core6 ENVIRONMENTAL

A FRAMEWORK TO ASSESS CLIMATE CHANGE IMPACTS ON CONTAMINATED SITES IN BRITISH COLUMBIA

A Framework to Assess Climate Change Impacts on Contaminated Sites in British Columbia

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R2	2023-10-13	SM, JT	Final Report. Incorporating CSAP's final comments.
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NOTE TO READER

This document was prepared for the Contaminated Sites Approved Professional Society (CSAP) for use by Approved Professionals in their work. The BC Ministry of Environment and Climate Change Strategy (ENV) has not endorsed this document and the information in this document in no way limits the director's exercise of discretion under the Environmental Management Act.

CSAP has recommended that Approved Professionals use their professional judgement[1] in applying any guidance, including this document. As the science upon which contaminated sites remediation is based is relatively young and because no two sites that involve the natural environment are the same, the need to exercise professional judgement within the regulatory process is recognized.

Ultimately, submissions for Environmental Management Act instruments need to meet regulatory requirements. The onus is on qualified professionals and Approved Professionals to document the evidence upon which their recommendations depend.

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The conclusions and recommendations of this document are based upon applicable legislation and policy existing at the time the document was prepared. Changes to legislation and policy may alter conclusions and recommendations.

[1] https://csapsociety.bc.ca/wp-content/uploads/ATT-3_-CSAP-Professional-Judgement-May2nd.pdf

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EXECUTIVE SUMMARY

Climate change is expected to have varying effects on different regions of British Columbia (BC), such as intense rainfall and sea level rise in the South & West Coast region, and higher temperatures and drought in the south-central Okanagan region. These effects represent hazards that could impact contaminated sites, leading to the destabilization or mobilization of contaminants and potentially reaching receptors through various fate and transport processes. However, assessing the degree to which these hazards will affect a contaminated site and the resulting impacts is complex and difficult due to the site-specific nature of the risks.

While there are several guidance documents available for assessing climate change risks at contaminated sites, such as the Federal Contaminated Sites Action Plan, there is no such guidance under the provincial government of BC. However, the Province released the discussion paper '*Making Contaminated Sites Climate Ready*' in 2022 which presents a number of potential actions the BC Ministry of Environment and Climate Change Strategy (BC ENV) is considering to address climate change and further incorporate sustainability in BC's contaminated sites framework. To address this gap, the Contaminated Sites Approved Professionals (CSAP) Society has retained Core6 Environmental Ltd. (Core6) to develop a framework document to support environmental practitioners in assessing potential climate change impacts on contaminated sites in BC.

The intent of this document is to provide environmental practitioners with useful tools and a framework to use when conducting a vulnerability assessment of contaminated sites in BC. Currently, there is no legislative or regulatory requirement under the provincial government to conduct a vulnerability assessment of contaminated sites to climate change and no guidance has yet been developed to assist environmental practitioners with this process. However, a client or stakeholders may require environmental practitioners to conduct climate change vulnerability assessments. Alternatively, as leaders in environmental protection, responsible practitioners may choose to conduct such assessments (or portions of them) as best practice. Should new policies or regulatory updates be released by the provincial government, this document will need to be revised to reflect the legislative and/or regulatory changes.

The framework document provides tools for practitioners to consider climate change hazards during site investigations and risk management of contaminated sites. The framework aims to identify the climate change hazards most likely to affect a contaminated site based on its location and site characteristics, evaluate the potential impacts of those hazards, and conduct a climate change vulnerability assessment for a given contaminated site in BC. This framework document provides tools and methodologies for environmental practitioners to assess a contaminated site vulnerability to climate change. However, practitioners are expected to use their knowledge of the site (through the completion of site investigation) and their professional judgement to apply this framework.

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ACRONYMS & ABBREVIATIONS

AR5	IPCC's Fifth Assessment Report
AR6	IPCC's Sixth Assessment Report
BC	British Columbia
BC ENV	British Columbia Ministry of Environment and Climate Change Strategy
C3S	Copernicus Climate Change Services
CCAP	Climate Change Adaptation Program
CCME	Canadian Council of Ministers of the Environment
CIER	Centre for Indigenous Environmental Resources
CMIP6	Sixth Coupled Model Intercomparison Project
Core6	Core6 Environmental Ltd.
CSM	Conceptual Site Model
CSR	Contaminated Site Regulation
DMF	Decision-Making Framework
FCSAP	Federal Contaminated Sites Action Plan
GCMs	Global Climate Models
GHG	Greenhouse Gas
HHERA	Human Health and Ecological Risk Assessment
IPCC	Intergovernmental Panel on Climate Change
LNAPL	Light Non-Aqueous Phase Liquid
PCOC	Potential Contaminant of Concern
RCMs	Regional Climate Models
RCP	Representative Concentrating Pathway
SSP	Shared Socioeconomic Pathway
US EPA	United States Environmental Protection Agency
ITRC	Interstate Technology Regulatory Council

1 INTRODUCTION

1.1 Background

Different regions of British Columbia are expected to experience varying effects of climate change, such as intense rainfall and sea level rise in the South and West Coast, and higher temperatures and drought in the south-central Okanagan region. These adverse effects represent sources of potential damage or degradation of the natural conditions and are therefore referred to as hazards. Climate change hazards have the potential to impact contaminated sites, leading to the destabilization or mobilization of contaminants, which could then reach sensitive receptors owing to various fate and transport processes. The degree to which these hazards will affect a contaminated site and the resulting impacts are highly site-specific, complex, and difficult to assess.

The intent of this document is to provide environmental practitioners with useful tools and a framework to use when conducting a vulnerability assessment of contaminated sites in BC. Currently, there is no legislative or regulatory requirement under the provincial government to conduct a vulnerability assessment of contaminated sites to climate change and no guidance has yet been developed to assist environmental practitioners with this process. However, a client or stakeholders may require environmental practitioners to conduct climate change vulnerability assessments. Alternatively, as leaders in environmental protection, responsible practitioners may choose to conduct such assessments (or portions of them) as best practice. Should new policies or regulatory updates be released by the provincial government, this framework document will need to be revised to reflect the legislative and/or regulatory changes.

1.2 Objectives and Scope of Work

This document outlines a framework that environmental practitioners may use to consider climate change during site investigations and risk management of contaminated sites. While this framework contains a substantial amount of information, practitioners are expected to use their professional judgement when using this document. The document intends to assist the environmental practitioners to:

- Identify the climate change hazards most likely to affect any specific contaminated site in BC, considering multiple factors.
- Identify the potential impacts of those climate hazards on different site contamination scenarios and associated effects on the site risk management.
- Conduct a climate change vulnerability assessment for a given contaminated site in BC, to identify which climate hazards, and site contamination and risk management scenarios warrant the greatest priority and attention.

