (Badger)	n/a		
	MSdw/Gb				
	MSdw/Gg				
Avalanche	ESSFdk1/Vh	Recreation FN Cultural Use Wildlife Habitat (Grizzly Bears) High Biodiversity Value Rare and Listed Plant Habitat			
	ESSFdk1/Vs				
	ESSFdkw/Vh				
	ESSFdkw/Vs				
	ESSFdkw/Vt				
	MSdw/Vh				
	MSdw/Vs				
	MSdw/Vt				
Dry Forest	ESSFdk1/102	Recreation FN Cultural Use Wildlife Habitat (Winter Range - Ungulate) Wildlife Habitat (Birds, Small Mammals) Wildlife Habitat (Badger)	Recreation FN Cultural Use Wildlife Habitat (Winter Range - Ungulate) Wildlife Habitat (Birds) Wildlife Habitat (Lynx)	Commercial Forestry Recreation FN Cultural Use Wildlife Habitat (Winter Range - Ungulate) Wildlife Habitat (Birds) Wildlife Habitat (Cavity Dependent)	Commercial Forestry Recreation FN Cultural Use Wildlife Habitat (Winter Range - Ungulate) Wildlife Habitat (Birds) Wildlife Habitat (Cavity Dependent) High Biodiversity Value Rare and Listed Plant Habitat
	ESSFdk1/103				
	ESSFdkw/102				
	ESSFdkw/103				
	MSdw/102				
	MSdw/103				
Mesic Forest	ESSFdk1/101	Recreation FN Cultural Use Wildlife Habitat (Summer Range - Ungulate) Wildlife Habitat (Birds, Small Mammals) Wildlife Habitat (Badger)	Recreation FN Cultural Use Wildlife Habitat (Summer Range - Ungulate) Wildlife Habitat (Birds) Wildlife Habitat (Lynx)	Commercial Forestry Recreation FN Cultural Use Wildlife Habitat (Summer Range - Ungulate) Wildlife Habitat (Birds) Wildlife Habitat (Cavity Dependent)	Commercial Forestry Recreation FN Cultural Use Wildlife Habitat (Summer Range - Ungulate) Wildlife Habitat (Birds) Wildlife Habitat (Cavity Dependent) High Biodiversity Value Rare and Listed Plant Habitat
	ESSFdk1/104				
	ESSFdkw/101				
	MSdw/101				
	MSdw/104				
Wet Forest	ESSFdk1/110	Recreation FN Cultural Use Wildlife Habitat (Winter Range - Moose) Wildlife Habitat (Birds, amphibians) High Biodiversity Value Rare and Listed Plant Habitat	Recreation FN Cultural Use Wildlife Habitat (Winter Range - Moose) Wildlife Habitat (Birds, amphibians) Wildlife Habitat (Lynx) High Biodiversity Value Rare and Listed Plant Habitat	Commercial Forestry Recreation FN Cultural Use Wildlife Habitat (Winter Range - Moose) Wildlife Habitat (Birds, amphibians) Wildlife Habitat (Cavity Dependent) High Biodiversity Value Rare and Listed Plant Habitat	Commercial Forestry Recreation FN Cultural Use Wildlife Habitat (Winter Range - Moose) Wildlife Habitat (Birds, amphibians) Wildlife Habitat (Cavity Dependent) High Biodiversity Value Rare and Listed Plant Habitat
	ESSFdk1/111				
	ESSFdkw/110				
	MSdw/110				
	MSdw/111				
Rock Talus Cliffs	ESSFdk1/Rt	Recreation FN Cultural Use Wildlife Habitat (Birds, Small Mammals) Wildlife Habitat (Escape Terrain) Rare and Listed Plant Habitat	n/a		
	ESSFdk1/Ro				
	ESSFdk1/Mihw				
	ESSFdk1/Rt				
	MSdw/Ro				
	MSdw/Mihw				
	MSdw/Rt				

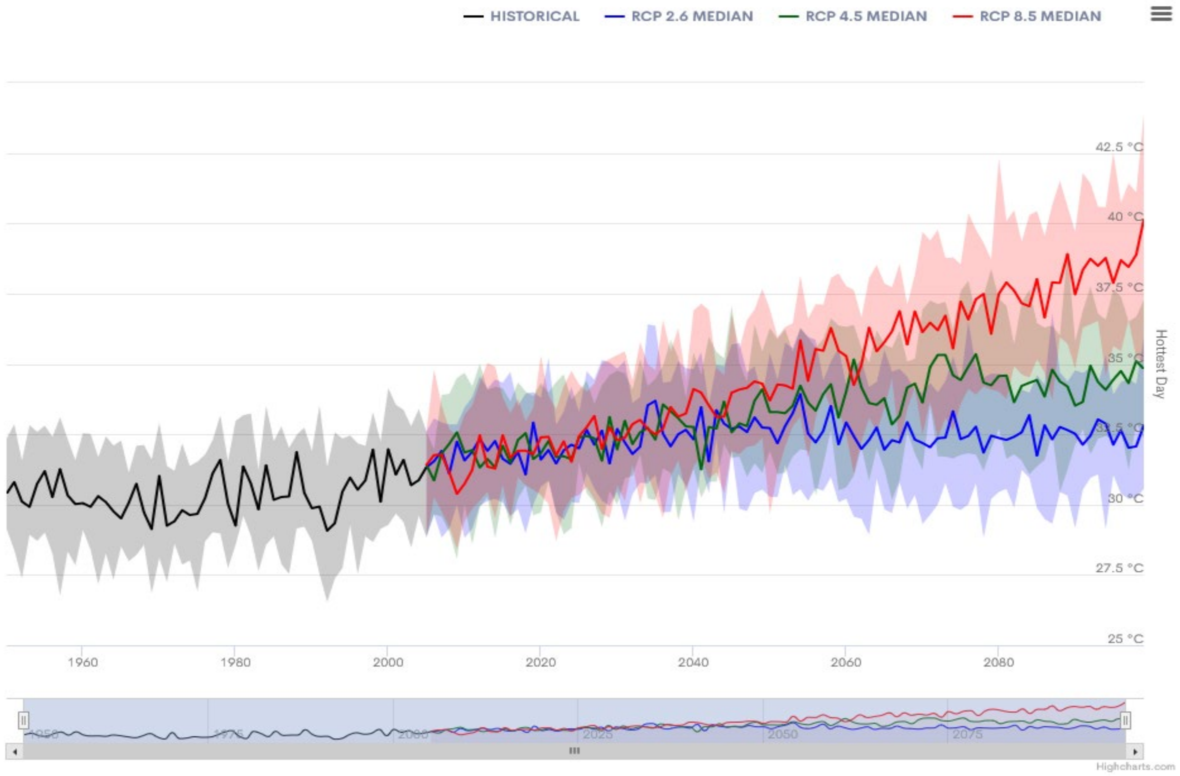
Appendix F - Climate Information for Sparwood, British Columbia

F.1 Temperature

Hottest day

This is the highest maximum temperature value in this time period.