A review of multiple Canadian and international documents related to climate change and contaminated sites was completed to prepare this framework. They are detailed in Section 3 and referenced throughout the framework document, where relevant.

2 FRAMEWORK APPROACH

The steps laid out in this framework document start with a high-level overview of the regional climate change projections for a given contaminated site in BC, and potential climate change hazards that may be applicable to the site based on the sites location. The following steps consist of identifying what factors may increase the vulnerability of a site to climate change, understanding how each climate change hazard has the potential to affect subsurface contamination and illustrating these in a future conceptual site model. The different methodologies available to assess the vulnerability of a contaminated site to climate change are discussed in Section 6. Prior to starting the vulnerability assessment, environmental practitioners need to decide on the most appropriate climate data set (emission scenario) and time horizon to consider in the assessment. This is explained in the sub-sections below.

2.1 Climate Model Projections and Downscaling

Global Climate Models (GCMs) represent physical processes in the atmosphere, oceans, cryosphere and land surface. They are used to simulate the response of the global climate system to the increase in GHG concentrations, using different emission scenarios. These tools assess the impacts of future GHG concentrations on changes in temperature, precipitation, wind speed, etc. GCMs are large-scale climate models which are run at a very coarse resolution, with grids often larger than 100x100 km^2 (C3S, 2019). This resolution is generally too coarse for site-specific assessments, therefore downscaling techniques have been developed to make climate predictions at finer temporal and spatial scales, to fit the purpose of local level analysis and planning. Downscaling tools such as high resolution regional climate models (RCMs) can then be used to simulate the scenarios on a finer spatial scale, using finer level local conditions. There are two main approaches to downscaling climate model outputs:

- Dynamical downscaling: where outputs from GCMs are used to drive higher resolution regional climate models with a better representation of local terrain and other conditions; and
- Statistical downscaling: where statistical links are established between large-scale climate phenomena and observed local-scale climate.

2.2 Emission Scenario

2.2.1 Fifth Assessment Report (AR5)

The Representative Concentrating Pathways (RCPs) are a set of four scenarios that were developed by the Intergovernmental Panel on Climate Change (IPCC) in the Fifth Assessment Report (AR5) to project different levels of future greenhouse gas (GHG) emissions and their potential impacts on the climate (IPCC, 2014). These scenarios are based on assumptions about global population growth, economic development, energy consumption, and technological progress (van Vuuren *et al*, 2011). The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5).

RCP2.6

According to the IPCC's Fifth Assessment Report (AR5), released on 2014, the RCP2.6 scenario represents a future with the lowest GHG among the three scenarios. In this scenario, global CO_2 emissions peak in the 2010s and decline thereafter, reaching net-zero CO_2 emissions by the year 2100. This scenario assumes that there will be a rapid adoption of low-carbon energy sources, reforestation, and other related improvements (IPCC, 2014). RCP2.6 is likely to keep global temperature rise below 2 °C and the mean sea level rise below 0.4 m by 2100 (IPCC, 2014).

RCP4.5

The RCP4.5 is one of the two intermediate stabilization pathways (lower medium) among the four representative concentration pathways. This scenario assumes that global GHG emissions will stabilize by the mid-21st century and then begin to decline. This scenario assumes that there will be moderate efforts to reduce emissions, such as the adoption of renewable or cleaner energy sources (IPCC, 2014). RCP4.5 is more likely than not to result in global temperature rise between 2 °C and 3 °C, by 2100 with a mean sea level rise 35% higher than that of RCP2.6.

RCP6.0

RCP6.0 is one of the two intermediate stabilization pathways (higher medium) among the four representative concentration pathways. This scenario uses a high greenhouse gas emission rate with a peak around 2080 and then decline owing to the employment of a range of technologies and strategies for reducing greenhouse gas emissions. Projections for temperature according to RCP6.0 include continuous global warming through 2100 and the global temperature rise by about 3°C to 4 °C by 2100. The mean sea level rise projected for RCP6.0 is similar to RCP4.5 (0.48 m) (IPCC, 2014).

RCP8.5

The RCP8.5 scenario represents the worst-case scenario with the highest GHG emissions. It assumes a future where there are no climate policies in place and fossil fuels remain the primary energy source. Under this scenario, global GHG emissions continue to rise throughout the 21st century, leading to a temperature increase of around 4.5°C by the end of the century (Riahi *et al.*, 2017) and a mean sea level rise of 0.63 m (IPCC, 2014).

2.2.2 Sixth Assessment Report (AR6)

A synthesis of the new IPCC's Sixth Assessment Report (AR6) had been released in March 2023. The RCP scenarios have been updated to the Shared Socioeconomic Pathways (SSPs) and provide a more nuanced and comprehensive range of future pathways to consider when evaluating potential impacts of different policy and technology options on the future climate. This is due to the inclusion of the sixth Coupled Model Intercomparison Project (CMIP6) model which generally have increased complexity and spatial resolution, representing the atmosphere, oceans, and small-scale processes such as clouds, water vapour, and aerosols in more detail compared to the CMIP5 models used in the AR5 report (ClimateData.ca, 2023). Additionally, the

CMIP6 model runs GHG concentrations starting in 2015, not 2006 as with the CMIP5 model. Other differences between the AR5 and AR6, pertinent to the GHG emission scenarios include the following:

- The lowest GHG emissions scenario in AR6 is SSPE1-1.9 which represents an aim to limit global warming to 1.5°C instead of 2°C as in the AR5, by achieving net-zero CO_2 emissions around the mid-century and negative emissions thereafter which was not considered in the AR5.
- The SSP2-4.5 scenario is similar to the RCP4.5 scenario, but with greater uncertainty due to the broader range of social and technological drivers.
- The SSP3-7.0 scenario represents a high GHG emission scenario where CO_2 emissions double by 2100 with an estimated warming of 3.6°C by 2100. This scenario replaces RCP6.0.
- The SSP5-8.5 scenario is also similar to the RCP8.5 scenario, but with a slightly lower range of warming projections due to the inclusion of more recent research on climate sensitivity.