Figure F.1 Hottest day

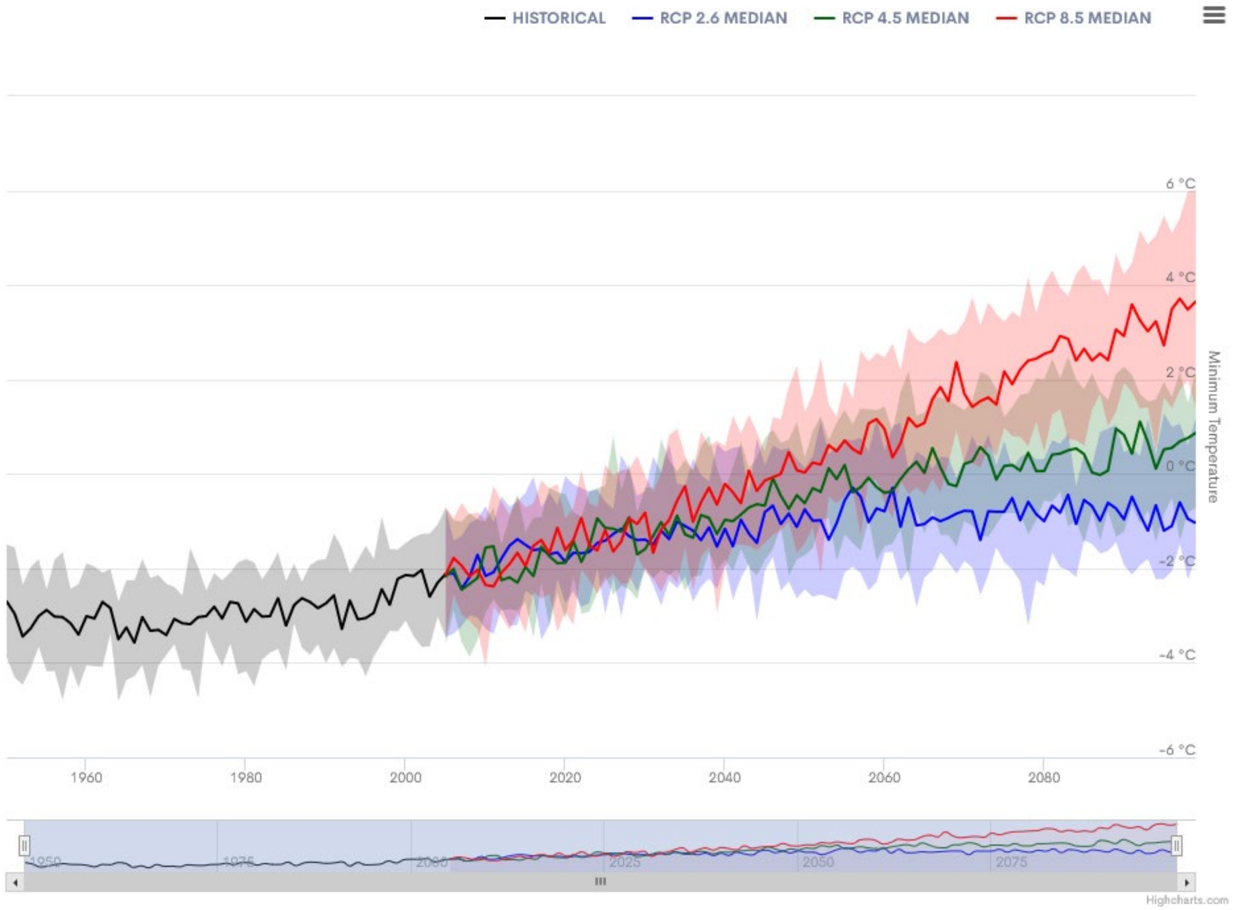


Source: Climatedata.ca

Minimum temperature

This is the average minimum temperature for a given time period and is derived by averaging all the daily minimum temperatures in that time period.

Figure F.2 Minimum temperature

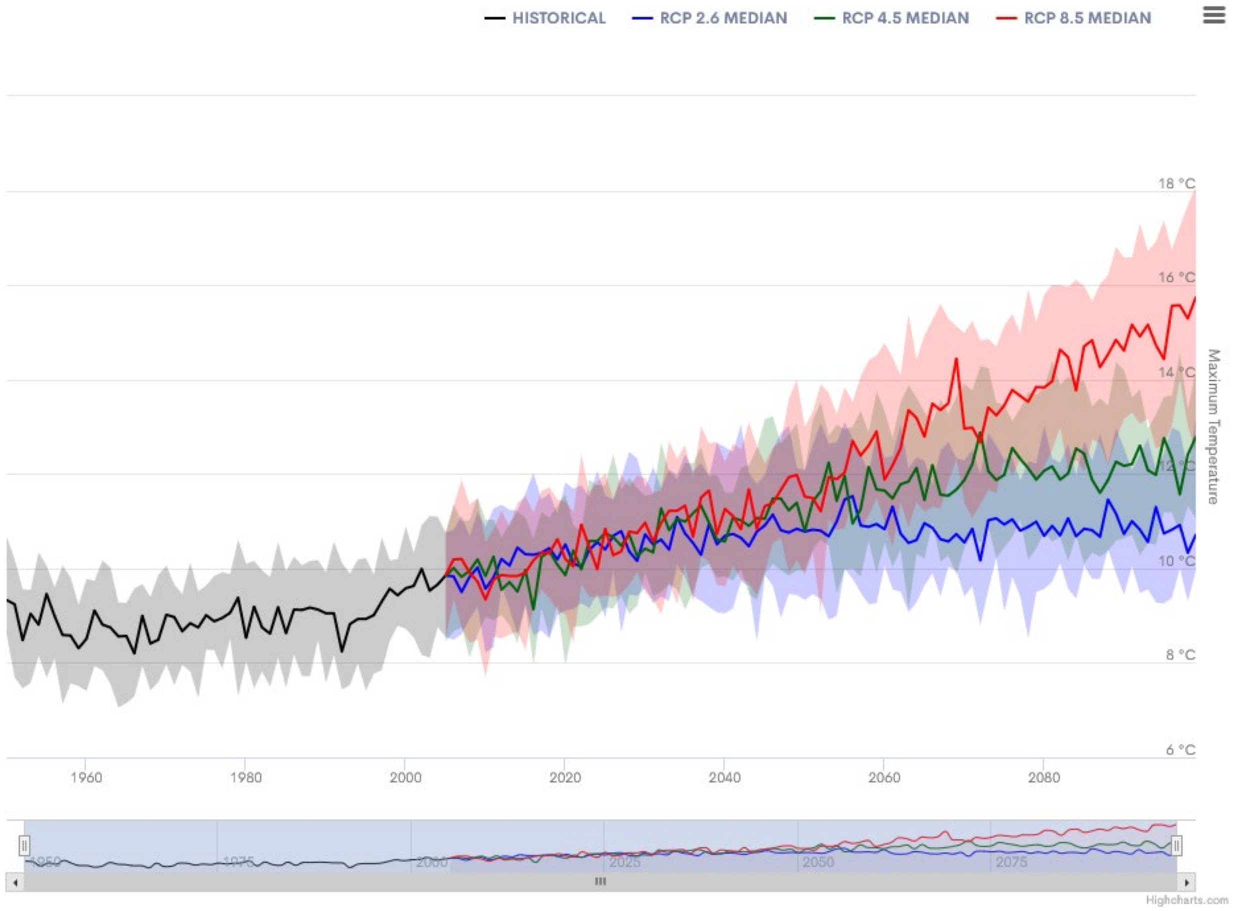


Source: Climatedata.ca

Maximum temperature

This is the average maximum temperature for a given time period and is derived by averaging all the daily maximum temperatures in that time period.

Figure F.3 Maximum temperature

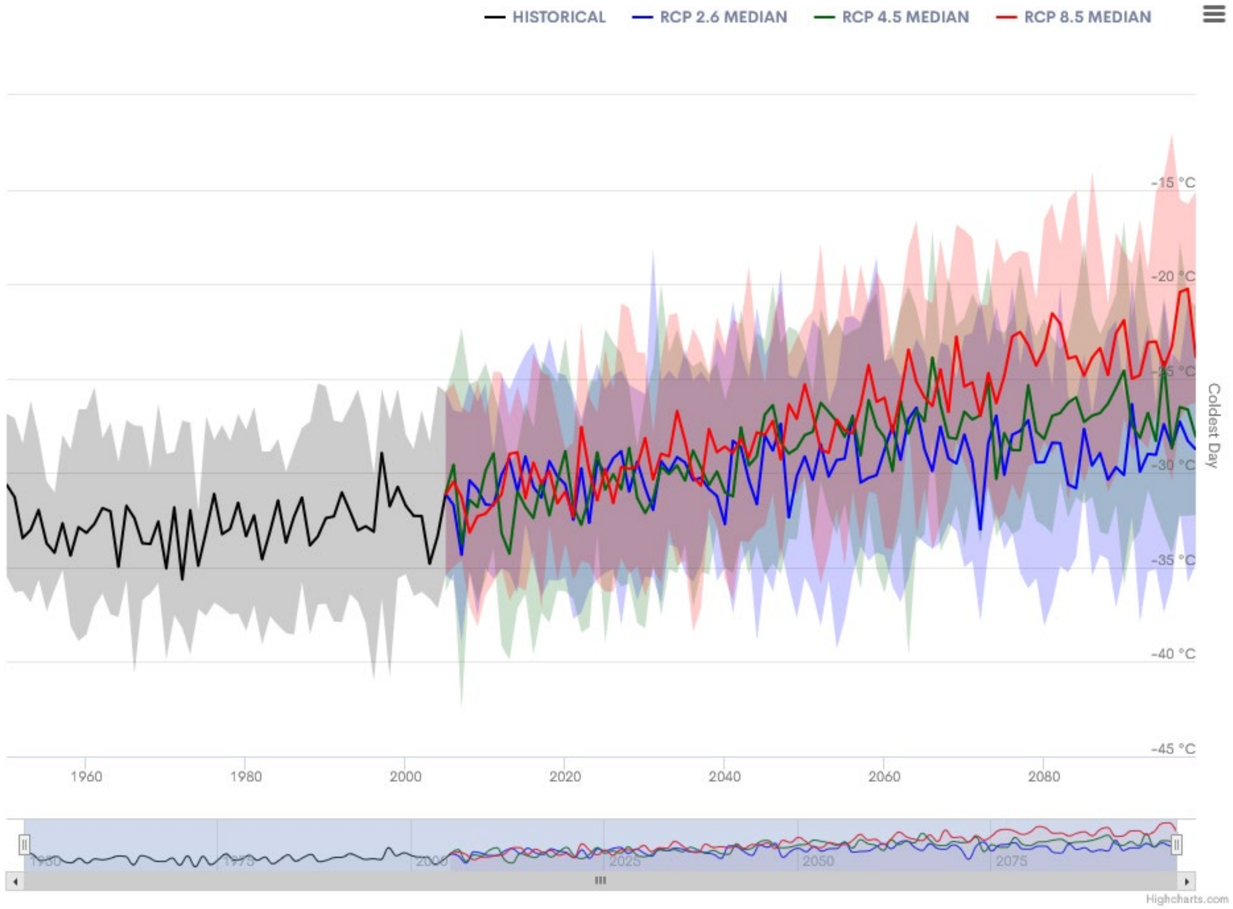


Source: Climatedata.ca

Coldest day

This is the lowest minimum temperature value in this time period.