There is not a significant difference in climate projections between the SSP1-1.9, SSP2-4.5, SSP2-7.0 and SSP5-8.5 scenarios up until the year 2040 after which the scenarios' start to diverge quickly. The reason for this is that the climate system responds relatively slowly to changes in GHG concentrations. So the choice of emission scenario is not important until mid-century.

2.2.3 Selecting Emission Scenarios

Selecting appropriate GHG emission scenarios for a climate change vulnerability assessment is essential to determine the climate change projections for a region or a particular site location. The CMIP6 climate model has been included in the ClimateData.ca datasets and is therefore available to use for climate projections for a contaminated site. It is important for practitioners to use the most updated climate projections and understand the uncertainties around these projections to assess climate change hazards to a contaminated site. Therefore, vulnerability assessments may need to be updated and adjusted as new information becomes available.

The government of Canada recommends the use of several emissions scenarios for decision-making including future climate data (Government of Canada, 2018). This will help to account for uncertainty about the amount of GHG emissions in the future.

The "Precautionary Principle" is defined by FCSAP (2022) and the Government of Canada (2020) as "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". In accordance with the FCSAP (2022) document and in alignment with the Precautionary Principle, it is recommended that practitioners consider the worst-case emission scenario (i.e., RCP 8.5 or SSP5-8.5) as a first priority when assessing the potential climate change impact on a contaminated site. Other emission scenarios (such as RCP 4.5 or SSP2-4.5) may be used for comparative purpose. However, it is recommended that practitioners should not base their climate change vulnerability assessment on the RCP 2.6 (or SSPE1-1.9) scenario, as this is considered an ambitious scenario.

2.3 Time Horizon

To determine the climate projections for a region or a particular site, one or more emission scenario should be selected, as well as a time horizon: short-term (e.g. up to 2040), mid-term (2041 to 2070) and long-term (2071 to 2100). The selected time horizon may be adapted depending on the available data for the various climate variables associated with the different climate change hazards, and the lifecycle of the contaminated site (FCSAP, 2022). Other aspects that need to be considered when deciding on a time horizon include the remedial time target and foreseeable changes in future land use. Although the long-term time horizon should be considered at a minimum to complete a climate change vulnerability assessment, it is recommended to consider climate projections under various time horizons, for different reasons including:

- Depending on the climate change hazards, the long-term horizon does not necessarily represent the worst-case scenario.
- The site's intended use and the duration of that use as the site would likely be subject to an updated site assessment at the time of future redevelopment.
- Change in contaminated site legislation and assessment standards. Over the past 26 years (i.e. since 1997), BC Contaminated Site Legislation has been amended on fourteen occasions and ongoing changes are likely. As such, the longer the term of climate scenarios predictions used will result in the least accurate overall effect considering the regulatory regime at the time of prediction.
- Even though a site has been considered remediated, site conditions may change in the future due to climate change and cause the residual contamination to re-mobilize.
- A remedial or risk management strategy may not be warranted for a short-term horizon but could become warranted for a longer horizon. In addition, assessing climate change projections and impacts for different time horizons potentially may aid practitioners in selecting the most cost-effective, sustainable and resilient remedial option.

The climate change vulnerability assessment may need to be updated regularly due to the general uncertainties associated with climate change (see Section 4.5), especially as the time horizon increases, or due to a change in site use in the future. The frequency of an assessment revision will be based on the practitioner's knowledge of the sites and climate change science and projections.

2.4 Framework Overview

This document aims to provide a framework that practitioners may use to consider climate change during the investigation and management a contaminated site using a three-step process. **Figure A** below shows a flow chart illustrating how the three-steps process ties into the overall management of a contaminated site. The three steps are as follow:

1. The first step is to review and understand the regional climate change projections and downscaled climate projections for the site. This involves identifying potential climate change hazards that could affect the site and site-specific factors that can increase or decrease the vulnerability of the site.

2. The second step is to understand how the identified climate change hazard(s) applicable to the site may affect the site's physical and environmental conditions, which in turn could affect the site's contamination.
3. The last step includes assessing the site's vulnerability to climate change based on the identified hazards (i.e., exposure), the potential impacts on site's contamination (i.e., sensitivity) and the site's ability to adapt (i.e., adaptive capacity). This involves evaluating the site's existing infrastructure and management practices to determine how well they can withstand and respond to potential climate change hazards. It also includes assessing the inherent adaptive capacity of the natural system.

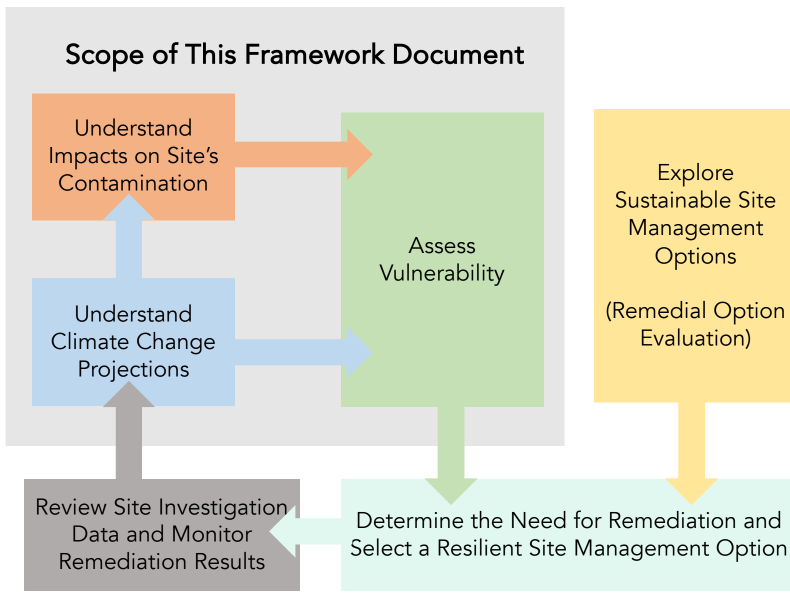


Figure A: Scope of the Framework Document

3 RESOURCES

The provincial and federal governmental bodies are becoming more aware of potential impacts that climate change can have on contaminated sites. In response, various documents and draft reports have been released by the British Columbia (BC) government and the federal Canadian government to help assess climate change related hazards, although not specific to contaminated sites. In addition, the United States (US) have a number of useful resources relating to adapting contaminated sites to climate change. These documents are briefly discussed in the following sub-sections. It is recommended that practitioners familiarize themselves with the following documents.

3.1 British Columbia

The *BC Climate Change Accountability Act* requires BC Ministry of Environment and Climate Change Strategy (BC ENV) to prepare a public report every even-numbered calendar year, starting in 2020, describing the risks to BC from climate change, progress toward reducing those risks, actions taken to achieve that progress, and plans to continue risk-reduction efforts.

3.1.1 The Preliminary Strategic Climate Risk Assessment for British Columbia (BC ENV, 2019)

In preparation for the expected changing climate in British Columbia in the 2050s (2040-2059), the BC Government prepared a *Preliminary Strategic Climate Risk Assessment for British Columbia* to present a strategic climate risk assessment framework that comprises four crucial steps:

1. Understanding the context
2. Identifying risk events
3. Analyzing risks
4. Evaluating risks

Serving as the initial phase of the *Climate Preparedness and Adaptation Strategy*, the report aims to convey climate risks within the province and prioritize the types of risk management responses needed. The assessment also highlights important knowledge gaps and process improvements that would further enhance the understanding of climate risks. This report represents the first step towards meeting the *BC Climate Change Accountability Act* requirements.

3.1.2 Climate Preparedness and Adaptation Strategy (CPAS): Actions for 2022-2025 (CleanBC, 2022)

Based on the findings of the *Preliminary Strategic Climate Risk Assessment for British Columbia* (2019) and feedback from Indigenous and public engagement on the draft *CPAS (2021-2022)* and other factors such as the extreme weather events of 2021, the BC government developed a series of actions to prioritize for the 2022-2025 period. The CPAS outlines a broad range of actions to address climate impacts and build resilience across BC. These actions are grouped into six guiding principles:

1. Build a shared path on climate resilience with Indigenous Peoples;
2. Take an equity-informed approach;
3. Enhance health and well-being of all;
4. Promote nature-based solutions to enhance community resilience;
5. Align emissions reduction with climate adaptation; and
6. Take a proactive approach: the business case for adaptation.

Based on these principles, key pathways are outlined in the CPAS and are used to inform a comprehensive set of proposed actions for 2022-2025, including:

- Integrating the changing climate into governance and decision-making;
- Expanding education on climate impacts and adaptation;
- Supporting resilient community planning and disaster risk management;
- Strengthening individual and community health and wellness in a changing climate;
- Promoting watershed security and strengthening marine resilience;
- Enhancing tools and approaches for managing ecosystems, parks and protected areas;
- Increasing the resilience of our buildings and infrastructure; and
- Supporting business and industry to respond to climate risks.

3.1.3 Making Contaminated Sites Climate Ready (BC ENV, 2022)

This discussion paper from the Land Remediation Section of the BC ENV was prepared to seek feedback and comments for a number of proposed actions made by BC ENV to address climate change adaptation and further incorporate sustainability in BC's contaminates sites policy and legislative framework. It was developed following engagement sessions with Indigenous groups and reviews of policies and regulations in other jurisdictions, to support the BC's CPAS. The key themes identified through engagement sessions with Indigenous Peoples on contaminated sites in a changing climate included:

- Engaging with Indigenous Peoples early and often;
- Protecting Indigenous land uses;
- Incorporating Indigenous knowledge;
- Importance of relationship building;
- The concept of "everything is connected"; and
- Importance of shared decision-making.

In addition, the paper summarizes the findings of two jurisdictional scans commissioned to review how jurisdictions outside of BC address management of contaminated sites in a changing climate. The first scan reviewed climate adaptation and sustainable practices for remediation of contaminated sites across jurisdictions. The second scan focused on regulatory groundwater remediation requirements intended to protect current and future groundwater resources, with a focus on protecting drinking water aquifers.

Based on the Indigenous engagement sessions and the jurisdictional scans, BC ENV formulated a number of proposed actions to strengthen the BC's contaminated sites policy and legislative framework. The proposed actions focused on six key opportunities:

1. Indigenous Peoples engagement
2. Adaptation to current and predicted climate change
3. Remediation alternatives evaluation
4. Periodic review of remedial actions
5. Remediation requirements for viable groundwater aquifers
6. Financial security

3.2 Canada

3.2.1 Implementation Framework for Climate Change Adaptation Planning at A Watershed Scale (CCME, 2015)

The *Implementation Framework for Climate Change Adaptation Planning at a Watershed Scale* (2015) was developed by the Water Monitoring and Climate Change Project Team of the Canadian Council of Ministers of the Environment (CCME). It introduces a methodology designed to identify and manage vulnerabilities and risks arising from climate change and build resiliency within a watershed. It is developed from established international and domestic climate change adaptation frameworks as well as insights from a survey of climate change adaptation practitioners across Canada. This approach outlines seven essential steps that include both top-down and bottom-up assessments, to adaptively manage watersheds and reduce climate risks. Although the approach was specifically developed for watersheds, this iterative and flexible process contain valuable transferable information and methodologies that could be applicable to adapt the management of contaminated sites to the changing climate. The seven key steps of the framework, which could be applied to a framework assessing climate change impacts to contaminated sites, include:

1. Initiate adaptation process;
2. Increase knowledge and collect data;
3. Assess current vulnerability;
4. Assess future risks;
5. Generate adaptation solutions;
6. Implement adaptation solutions; and
7. Monitor and review.

3.2.2 Guidance on Good Practices in Climate Change Risk Assessment (CCME, 2021)

The CCME developed a guidance document to inform good practices in conducting climate risk assessments across various jurisdictions (federal, provincial or territorial) in Canada, including the selection of the most appropriate approach and supporting frameworks. The information contained in this document was developed through a literature review on climate change risk evaluation methodologies that have been used at various scales in Canada and internationally. The literature review was followed by a series of expert interviews with both developers and users of climate change risk evaluation frameworks.

The document provides an explanation of the various approaches and their advantages and disadvantages. It also outlines six main questions that users should consider prior to undertaking a climate change risk evaluation and presents six good practices, explaining the extent to which they meet the guiding principles of effective climate change risk evaluations. Case studies are included for each good practice to demonstrate how the framework was applied at a given scale or jurisdiction.

3.2.3 Integrating Climate Change Adaptation Considerations into Federal Contaminated Sites Management (FCSAP, 2022)

This document was released under the Federal Contaminated Sites Action Plan (FCSAP) Secretariat and can be used with the 10-step Decision-Making Framework (DMF) outlining the specific activities, requirements, and key decisions to effectively address federal contaminated sites in Canada. The document provides examples of climate change impacts and climate change adaptation measures to consider when managing federal contaminated sites throughout each step of the DMF, during all stages of assessment and remediation/risk management (R/RM), including long-term monitoring (LTM) activities. The document provides examples of CSMs under future climatic conditions. It also provides recommended best practices to adapt contaminated sites management approaches to potential climate change hazards and their resulting impacts. Although the document focuses on climate change adaptation, Appendix A of the DMF contains some information on climate change mitigation within the context of contaminated sites.