Figure F.4 Coldest day



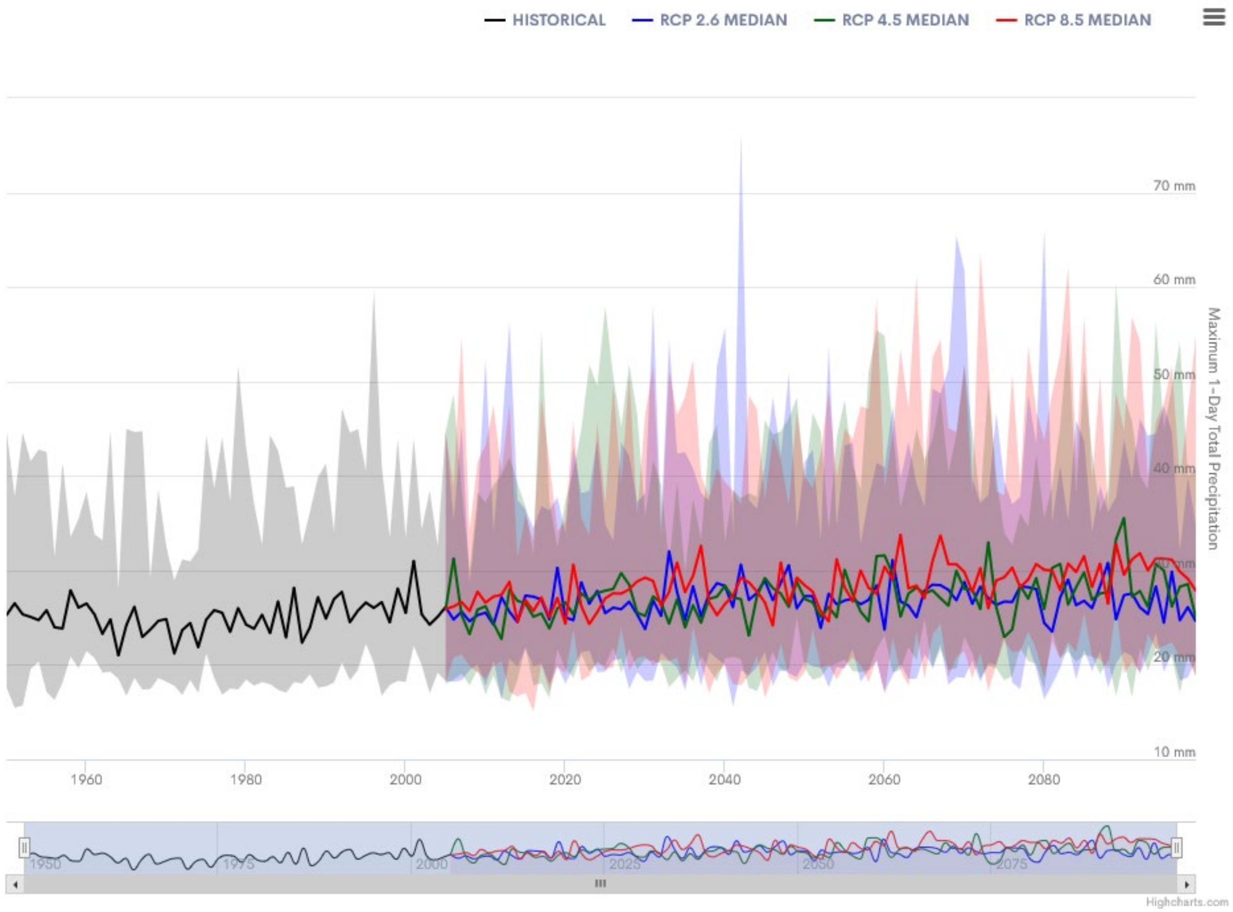
Source: Climatedata.ca

F.2 Precipitation

Maximum One – day total precipitation

This is the largest precipitation total on a single day.

Figure F.5 Maximum One – day total precipitation

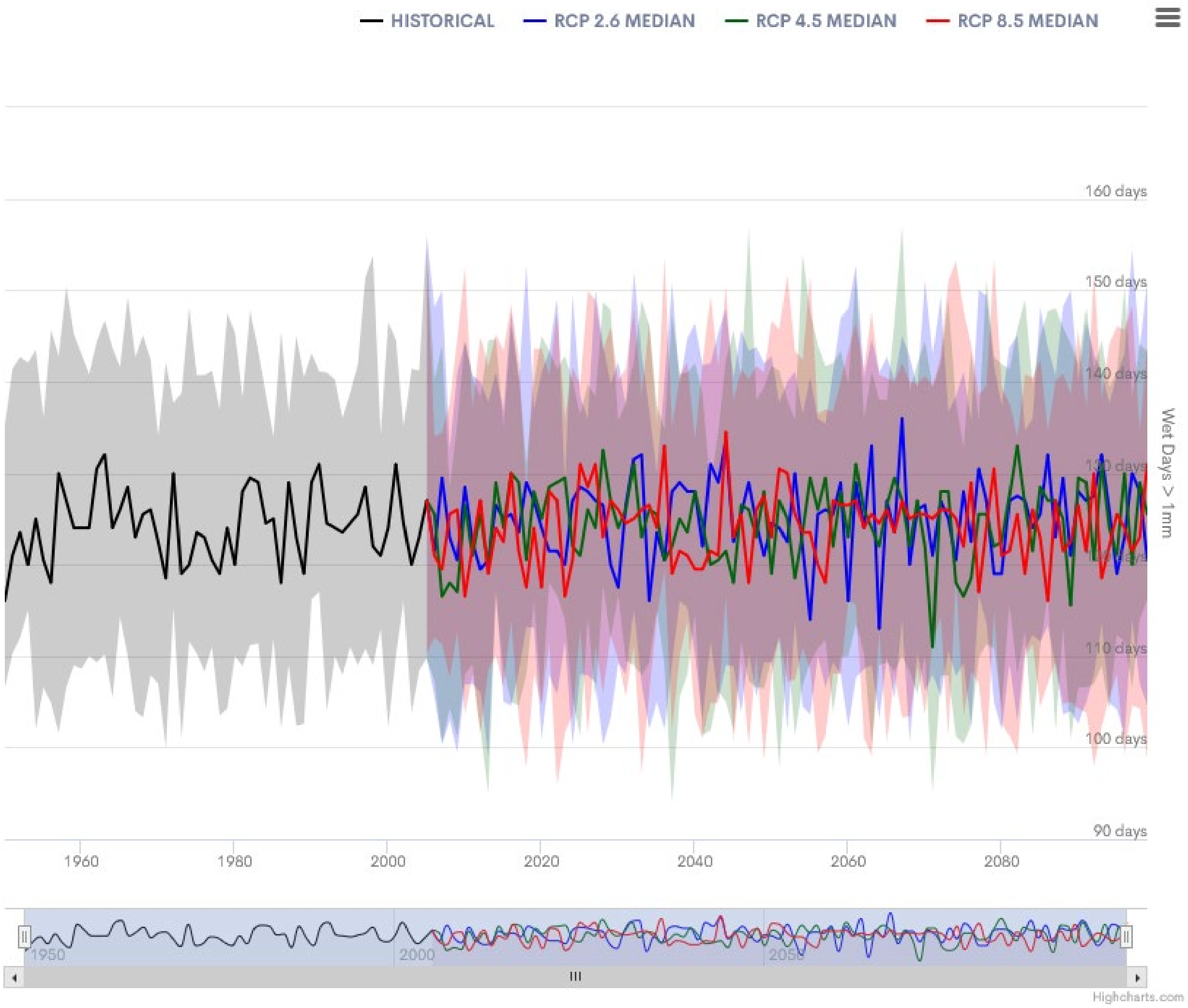


Source: Climatedata.ca

Wet days > 1mm

Number of days with daily precipitation totals greater than 1 mm.