3.3 United States

3.3.1 US Environmental Protection Agency

The United States (US) Environmental Protection Agency (EPA) has a large section on their website dedicated to climate change, including climate change science, impacts, adaptation plans, etc. EPA’s Superfund program is responsible for cleaning up some of the nation’s most contaminated land and responding to environmental emergencies, oil spills and natural disasters. As contaminated sites may be vulnerable to the impacts of climate change and extreme weather events, the EPA's Superfund program developed an approach that raises awareness of these vulnerabilities and applies climate change and weather science as a standard operating practice in cleanup projects. The approach involves periodic screening of Superfund remedy vulnerabilities, prioritizing the Superfund program's steps to adapt to a changing climate, and identifying measures to assure climate resilience of Superfund sites. Some of the program initiatives and information about strategies that can be used to evaluate and strengthen climate resilience at Superfund sites are available online at Superfund Climate Resilience.

In addition, the U.S. EPA updated a series of fact sheets designed to help site cleanup managers and other stakeholders identify, prioritize and implement site-specific measures for increasing remedy resilience to climate change and extreme weather events. This fact sheet addresses remedies for contaminated sediment, contaminated waste containment systems and groundwater remediation systems. The Superfund program also uses green remediation strategies to achieve greener cleanups. Green remediation is the practice of considering all environmental effects of remedy implementation and incorporating options to minimize the environmental footprints of cleanup actions. The Green Remediation Focus include an industry standard, best management practices (BMPs), monthly news, technical information, project examples and footprint analysis tools.

The US EPA developed a Climate Resilience Evaluation and Awareness Tool (CREAT) Risk Assessment Application for Water Utilities which assists the water sector in understanding and assessing climate-related risks to utility assets and operations. Throughout five modules, users consider climate change impacts and identify adaptation option to increase resilience. To help the users in their risk assessment, US EPA also developed

- a CREAT climate change scenario projection map, which is an interactive online GIS tool to visualize climate change projections for different climate conditions; and
- a vulnerability self-assessment tool (VSAT Web) that can help drinking water and wastewater utilities to conduct an risk and resilience assessment.

3.3.2 Interstate Technology Regulatory Council

The Interstate Technology Regulatory Council (ITRC) publishes and produces guidance documents and training courses that help state environmental agencies and others gain valuable technical knowledge and develop consistent regulatory approaches for reviewing and approving specific technologies. These include technical overviews, case studies, and technical and regulatory guidance documents. The ITRC developed a comprehensive guidance online document relating to sustainable resilient remediation (SRR), providing resources to help practitioners integrate sustainability and resilience practices into remediation projects. It includes a strong resilience component to address the increasing threat of extreme weather events and wildfires. While sustainability considers a remedy's impact on the environment, resilience considers the environment's impact on the remedy. To be truly sustainable, a remedy must maintain functionality for the duration of its design life and do so by being resilient to extreme events and changing conditions. The interconnectedness of sustainability and resilience, particularly as they relate to the cleanup of contaminated sites, reemphasizes the importance of an integrated approach. Recommendations for careful and continuous consideration of the social and economic costs and benefits of a cleanup project are also included.

The SRR guidance presents a number of useful resources, including:

- A summary of the state survey performed about SRR, including opportunities and barriers.

- An online map with links to available state and federal resources to quickly find examples and best practices from different states and federal agencies.
- Expanded information about resources for the social and economic dimensions of sustainability, including state-of-the-art social and economic evaluation tools.
- An updated framework that illustrates how and why sustainability and resilience should be integrated throughout the remedial project life cycle.
- Checklists of key sustainable best management practices to address resilience based on specific vulnerabilities at a site as well as resources for additional information.
- Case studies illustrating the application of SRR considerations.
- A list of recommendations for the future.

3.3.3 Sustainable Remediation: Climate Change Resiliency and Green Remediation (Washington State, 2023)

The Toxic Cleanup Program (TCP) from the Washington State Department of Ecology developed a guidance document on *Sustainable Remediation: Climate Change Resiliency and Green Remediation* (2023) which provides a framework and recommendations for contaminated sites practitioners to increase the resiliency of cleanup remedies to climate change impacts. The framework includes a step-by-step process to identify and select adaptation measures at each phase of the cleanup process, from site investigation, remedial option evaluation, remedial activities to operation and maintenance, including long-term monitoring. These steps include information and methodologies on:

- Conducting site-specific vulnerability assessments.
- Incorporating climate change in conceptual site models (CSMs).
- Identifying gaps in information.
- Identifying adaptation measures.

Additionally, the guidance recommends the adoption of green remediation best management practices to enhance environmental benefits and reduce impacts from cleanup activities. It also provides a number of case studies specific to Washington State.

3.4 Climate Data Resources

Many other resources exist that can be helpful to practitioners who are assessing a contaminated site's vulnerability to climate change in BC. Some of these resources are online tools that can be used to visualize and analyze climate data for a specific site. A summary of additional climate change hazard resources is provided in **Table A**. This is not a comprehensive list of references, but rather a starting point for researching climate change data. Further resources can be found in the Canadian Centre for Climate Services Library of climate resources.

Online tools provide tutorials and/or instructions on how to best use the tools for the outcomes required and the desired output format (maps, graphs, data format). In some cases, different emissions scenarios can be selected to compare climate impacts. Recommendations on which emissions scenarios to select are discussed in Section 2.1. of this document.