Figure F.6 Wet days > 1mm

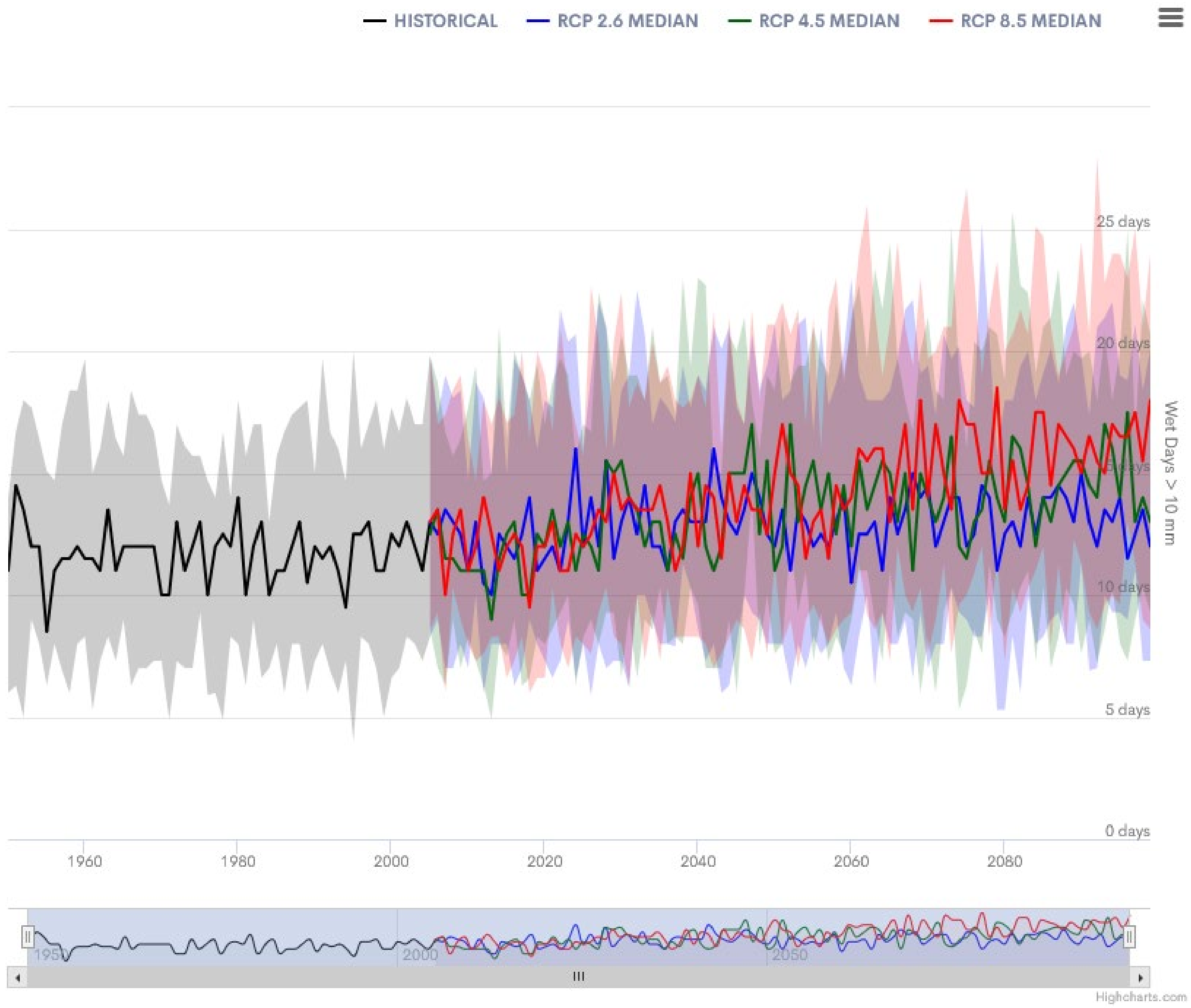


Source: Climatedata.ca

Wet days > 10mm

Number of days with daily precipitation totals greater than 10 mm.

Figure F.7 Wet days > 10mm

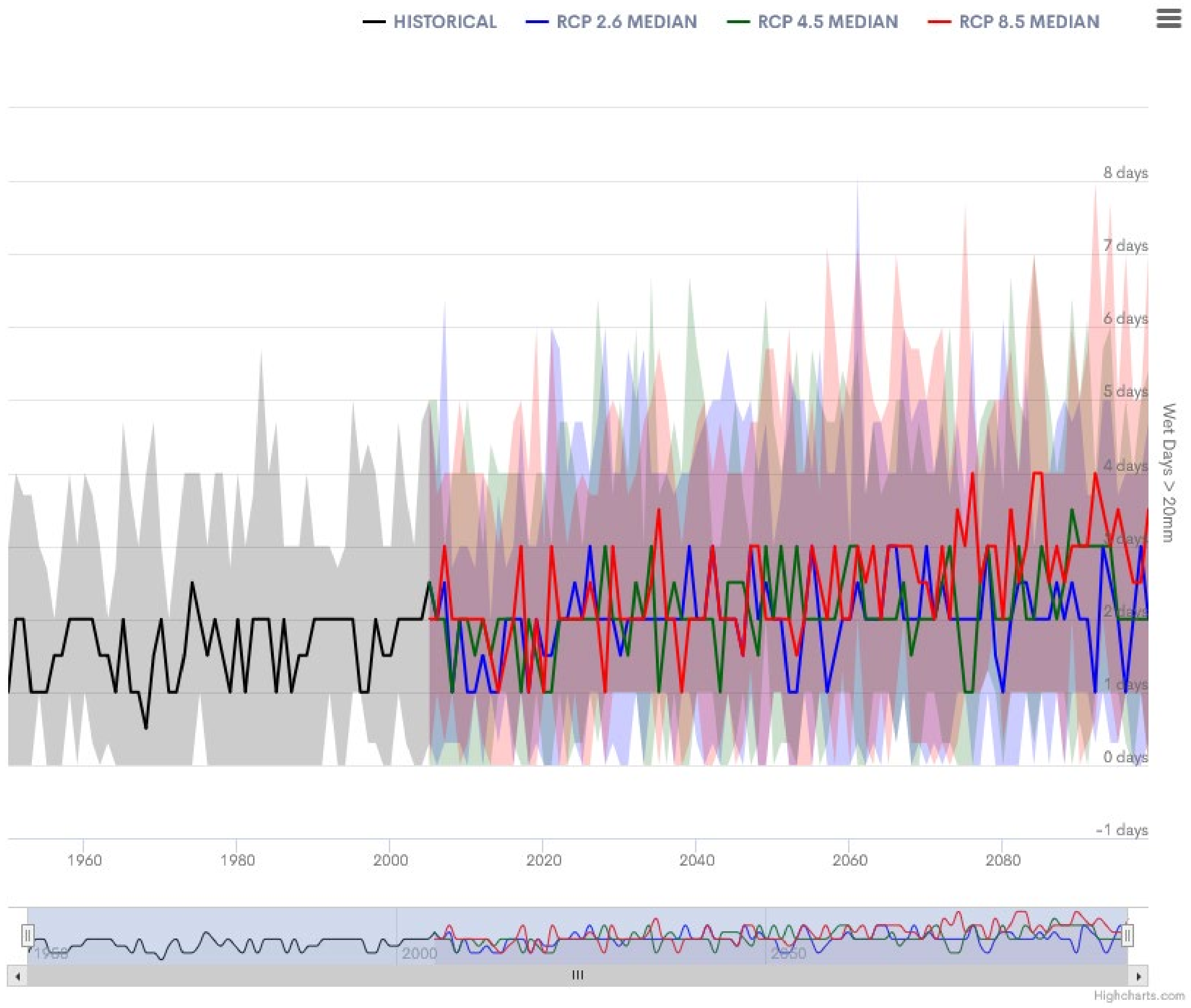


Source: Climatedata.ca

Wet days > 20mm

Number of days with daily precipitation totals greater than 20 mm.

Figure F.8 Wet days > 20mm



Source: Climatedata.ca

Appendix G - Sensitivity and Adaptive Capacity of the Social – Ecological System

				Sensitivity					Adaptive Capacity					Vulnerability	
				If the climate hazard occurs, will it affect the functionality of the ecosystem service?					Can the ecosystem service adjust to the projected climate-related impact with minimal cost or disruption?						
Climate Event	Factor	RCP	YEAR	No - Funtionality will stay the same (S1)	Unlike - Funtionality will likely stay the same (S2)	Yes - Funtionality is likely to get worse (S3)	Yes - Functionality will get worse (S4)	Yes - Functionality will become unmanageable (S5)	No - Will require substantial costs (> 30% cost overrun) and experts intervention (AC1)	No - Will require significant costs (16% to 30% cost overrun) and experts intervention (AC2)	Maybe - Will require some costs (6% to 15% cost overrun) and experts interventions (AC3)	Yes - But will require some slight costs (0.5% to 5% cost overrun) and experts intervention (AC4)	Yes -No to little costs (Less than 0.5% within budgeted costs) and experts intervention are n (AC5)		
Days with Tmax > 30C	Parks and Natural Areas - Catastrophic fire - Urban Fire Disturbance	8.5	2030				S4					AC4		V3	Medium
			2060				S4				AC3			V4	Medium - High Vulnerability
			2090				S4				AC3			V4	Medium - High Vulnerability
Days with Tmax > 30C Maximum 1-Day Total Precipitation	Disturbance on Aquatic Ecosystem	8.5	2030				S4			AC2				V4	Medium - High Vulnerability
			2060					S5	AC1					V5	High Vulnerability
			2090					S5	AC1					V5	High Vulnerability
Days with Tmax > 30C Maximum 1-Day Total Precipitation	Road Maintenance	8.5	2030			S3					AC3			V3	Medium
			2060				S4			AC2				V4	Medium - High Vulnerability
			2090				S4			AC2				V4	Medium - High Vulnerability
Days with Tmax > 30C Min/Max Temperature	Increasing stream temperature	8.5	2030			S3						AC4		V3	Medium
			2060			S3						AC4		V3	Medium
			2090			S3						AC4		V3	Medium
Days with Tmax > 30C Min/Max Temperature	Vegetational changes / habitat shifting - wildlife (elk) habitat suitability (BGC)	8.5	2030				S4			AC2				V4	Medium - High Vulnerability
			2060					S5		AC2				V5	High Vulnerability
			2090					S5		AC2				V5	High Vulnerability
Maximum 1-Day Total Precipitation	Riparian protection area	8.5	2030			S3						AC4		V3	Medium
			2060			S3						AC4		V3	Medium
			2090			S3						AC4		V3	Medium
Maximum 1-Day Total Precipitation	Economic Development: fishing and tourism	8.5	2030				S4			AC2				V4	Medium - High Vulnerability
			2060					S5		AC2				V5	High Vulnerability
			2090					S5		AC2				V5	High Vulnerability
Wet Days >20mm Flooding / lagoon failure / Emergency Plan	Residents age / population	8.5	2030		S2							AC4		V2	Medium - Low Vulnerability
			2060			S3						AC4		V3	Medium
			2090			S3						AC4		V3	Medium
Maximum 1-Day Total Precipitation	WWTP	8.5	2030				S4					AC4		V3	Medium -
			2060				S4				AC3			V4	Medium - High Vulnerability
			2090				S4				AC3			V4	Medium - High Vulnerability
Maximum 1-Day Total Precipitation Days with Tmax > 30C	Drink water Plant	8.5	2030				S4		AC1					V5	High Vulnerability
			2060					S5	AC1					V5	High Vulnerability
			2090					S5	AC1					V5	High Vulnerability