Table A: Climate Change Resources Summary

Source	Resource	Type	Details
Intergovernmental Panel on Climate Change (IPCC)	Climate Change 2023: Synthesis Report of the IPCC Sixth Assessment Report (AR6)	Online document	Provides an overview of the state of knowledge concerning the science of climate change and emphasizes new results and emissions scenarios since the IPCC Fifth Assessment Report (AR5).
Pacific Climate Impacts Consortium's	Plan2Adapt	Web tool	A tool which can generate maps, plots, and data describing projected future climate conditions for regions throughout British Columbia. Plan2Adapt uses the Representative Concentration Pathway 8.5 (RCP 8.5) future climate scenario from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). The results shown are computed from daily statistically downscaled scenarios that have been developed using the Bias Correction with Constructed Analogues and Quantile mapping, Version 2 (BCCAQv2) method.
	Climate Explorer	Web tool	A more sophisticated complement to the Plan2Adapt tool. This tool can be used to locate, visualize and download hydrologic impacts, regional climate impacts, and climate analysis data to project future climate conditions in regions within Pacific and Yukon in the form of maps and graphs. It uses global climate model output from CMIP5 and CMIP6.
Environment and Climate Change Canada (ECCC), the Computer Research Institute of Montréal (CRIM), CLIMAtlantic, Ouranos, the Pacific Climate Impacts Consortium (PCIC), the Prairie Climate Centre (PCC), and HabitatSeven	ClimateData	Web tool	The tool can be used to visualize and analyze climate data with CMIP5 and CMIP6 based climate projections and historical data. Maps and graphs generated are at local and regional scale.

Source	Resource	Type	Details
Western University, London Ontario, Canada	IDF_CC Tool 6.5	Web tool	This tool can be used to provide estimates of intensity–duration–frequency (IDF) curves for a variety of return periods and duration based on historical data, as well as future climate conditions. IDF curves can be generated using all the major climate models and the four standard emissions scenarios, allowing the user to assess IDF data for a variety of outcomes.
BC Regional Adaptation Collaborative Program	Retooling for Climate Change	Web Tool	Compiles adaptation tools and resources for BC local governments, First Nations, and the natural sectors to prepare for the impacts of climate change.
Government of British Columbia	British Columbia Drought Information Portal (DIP)	Web Tool	Geographic drought level information system for British Columbians. The application uses multiple embedded maps to provide information on provincial drought levels, historical drought time-lapse information, stream watch, streamflow map, snow basin indices, etc.

4 UNDERSTANDING CLIMATE CHANGE IMPACTS

Attached **Tables 1** to **3** will assist practitioners to address the following questions when considering potential climate change impacts at their sites. The first two questions can be answered by referring to **Table 1** while questions 3 and 4 can be answered with the help of **Tables 2** and **3**, respectively:

1. Which climate change hazards occur in BC and are relevant for a given site?
2. What are the climate projections associated with those hazards under future climate scenario(s) and time horizons?
3. What site-specific factors may increase or decrease the vulnerability of a given site to the identified climate change hazards?
4. How might the identified climate change hazard(s) influence contaminant concentration and distribution, mobility, and fate and transport?

To illustrate how to use the tools detailed in this report, a hypothetical case study will be presented throughout Section 4 as an example of how to apply to a contaminated site the information provided in each sub-section. A detailed description of the case study site is provided below.

4.1 Case Study Site Description

The case study site is assumed to be a large industrial property that was historically contaminated by petroleum hydrocarbons (contaminated soil, groundwater and vapour) over a long period of industrial activities. A light non-aqueous phase liquid (LNAPL) plume is also present. The site is adjacent to a large river located in the Okanagan region.

Environmental work including Stage 1 and 2 Preliminary Site Investigations (PSI) as well as a Detailed Site Investigation (DSI) have been conducted at the site; therefore information on the contaminant type(s), concentrations, sources, and extents are known. In this particular example, the primary sources have been remediated, and residual soil, vapour, dissolved phase groundwater and LNAPL were determined to be stable, and not reported to extend off-site. A Human Health and Ecological Risk Assessment (HHERA) was completed and risks to human health and the environment were found to be acceptable. A certificate of compliance (CoC) was obtained for the site for industrial use, with the conditions of the CoC stating that groundwater at the site must not be used for drinking purpose and that future buildings at the site must be of slab-on-grade construction.

The site owner wants to sell the property. A developer is interested to purchase the site and redevelop it as a mixed-use area comprising of low-density residential dwellings, a school and a park. The developer retained a consultant to re-assess the site based on the change in land use, how climate change will impact the site contamination in the future and if further investigation and/or remediation work is required. To evaluate the potential future climate change impacts on the existing contamination, the practitioner would use the framework provided in this document.

4.2 Identified Climate Change Hazards and Regional Projections

4.2.1 Identified Climate Change Hazards in BC

The following section summarizes the climate change hazards identified to occur in BC based on information reviewed in BC ENV (2019), CleanBC (2022), FCSAP (2022), the ITRC and Washington State (2023). For the potential effects of these hazards on contaminated sites, refer to Section 4.3.

Flooding

Climate change is projected to increase the frequency and severity of river and coastal flooding in BC. The province can expect more frequent and intense rainfall events, which can lead to flash flooding and landslides. Rising sea levels will exacerbate coastal flooding, particularly during storm surges and king tides. Changes in snowmelt patterns due to warming temperatures will also increase the risk of spring flooding.

Drought

More frequent and severe droughts are expected in many parts of BC, especially the interior and southern regions of the province. Warmer temperatures will increase evaporation and evapotranspiration rates, leading to drier conditions. Reduced snowpack and earlier snowmelt will also contribute to droughts and lower river flow in the summer. Under the RCP8.5 scenario, the past average longest period of consecutive days without rain (under 1 mm) in BC is 21 days. Dry spells on average are expected to increase to 26 days by the 2050s, and 29 days by the 2080s (BC ENV, 2019).

Wildfires

Wildfires are a major climate change hazard in British Columbia, and the province is expected to experience more frequent and intense wildfires due to climate change. Warmer and drier conditions increase the risk of wildfire ignition and spread, particularly in forested areas.

The *Preliminary Strategic Climate Risk Assessment for British Columbia* (2019) report notes that the 2017 and 2018 wildfire seasons in British Columbia were among the most severe on record, with over 2.5 million hectares burned and over 65,000 people evacuated. These events had significant impacts on public health and safety, infrastructure, and the economy, particularly in rural and Indigenous communities.

Extreme Weather / Precipitation

The climate change projections for BC in this section are based on historical baseline for the years between 1971 and 2000 and the climate models from the Coupled Model Intercomparison Project 5 (CMIP5) provided in the Climate Change Projections for Metro Vancouver (2016) report.

Although the annual precipitation is predicted to increase by only 5% by 2050, the distribution of precipitation across the seasons will change significantly in BC (Metro Vancouver, 2016). Precipitation during fall will increase by 11% by 2050 and 20% by 2080, whereas the precipitation during summer will decrease by 19% by 2050 and 29% by 2080. Furthermore, it is also predicted that heavy or extreme rainfall events (storms) will increase in frequency and intensity. Atmospheric convection changes due to climate change is predicted to increase the frequency of strong wind events, especially in spring, by up to 14% in the Georgia Basin (Haughian et al., 2012). The Georgia Basin is the marine water body which includes the Puget Sound, Strait of Georgia and Strait of Juan de Fuca.