Appendix H - Case Study Hazard Assessment

										1					2					3					4					5					6					7				
H	Mine Closure Components	Components Response Considerations						Scenario		Mean Daily Temperature					Max/Min Temperature					Days with Tmax > 25C					Days with Tmax > 30C					Total Precipitation (mm)					Maximum 1-Day Total Precipitation (mm)					Wet Days >20mm				
		Structural Design	Watershed, Surface Water & Groundwater	Operations, Maintenance & Materials Performance	Emergency Response	Social Effects	Environmental Effects			RCP 4.5: 4.97°C (76.2%); 6.02°C (113.5%); 6.32°C (124.3%) RCP 8.5: 5.15°C (82.7%); 7.20°C (155.5%); 8.48°C (200.7%)				Mean temperature is the average temperature on a given day and is usually obtained by averaging the daily maximum and minimum temperatures.	Min: RCP 4.5 : -0.94°C / -0.16°C / -0.45°C RCP 8.5: -0.68°C / 1.37 °C / 2.66 °C Max: RCP 4.5: 10.86°C / 11.89°C / 12.19°C RCP 8.5: 11.03°C / 13.03°C / 14.29°C				This is the average maximum and minimum temperature for a given time period and is derived by averaging all the daily maximum and minimum temperatures in that time period.	RCP 4.5: 81%; 122%; 133% RCP 8.5: 90%; 170%; 232%				High temperatures are important. They determine if plants and animals can thrive, they limit or enable outdoor activities, define how we design our buildings and vehicles, and shape our transportation and energy use. It is useful to know how high summer temperatures are likely to become in the future, to make sure that our cooling and air-conditioning systems can reliably deal with these extremes.	RCP 4.5: 11 (330%); 17.5 (585%);19.8 (675%) RCP 8.5: 12.3 (379%); 26.7 (943%); 40.6 (1488%)				When temperatures are very hot, people - especially the elderly - are much more likely to suffer from heat exhaustion and heat stroke. Many outdoor activities become dangerous or impossible in very high temperatures. In general, Canadians are not used to extremely hot summers, and further warming will bring new and unusual risks as well as a very different experience of the summer season.	RCP 4.5: 658.4 / 669.1 / 674.3 RCP 8.5: 653.8 / 687.7 / 698.6				This is the total precipitation (rain and snow) for a given time period.	RCP 4.5 31.08 (10%); 31.48 (11%); 31.87 (12%) RCP 8.5: 31.23 (10%); 33.76 (19%); 34.52 (22%)				This is the largest precipitation total on a singleday.	RCP 4.5: 2.44 (36%); 2.6 (47%); 2.7 (52%) RCP 8.5: 2.4 (35%); 2.9 (65%); 3.3 (83%)				Number of precipitatio than
H1	Lagoon Tailings Area	Mark Relevant Responses ✓						RCP	Year	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale Fo Score
H1A	Lagoon A	✓						4.5	2030	N					N					N					N					N					Y	1	4	4	Increase in total precipitation on asingle day would affect the load carrying capacity	Y	1	4	4	Increase in nu daily precipita than 20mm loadcarr
									2060	N					N					N					N					N					Y	1	4	4		Y	1	4	4	
									2090	N					N					N					N					N					Y	1	4	4		Y	1	4	4	
								8.5	2030	N					N					N					N					N					Y	2	5	10		Y	1	5	5	
									2060	N					N					N					N					N					Y	2	5	10		Y	1	5	5	
									2090	N					N					N					N					N					Y	2	5	10		Y	2	5	10	
			✓					4.5	2030	N					N					N					N					Y	1	3	3	Increase in precipitation would contribute to floods and more runoff on the watershed	Y	1	4	4	Increase in total precipitation on a single day would produce runoff and flooding in the watershed	Y	1	4	4	Increase in nu daily precipita than 20mm runoffand wa
									2060	N					N					N					N					Y	2	3	6		Y	1	4	4		Y	1	4	4	
									2090	N					N					N					N					Y	3	4	12		Y	1	4	4		Y	2	4	8	
								8.5	2030	N					N					N					N					Y	2	3	6		Y	1	4	4		Y	1	4	4	
									2060	N					N					N					N					Y	3	4	12		Y	2	5	10		Y	2	5	10	
									2090	N					N					N					N					Y	3	4	12		Y	2	5	10		Y	3	5	15	
								4.5	2030	N					N					N					N					N					N					N				
									2060	N					N					N					N					N					N					N				
									2090	N					N					N					N					N					N					N				
								8.5	2030	N					N					N					N					N					N					N				
									2060	N					N					N					N					N					N					N				
									2090	N					N					N					N					N					N					N				
H1B	Lagoon B	✓						4.5	2030	N					N					N					N					N					Y	1	4	4	Increase in total precipitation on asingle day would affect the load carrying capacity	Y	1	4	4	Increase in nu daily precipita than 20mm loadcarr
									2060	N					N					N					N					N					Y	1	4	4		Y	1	4	4	
									2090	N					N					N					N					N					Y	1	4	4		Y	1	4	4	
								8.5	2030	N					N					N					N					N					Y	2	5	10		Y	1	5	5	
									2060	N					N					N					N					N					Y	2	5	10		Y	1	5	5	
									2090	N					N					N					N					N					Y	2	5	10		Y	2	5	10	
			✓					4.5	2030	N					N					N					N					Y	1	3	3	Increase in precipitation would contribute to floods and more runoff to the watershed	Y	1	4	4	Increase in total precipitation on a single day would produce runoff and flooding in the watershed	Y	1	4	4	Increase in nu daily precipita than 20mm runoffand wa
									2060	N					N					N					N					Y	2	3	6		Y	1	4	4		Y	1	4	4	
									2090	N					N					N					N					Y	3	4	12		Y	1	4	4		Y	2	4	8	
								8.5	2030	N					N					N					N					Y	2	3	6		Y	1	4	4		Y	1	4	4	
									2060	N					N					N					N					Y	3	4	12		Y	2	5	10		Y	2	5	10	
									2090	N					N					N					N					Y	3	4	12		Y	2	5	10		Y	3	5	15	
H1C	Lagoon C	✓						4.5	2030	N					N					N					Y	2	4	8	Very hot days could reduce moisture and unfroze entrapped cold soil, causing structure deformation in the long term	N					Y	1	4	4	Increase in total precipitation on asingle day would affect the load carrying capacity	Y	1	4	4	Increase in nu daily precipita than 20mm loadcarr
									2060	N					N					N					Y	3	5	15		N					Y	1	4	4		Y	1	4	4	
									2090	N					N					N					Y	3	5	15		N					Y	3	5	15		Y	3	5	15	
								8.5	2030	N					N					N					Y	4	5	20		N					Y	3	5	15		Y	3	5	15	
									2060	N					N					N					Y	5	6	30		N					Y	5	6	30		Y	5	6	30	
									2090	N					N					N					Y	6	6	36		N					Y	5	6	30		Y	5	6	30	
			✓					4.5	2030	N					N					N					Y	2	3	6	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	Y	1	4	4	Increase in precipitation would contribute to floods and more runoff to the watershed	Y	1	3	3	Increase in total precipitation on a single day would produce runoff and flooding in the watershed	Y	1	3	3	Increase in nu daily precipita than 20mm runoffand fl
									2060	N					N					N					Y	3	4	12		Y	2	4	8		Y	1	3	3		Y	1	3	3	
									2090	N					N					N					Y	3	4	12		Y	3	4	12		Y	2	4	8		Y	2	4	8	
								8.5	2030	N					N					N					Y	4	5	20		Y	3	4	12		Y	2	4	8		Y	3	4	12	
									2060	N					N					N					Y	5	6	30		Y	4	5	20		Y	3	5	15		Y	5	5	25	
									2090	N					N					N					Y	5	6	30		Y	5	6	30		Y	5	6	30		Y	5	6	30	
						✓		4.5	2030	N					N					N					Y	3	3	9	Very hot days would affect workforce performance with heat exhaustion	N					Y	1	3	3	Increase flooding events would produce erosion and runoff to theElk River	Y	1	3	3	Increase in nu daily precipita than 20mm flooding ever the
									2060	N					N					N					Y	4	3	12		N					Y	1	3	3		Y	1	3	3	
									2090	N					N					N					Y	4	3	12		N					Y	3	4	12		Y	3	4	12	
								8.5	2030	N					N					N					Y	4	3	12		N					Y	4	5	20		Y	4	5	20	
									2060	N					N					N					Y	5	3	15		N					Y	4	5	20		Y	4	5	20	
									2090	N					N					N					Y	5	3	15		N					Y	4	5	20		Y	4	5	20	
							✓	4.5	2030	N					N					N					Y	3	5	15	A potential breach caused by structure deformation could result in the release of tailings to the Elk River, affecting aquatic life downstream	N					Y	1	3	3	Increase in total precipitation on a single day would increment runoff and water contaminants transport	Y	1	3	3	Increase in nu daily precipitat than 20mm v runoff and wa tra
									2060	N					N					N					Y	4	5	20		N					Y	1	3	3		Y	1	3	3	
									2090	N					N					N					Y	4	5	20		N					Y	3	4	12		Y	3	4	12	
								8.5	2030	N					N					N					Y	4	5	20		N					Y	3	4	12		Y	3	4	12	
									2060	N					N					N					Y	5	6	30		N					Y	4	5	20		Y	5	5	25	
									2090	N					N					N					Y	6	6	36		N					Y	4	5	20		Y	5	5	25	
H1D	Lagoon D	✓						4.5	2030	N					N					N					Y	2	4	8	Very hot days could reduce moisture and unfroze entrapped cold soil, causing structure deformation in the long term	N					Y	1	4	4	Increase in total precipitation on asingle day would affect the load carrying capacity	Y	1	4	4	Increase in nu daily precipita than 20mm loadcarr
									2060	N					N					N					Y	3	5	15		N					Y	1	4	4		Y	1	4	4	
									2090	N					N					N					Y	3	5	15		N					Y	3	5	15		Y	3	5	15	
								8.5	2030	N					N					N					Y	4	5	20		N					Y	3	5	15		Y	3	5	15	
									2060	N					N					N					Y	5	6	30		N					Y	5	6	30		Y	5	6	30	
									2090	N					N					N					Y	6	6	36		N					Y	5	6	30		Y	5	6	30	
			✓					4.5	2030	N					N					N					Y	2	3	6	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	Y	1	4	4	Increase in precipitation would contribute to floods and more runoff to the watershed	Y	1	3	3	Increase in total precipitation on a single day would produce runoff and flooding in the watershed	Y	1	3	3	Increase in nu daily precipita than 20mm runoffand wat
									2060	N					N					N					Y	3	4	12		Y	2	4	8		Y	1	3	3		Y	1	3	3	
									2090	N					N					N					Y	3	4	12		Y	3	4	12		Y	2	4	8		Y	2	4	8	
								8.5	2030	N					N					N					Y	4	5	20		Y	3	4	12		Y	3	5	15		Y	3	5	15	
									2060	N					N					N					Y	5	6	30		Y	4	5	20		Y	5	6	30		Y	5	6	30	
									2090	N					N					N					Y	5	6	30		Y	5	6	30		Y	5	6	30		Y	5	6	30	
					✓			4.5	2030	N					N					N					Y	1	4	4	Very hot days will increase incidence of heat-related illness, reducing Emergency Response capacity	N					Y	2	3	6	Increase in total precipitation on asingle day would increase the required evacuation area in a breaching event	Y	2	3	6	Increase in nu daily precipitat than 20mm w required eva breach
									2060	N					N					N					Y	2	4	8		N					Y	2	3	6		Y	2	3	6	
									2090	N					N					N					Y	2	4	8		N					Y	3	4	12		Y	3	4	12	
								8.5	2030	N					N					N					Y	2	4	8		N					Y	4	5	20		Y	4	5	20	
									2060	N					N					N					Y	3	5	15		N					Y	5	6	30		Y	5	6	30	
									2090	N					N					N					Y	4	5	20		N					Y	6	6	36		Y	5	6	30	
						✓		4.5	2030	N					N					N					Y	3	3	9	Very hot days would affect workforce performance with heat exhaustion	N					Y	1	3	3	Increase flooding events would produce erosion and runoff to theElk River	Y	1	3	3	Increase num daily precipita than 20mm erosion and
									2060	N					N					N					Y	4	3	12		N					Y	1	3	3		Y	1	3	3	
									2090	N					N					N					Y	4	3	12		N					Y	3	4	12		Y	3	4	12	
								8.5	2030	N					N					N					Y	4	3	12		N					Y	1	3	3		Y	1	3	3	
									2060	N					N					N					Y	5	3	15		N					Y	3	4	12		Y	3	4	12	
									2090	N					N					N					Y	5	3	15		N					Y	5	5	25		Y	5	5	25	
							✓	4.5	2030	N					N					N					Y	3	5	15	Very hot days cause structure deformation that could result in the release of tailings to the Elk River, affecting aquatic life downstream	N					Y	1	3	3	Increase in total precipitation on a single day would increment runoff and water contaminants transport	Y	1	3	3	Increase in nu daily precipitat than 20mm v runoff and wa tra
									2060	N					N					N					Y	4	5	20		N					Y	1	3	3		Y	1	3	3	
									2090	N					N					N					Y	4	5	20		N					Y	3	4	12		Y	3	4	12	
								8.5	2030	N					N					N					Y	4	5	20		N					Y	1	3	3		Y	1	3	3	
									2060	N					N					N					Y	5	6	30		N					Y	5	5	25		Y	5	5	25	
									2090	N					N					N					Y	6	6	36		N					Y	5	5	25		Y	5	5	25	