It should be noted that the climate prediction models show some uncertainty regarding the amount of precipitation to be expected but agree on increasing and decreasing precipitation trends.

Erosion / Landslides

Climate change is projected to increase the risk of erosion and landslides in BC, particularly in coastal and mountainous areas. Increased precipitation can lead to increased soil saturation, which can trigger landslides (BC ENV, 2019). In coastal areas, rising sea levels can exacerbate erosion, particularly during storm surges and king tides. The cumulative effects of wildfires followed by extreme precipitation can also lead to increased erosion and landslides, as it occurred in BC in 2021.

Increased Temperatures / Heat Waves

Climate prediction models for BC indicate a temperature increase in all seasons which will lead to increased precipitation during fall, winter, and spring and drier summer months (Metro Vancouver, 2016). Annual temperatures are projected to increase by an average of 2.9 °C by mid-century (2050s) and by 4.9 °C by the 2080s and are similar in nighttime and daytime temperatures. These projections are based on the historical baseline for the years between 1971 and 2000 and projections are based on the climate models from the CMIP5. Heat waves are also expected to become more frequent and severe in the future, especially in late spring and summer months, owing to climate change.

Sea Level Rise

One of the biggest climate change induced factors expected for coastal areas in BC is sea level rise. About 75% of global sea level rise is attributed to the melting of glaciers and heating of surface water, as warmer water results in a larger volume (IPCC, 2014). Locally, rising temperatures in BC will also increase melting of permanent snow (glaciers) which will increase runoff into the ocean and will consequently change its salinity. Other influences on sea level rise are atmospheric low-pressure systems and the associated winds, tectonic plate movement, uplift due to post-glacial rebound of land, and subsidence due to sediment deposition by rivers (Bornhold, 2008). According to the *Projected Sea Level Changes for British Columbia in the 21st Century* (2008) report, localized subsidence along the Fraser River Delta is increased further by more than 1 mm per year due to sediment compaction caused by large construction projects such as port facilities.

The Intergovernmental Panel on Climate Change (IPCC) indicates a global mean sea level (GMSL) rise under SSP1-1.9 GHG emissions scenario will likely be 0.15 to 0.23 m by 2050 and 0.28 to 0.55 m by 2100 relative to 1995 – 2014. The GMSL rise under the SSP5-8.5 GHG emissions scenario is projected to be from 0.20 to 0.29

m by 2050 and 0.63 to 1.01 m by 2100. The mentioned GMSL projections have a medium confidence level. It is likely that these GMSL rise levels translate to a likely increase in average sea level of 0.1 to 0.2 m from 2020 to 2050 for the BC coast (Sweet *et al*, 2022). After 2050, the projections vary more widely between emissions scenarios.

Additionally, increasing atmospheric carbon dioxide can also cause ocean acidification which may lead to changes in contaminant behaviour on sites.

Glacier / Snowpack Loss

Glaciers and snowpack play a significant role in regulating regional hydrological systems. Their melting contributes to the availability of water resources, including recharge of groundwater and maintenance of river flow during dry periods. As glaciers shrink and snowpack decreases, changes in hydrological regimes will occur. Climate change is causing glaciers and snowpack to melt at an accelerated rate in BC. This will impact water availability and quality, particularly in the summer months. Reduced snowpack will lead to reduced runoff, which can lead to drier conditions. Additionally, as glaciers melt and snowpacks decrease, the water flow patterns will change.

As this climate change hazard is not anticipated to directly impact contaminated sites, it is briefly discussed in **Table 1** but not evaluated in the remainder of the document.

Species Distributions Invasive / Non-Invasive

Climate change is expected to cause shifts in the distribution and abundance of many plant and animal species in BC. Some species will benefit from warmer temperatures and longer growing seasons, while others will be negatively impacted by changing habitats and increased competition. These impacts can have cascading effects on ecosystems, including impacts on food webs and nutrient cycling. As this climate change hazard is not anticipated to directly impact contaminated sites, it is briefly discussed in **Table 1** but not evaluated in the remainder of the document.

4.2.2 Regional Climate Change Projections

The climate variable projections for four different regions in BC were compared to a baseline timeline from the years 1971 to 2000. Quantitative data for each region and references are presented in the attached **Table 1**. The location of each region and their respective boundaries are shown in attached **Figure 1**.

Table 1 can be used to determine which hazards are likely to impact the region in which a site is located. This can be used as the first step in assessing the potential impacts of climate change on a site, however, these projections only provide a broad indication of potential hazards. It is advised to conduct a more comprehensive assessment of a site, taking into account its specific location in relation to geographical features, which might either be affected by or contribute to climate change-related impacts on a contaminated site. Additionally, when looking at potential impacts to a site, it is recommended to understand that climate hazards often occur simultaneously and are strongly interlinked. Compound risk events can have linked probabilities driven by the same underlying conditions and can in some cases trigger each other, consequently resulting in back-to-back events that can be greater than those of any single event alone. This is due to the additional impacts of subsequent events and greater sensitivities or lower adaptive capacity of systems still recovering from previous events. For example, a seasonal or long-term water shortage followed by wildfire, which in turn primes the landscape for severe landslides following heavy precipitation.

CASE STUDY: Regional Climate Projections

The first step of the climate change vulnerability evaluation was to identify the regional projections for the Okanagan region where the site is located. Based on **Table 1** these projections include:

- Increased temperatures and frequency of heatwaves.
- Increased frequency and duration of droughts causing increased soil impermeability.
- Increased frequency and intensity of river flooding due to more snow melt and increased precipitation in spring.
- Increased severity and burned areas due to wildfires.
- Increased frequency of landslide triggered by increased precipitation in spring.

Severe wildfire season and seasonal water shortage are the two highest risks overall facing the province of BC (BC ENV, 2019). According to climate models, the South and West Coast region of BC can expect an annual temperature increase of 1.5 to 2.5°C by 2050, with the greatest warming occurring in winter and spring (Bush, E. and Lemmen, D.S., 2019). This temperature increase is expected to lead to more frequent and intense heat waves, particularly in urban areas (Metro Vancouver, 2016), drier conditions and reduced snow accumulation, impacting water availability in the summer months (BC ENV, 2019). In rainfall-dominated regions, a water shortage could be caused by decreased summer precipitation, and in snowmelt-dominated regions a water shortage could be caused by earlier or more rapid snowmelt, or a reduced snowpack. The frequency and severity of wildfires are also projected to increase due to warmer temperatures and drier conditions (CCAP, 2023).