H	Mine Closure Components	Components Response Considerations						Scenario		1					2					3				
		Structural Design	Watershed, Surface Water & Groundwater	Operations, Maintenance & Materials Performance	Emergency Response	Social Effects	Environmental Effects			Mean Daily Temperature					Max/Min Temperature					Days with Tmax > 25C				
										RCP 4.5: 4.97°C (76.2%); 6.02°C (113.5%); 6.32°C (124.3%) RCP 8.5: 5.15°C (82.7%); 7.20°C (155.5%); 8.48°C (200.7%)				Mean temperature is the average temperature on a given day and is usually obtained by averaging the daily maximum and minimum temperatures.	Min: RCP 4.5 : -0.94°C / -0.16°C / -0.45°C RCP 8.5: -0.68°C / 1.37 °C / 2.66 °C Max: RCP 4.5: 10.86°C / 11.89°C / 12.19°C RCP 8.5: 11.03°C / 13.03°C / 14.29°C				This is the average maximum and minimum temperature for a given time period and is derived by averaging all the daily maximum and minimum temperatures in that time period.	RCP 4.5: 81%; 122%; 133% RCP 8.5: 90%; 170%; 232%				High temperatures are important. They determine if plants and animals can thrive, they limit or enable outdoor activities, define how we design our buildings and vehicles, and shape our transportation and energy use. It is useful to know how high summer temperatures are likely to become in the future, to make sure that our cooling and air-conditioning systems can reliably deal with these extremes.
H3	**Water Treatment**	Mark Relevant Responses ✓								Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score
H3A	Elkview Saturated Rock Fill Water Treatment Facility		✓					4.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
								8.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
				✓				4.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
								8.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
						✓		4.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
								8.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
							✓	4.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
								8.5	2030	N					N					N				
									2060	N					N					N				
									2090	N					N					N				
H4	**Biodiversity Management Plan**	Mark Relevant Responses ✓								Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score
H4A	Re-Vegetation		✓					4.5	2030	N					Y	2	3		Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	Y	2	3	6	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance
									2060	N					Y	2	3			Y	3	3	9	
									2090	N					Y	4	3			Y	3	3	9	
								8.5	2030	N					Y	2	3			Y	4	4	16	
									2060	N					Y	4	4			Y	5	4	20	
									2090	N					Y	5	4			Y	5	4	20	
				✓				4.5	2030	Y	1	3	3	Temperature increase modify growing patterns of trees and grass of previously selected seeds	Y	1	3	3	Temperature increase modify growing patterns of trees and grass of previously selected seeds	Y	1	3	3	Temperature increase modify growing patterns of trees and grass of previously selected seeds
									2060	Y	3	3	9		Y	3	3	9		Y	3	4	12	
									2090	Y	4	3	12		Y	3	3	9		Y	3	4	12	
								8.5	2030	Y	3	4	12		Y	4	4	16		Y	4	5	20	
									2060	Y	3	4	12		Y	4	4	16		Y	4	5	20	
									2090	Y	4	4	16		Y	5	4	20		Y	5	6	30	
						✓		4.5	2030	Y	1	4	4	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems	Y	1	3	3	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems	Y	1	3	3	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems
									2060	Y	3	4	12		Y	3	5	15		Y	3	4	12	
									2090	Y	3	5	15		Y	3	5	15		Y	3	4	12	
								8.5	2030	Y	4	5	20		Y	4	5	20		Y	4	5	20	
									2060	Y	5	6	30		Y	5	7	35		Y	5	6	30	
									2090	Y	5	6	30		Y	5	7	35		Y	5	6	30	
							✓	4.5	2030	Y	2	3	6	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal	Y	2	4	8	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal	Y	2	3	6	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradation and soil removal
									2060	Y	3	3	9		Y	3	4	12		Y	3	4	12	
									2090	Y	3	4	12		Y	3	4	12		Y	3	4	12	
								8.5	2030	Y	3	4	12		Y	3	4	12		Y	3	5	15	
									2060	Y	5	6	30		Y	5	5	25		Y	5	6	30	
									2090	Y	6	6	36		Y	6	6	36		Y	6	6	36	
H4B	Wildlife (ungulate)			✓				4.5	2030	Y	2	3	6	Temperature increase modify wildlife distribution patterns	Y	1	3	3	Change in seasons Temperature modify wildlife distribution patterns and carrying capacity	Y	1	3	3	Change in seasons Temperature modify wildlife distribution patterns and carrying capacity
									2060	Y	2	3	6		Y	3	3	9		Y	3	4	12	
									2090	Y	3	4	12		Y	4	4	16		Y	4	4	16	
								8.5	2030	Y	4	5	20		Y	4	5	20		Y	4	4	16	
									2060	Y	5	6	30		Y	5	6	30		Y	5	4	20	
									2090	Y	5	6	30		Y	5	6	30		Y	5	4	20	
						✓		4.5	2030	Y	1	2	2	Temperature increase modify wildlife population affecting traditional hunting	Y	1	3	3	Temperature increase modify wildlife population affecting traditional hunting	Y	1	3	3	Temperature increase modify wildlife population affecting traditional hunting
									2060	Y	2	3	6		Y	2	3	6		Y	2	4	8	
									2090	Y	2	3	6		Y	2	3	6		Y	2	4	8	
								8.5	2030	Y	3	4	12		Y	3	4	12		Y	3	4	12	
									2060	Y	4	5	20		Y	4	4	16		Y	4	5	20	
									2090	Y	5	5	25		Y	5	5	25		Y	5	5	25	
							✓	4.5	2030	Y	1	3	3	Temperature increase modify wildlife population due reduction of winter range habitat	Y	1	3	3	Temperature increase modify wildlife population due reduction of winter range habitat	Y	1	3	3	Temperature increase modify wildlife population due reduction of winter range habitat
									2060	Y	3	4	12		Y	3	4	12		Y	3	4	12	
									2090	Y	4	6	24		Y	4	4	16		Y	4	4	16	
								8.5	2030	Y	4	6	24		Y	4	4	16		Y	4	4	16	
									2060	Y	5	6	30		Y	5	5	25		Y	6	5	30	
									2090	Y	5	6	30		Y	5	5	25		Y	6	5	30	

Mine Closure Components	Scenario		4					5					6					7				
			Days with Tmax > 30C					Total Precipitation (mm)					Maximum 1-Day Total Precipitation (mm)					Wet Days >20mm				
			RCP 4.5: 11 (330%); 17.5 (585%);19.8 (675%) RCP 8.5: 12.3 (379%); 26.7 (943%); 40.6 (1488%)				When temperatures are very hot, people - especially the elderly - are much more likely to suffer from heat exhaustion and heat stroke. Many outdoor activities become dangerous or impossible in very high temperatures. In general, Canadians are not used to extremely hot summers, and further warming will bring new and unusual risks as well as a very different experience of the summer season.	RCP 4.5: 658.4 / 669.1 / 674.3 RCP 8.5: 653.8 / 687.7 / 698.6				This is the total precipitation (rain and snow) for a given time period.	RCP 4.5 31.08 (10%); 31.48 (11%); 31.87 (12%) RCP 8.5: 31.23 (10%); 33.76 (19%); 34.52 (22%)				This is the largest precipitation total on a singleday.	RCP 4.5: 2.44 (36%); 2.6 (47%); 2.7 (52%) RCP 8.5: 2.4 (35%); 2.9 (65%); 3.3 (83%)				Numbe precipi
Water Treatment			Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale Score
Elkview Saturated Rock Fill Water Treatment Facility	4.5	2030	Y	1	4	4	Very hot days would increase the algal growth in surface water	N					Y	1	3	3	Increase in total precipitation on asingle day would affect the SRF performance capacity	Y	1	3	3	Increase daily pre than 20m per
		2060	Y	2	4	8		N					Y	1	3	3		Y	1	3	3	
		2090	Y	3	5	15		N					Y	2	4	8		Y	2	4	8	
	8.5	2030	Y	4	5	20		N					Y	3	5	15		Y	3	5	15	
		2060	Y	4	5	20		N					Y	3	5	15		Y	3	5	15	
		2090	Y	5	6	30		N					Y	4	6	24		Y	4	6	24	
	4.5	2030	Y	1	2	2	Very hot days would influence selenium-consuming bacterial growth on plant	Y	1	3	3	Increase in precipitation would generate additional water to be treated, reducing the operation capacity	N					N				
		2060	Y	2	2	4		Y	1	3	3		N					N				
		2090	Y	3	2	6		Y	2	4	8		N					N				
	8.5	2030	Y	4	2	8		Y	1	3	3		N					N				
		2060	Y	4	3	12		Y	2	4	8		N					N				
		2090	Y	5	3	15		Y	2	4	8		N					N				
	4.5	2030	Y	1	3	3	Very hot days would increase the water temperature discharged	N					N					N				
		2060	Y	3	3	9		N					N					N				
		2090	Y	4	4	16		N					N					N				
	8.5	2030	Y	4	4	16		N					N					N				
		2060	Y	4	4	16		N					N					N				
		2090	Y	6	5	30		N					N					N				
	4.5	2030	Y	3	3	9	Very hot days would affect the system operability, reducing the removement of contaminants in the discharged water	N					Y	1	3	3	Increase in total precipitation on a single day would affect the quality and quantity of discharged water	Y	1	3	3	Increase daily pre than 2 quality ar
		2060	Y	4	3	12		N					Y	1	3	3		Y	1	3	3	
		2090	Y	4	3	12		N					Y	2	4	8		Y	2	4	8	
	8.5	2030	Y	5	4	20		N					Y	2	4	8		Y	2	4	8	
		2060	Y	6	5	30		N					Y	4	5	20		Y	4	5	20	
		2090	Y	6	5	30		N					Y	5	6	30		Y	5	6	30	
Biodiversity Management Plan			Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale For Severity Score	Y/N	P	S	R	Rationale Score
Re-Vegetation	4.5	2030	Y	2	3	6	Increased incidence of forest fires is expected to increase runoff, affecting watershed water balance	N					Y	1	2	2	Increase in total precipitation on a single day would produce runoff and flooding in the watershed	Y	1	2	2	Increase daily pre than 2 runo
		2060	Y	3	3	9		N					Y	2	2	4		Y	2	2	4	
		2090	Y	3	3	9		N					Y	2	2	4		Y	2	2	4	
	8.5	2030	Y	4	4	16		N					Y	2	2	4		Y	2	2	4	
		2060	Y	6	5	30		N					Y	4	3	12		Y	3	3	9	
		2090	Y	6	5	30		N					Y	5	3	15		Y	3	3	9	
	4.5	2030	Y	1	3	3	Temperature increase modify growing patterns of trees and grass of previously selected seeds	Y	1	4	4	Changes on water cycle will increase the change in existing plant species composition	Y	1	3	3	Changes on water cycle will increase the change in existing plant species composition	N				
		2060	Y	3	4	12		Y	1	4	4		Y	1	3	3		N				
		2090	Y	3	4	12		Y	3	5	15		Y	3	4	12		N				
	8.5	2030	Y	4	5	20		Y	1	4	4		Y	1	3	3		N				
		2060	Y	4	5	20		Y	3	5	15		Y	3	4	12		N				
		2090	Y	5	6	30		Y	3	5	15		Y	3	4	12		N				
	4.5	2030	Y	1	3	3	Temperature increase produce more wildfires and insect disturbance affecting the economic and social benefits produced on forest ecosystems	N					N					N				
		2060	Y	3	4	12		N					N					N				
		2090	Y	3	4	12		N					N					N				
	8.5	2030	Y	4	5	20		N					N					N				
		2060	Y	5	6	30		N					N					N				
		2090	Y	5	6	30		N					N					N				
	4.5	2030	Y	2	3	6	Increased incidence of droughts and forest fires is expected to reduce the erosion-protecting cover, resulting in soil degradationand soil removal	N					N					N				
		2060	Y	3	4	12		N					N					N				
		2090	Y	3	4	12		N					N					N				
	8.5	2030	Y	3	5	15		N					N					N				
		2060	Y	5	6	30		N					N					N				
		2090	Y	6	6	36		N					N					N				
Wildlife (ungulate)	4.5	2030	Y	1	3	3	Change in seasons Temperature modify wildlife distribution patterns and carrying capacity	Y	1	3	3	Changes on water cycle will increase the change in existing plant species composition used byanimals as forrage and shelter	Y	1	3	3	Changes on water cycle will increase the change in existing plant species composition used byanimals as forrage and shelter	N				
		2060	Y	3	4	12		Y	1	3	3		Y	1	3	3		N				
		2090	Y	4	4	16		Y	3	3	9		Y	3	4	12		N				
	8.5	2030	Y	4	4	16		Y	1	3	3		Y	1	3	3		N				
		2060	Y	5	4	20		Y	4	4	16		Y	4	4	16		N				
		2090	Y	5	4	20		Y	4	4	16		Y	4	4	16		N				
	4.5	2030	Y	1	3	3	Temperature increase modify wildlife population affecting traditional hunting	N					N					N				
		2060	Y	2	4	8		N					N					N				
		2090	Y	2	4	8		N					N					N				
	8.5	2030	Y	3	4	12		N					N					N				
		2060	Y	4	5	20		N					N					N				
		2090	Y	5	5	25		N					N					N				
	4.5	2030	Y	1	3	3	Temperature increase modify wildlife population due reduction of winter range habitat	N					Y	1	2	2	Changes on water cycle will affect Elk's seasonal habitat selection	Y	1	2	2	Changes Elk's seas
		2060	Y	3	4	12		N					Y	1	2	2		Y	1	2	2	
		2090	Y	4	4	16		N					Y	3	2	6		Y	3	2	6	
	8.5	2030	Y	4	4	16		N					Y	1	2	2		Y	1	2	2	
		2060	Y	6	5	30		N					Y	4	2	8		Y	4	2	8	
		2090	Y	6	5	30		N					Y	4	2	8		Y	4	2	8	

Appendix I - Contribution to Closure Maturity

Integration into Life of Asset planning

Climate risk identification will aid understanding of the asset context by providing knowledge regarding the main climate-related hazards, exposures, and vulnerabilities in the SES. The plan to manage the risk is refined as the time to closure decreases. Decision-makers will have enough information to review and approve the closure plan.

Knowledge base

Social and environmental data are analysed with future projections and climate scenarios, allowing information to be updated for monitoring progressive closure implementation. The closure vision is aligned with knowledge of potential climate risks and used to predict success of closure.

Closure vision, principles, and objectives

The SES perspective of the framework allows decision-makers to integrate a regional and holistic context into closure planning. This is important for a potential collaborative closure vision with different mines and land-based economic activities in the same watershed. The framework will provide the opportunity to develop this vision in consultation with external stakeholders, identifying the principles and objectives in an integrated watershed management plan.

Post-closure land use

Natural solutions and adaptation strategies based on ecosystem services will provide a sustainable approach for the end land use based on future capabilities and a socio-economic context. The framework will aid assessment of land use options in terms of feasibility and local land use planning strategies, boosting ecological and societal effects. With this knowledge, operations will be performed in alignment with identified post-closure land uses.

Engagement for closure

The identification of relevant ecosystem services that supports local livelihoods bring a strategic approach to incorporate local knowledge and empowers stakeholders in the decision-making process. Thus, the local stakeholders will endorse the closure criteria, and will be involve in the activities, execution, monitoring and reporting tasks of the closure progress.

Threats and opportunities including temporary or sudden closure

Analysis of potential threats from a climate change perspective incorporates knowledge regarding habitat shifts, projected changes in temperature and precipitation, and potential extreme local events. At the same time, long-term local government plans assess vulnerabilities, making it possible to incorporate opportunities based on the climate information identified as part of the risk assessment.

Closure activities

Potential closure activities will be assessed with the desired climate change adaptation outcomes in terms of restoration, management, and conservation. Thus, the likelihood of closure activities achieving the closure objectives will be maximised.

Success / closure / design criteria

The SES provides a multi-disciplinary perspective to design the closure plan. Further, it provides information to construct criteria based on climate data and company risk tolerance. Finally, monitoring of progressive closure provides the opportunity for corrective actions required for the closure plan to succeed.

Progressive closure

The climate risk scenario analysis provides information to help make decisions in which climate plays a role in understanding future ecosystems. This permits planning for progressive closure, for example, by incorporating seeds adapted to specific conditions or designing slopes to avoid runoff and erosion. Periodically revising climate risk allows for the closure plan knowledge base to be updated and actions adjusted to ensure the post-closure land use is sustainable over time.

Social and economic transition

This climate risk framework supports holistic watershed analysis, where the socio-economic impacts and opportunities of climate change are considered for closure and land restoration. Potential development projects and business plans will be related to local ecosystem services, aligned with local government plans. Local actors agree to and execute plans, with strong long-term ownership of outcomes.

Closure costs

Information related to future climate scenarios and adaptation strategies will support a financial analysis to define potential costs to close the mine for the closure implementation, post-closure, monitoring, and maintenance stages.

Closure execution plan

Climate data are analysed and integrated to inform closure planning, together with projections and climate scenario evaluation. The understanding of climate risks and adaptation strategies will provide information for long-term monitoring.

Monitoring, maintenance, and management

All potential climate risks, hazards from the mine site, and exposures and vulnerabilities in the watershed will provide detailed information to contribute to the design of a monitoring and data management system. The climate risk update supports management of short- and long-term adaptation outcomes, with specific indicators used to pursue closure objectives.

Relinquishment / Successful transition

Understanding land capabilities, potential climate impacts, adaptation strategies, and stakeholder views will assist definition of mine closure success criteria to ensure a positive transition.