Other potential high risk climate change consequences across BC are related to riverine flooding, sea-level rise and coastal storm surges (BC ENV, 2019). Precipitation is projected to increase in fall and winter and decrease in summer, leading to a longer dry season and increased risk of wildfires (Bush, E. and Lemmen, D.S., 2019). Sea levels are also projected to rise by 0.5 m by the 2050s (from 2000) (BC ENV, 2019), which will increase the risk of coastal flooding and erosion.

4.3 Site-Specific Factors Increasing or Decreasing Site Vulnerability to Climate Change

The following site-specific factors, listed as sub-sections below, play a major role in a site's vulnerability to climate change. Some of the questions a practitioner should ask themselves during the site assessment to assess the vulnerability of a site to climate change hazards, can be found in **Table 2**. Note that the table is not an exhaustive list but provides some example questions that are applicable to most sites. The sub-sections below also provide a short explanation of why these factors are important when assessing a site's vulnerability to climate change hazards. **Table 2** references the sources of information that practitioners could consult in order to determine how each site-specific factor applies to a given contaminated site. These sources include maps, online GIS tools, and websites, as well as the review of historical information pertaining to the site. For example, if a site has been subjected to flooding in the past, it is likely it could be impacted by flooding in the future due to climate change.

4.3.1 Location

The location of a site can significantly affect its vulnerability to climate change hazards. Sites located in low-lying areas, coastal regions or floodplains are particularly vulnerable to hazards such as sea-level rise, storm surges, and flooding. As sea level rises, contaminated sites in coastal areas are more likely to be inundated. Sites located in regions prone to heavy rainfall are also more susceptible to increased runoff, and landslides and erosion, which can damage site infrastructure.

4.3.2 Topography

Sites located on steep hillsides or slopes may be vulnerable to landslides and erosion during heavy rainfall, while sites located in valleys or depressions may be more susceptible to flooding. Conversely, sites located on a higher elevation may be more resilient to flooding but more prone to increased runoff.

4.3.3 Geology

Sites with contamination located within relatively porous and permeable geology, such as sand and gravel, may be more vulnerable to flooding or sea-level rise. Potential contaminants present in this type of material can be transported more rapidly towards sensitive receiving environments such as aquatic surface water bodies; however, they may also become relatively more diluted due to the higher amount of flow and dispersive spreading that occurs under these conditions. Conversely, a site with less permeable geology (e.g., silt and clay) can hinder flooding and sea-level rise effects and reduce potential contaminant transport; thereby making the site more resilient to certain climate change hazards. A proper conceptual site model which includes information on geology is critical when assessing potential climate change related impacts on contaminant migration.

4.3.4 Physical Hydrogeology

The physical hydrogeology of a site, including the presence of a regionally mapped aquifer below the site, groundwater table elevation, and direction of groundwater flow can also impact the site's vulnerability to climate change. Sites with a shallow groundwater table and groundwater tables that are more sensitive to seasonal fluctuations may be more vulnerable to climate change hazards depending on the contaminant location within the subsurface (i.e., contamination depth). Additionally, a change in the direction of groundwater flow can impact how dissolved contaminants move through the subsurface, potentially impacting uncontaminated areas and media.

4.3.5 Infrastructure

Lacking, aging, or poorly maintained infrastructure such as pipes, dykes, and drainage systems may increase the site vulnerability to climate change hazards. On the other hand, the presence of flood prevention infrastructure on or in proximity of the site may mitigate the impacts of climate change hazards. The presence and location of pavement at the site can influence its vulnerability to climate change hazards (e.g., limiting infiltration during extreme precipitation but increasing runoff, or reducing erosion). Infrastructure would also include piping and equipment for any in-situ remediation systems including risk management applications such as caps/barrier walls, etc. that, if present, can be impacted by various climate change hazards. Infrastructure also includes underground pipes and utility lines that if cracked, broken or leaking may create preferential pathways for NAPL, groundwater and vapour contamination. Climate change hazards such as flooding can also impact existing preferential pathways which could become more active, for example with a water table increase.

4.3.6 Vegetation Cover

The amount and type of vegetation can play a significant role in a site's vulnerability. Sites with dense vegetation cover may be more resilient to erosion and flooding as the roots of the plants can help stabilize the soil and reduce runoff. On the other hand, these sites would be more vulnerable to wildfires. Some types of vegetation can dry out quickly over summer months and cause wildfires to spread more easily.

CASE STUDY: Site Specific Vulnerability

Based on the location of the case study site, the following site-specific factors may play a role in the site's vulnerability to the previously identified potential climate change hazards:

1. **Location and Topography**: The site is situated within the 100-year river's floodplain. The site topography is relatively flat. Historical information also indicate that the site has been flooded multiple times in the past, mostly during spring. In addition, the site is located in an area that is often subject to drought in summer. However, it is not located in or near an area where landslides or wildfires have occurred.
2. **Geology**: The surficial geology of the site consists of mostly alluvial sediments (sand and gravel).
3. **Physical Hydrogeology**: The site is underlain by a regionally mapped aquifer associated with the river sediments. The water table is approximately 2 m below ground surface and is hydraulically connected to the river. Seasonal fluctuations in water levels are in the range of 1.0 to 1.5 m. The site area represents a discharge area for the regional aquifer and groundwater below the site flows to the north, towards the river.
4. **Infrastructure**: There is no existing infrastructure to mitigate impacts of flooding (i.e., no dike system) and drainage at the site is limited. Approximately 30% of the site is paved.
5. **Vegetation Cover**: The site has limited vegetation, mostly blackberry bushes and a couple of pine trees.
6. **Contaminants**: The main contaminants identified at the site in soil water and vapour include toluene, VPH, LEPH and naphthalene. The contaminants primary sources have recently been removed from site. The vapour, groundwater and LNAPL plumes were determined to be stable. The LNAPL plume is at the water table. The soil contamination was identified mostly within the vadose zone. The overall contamination is currently constrained within the site boundaries.

4.3.7 Contamination

The type, location, concentration, and extent of contamination as well as what media (sediment, groundwater, surface water, soil, vapour) and what phase (non-aqueous phase liquid [NAPL], solid, vapour or aqueous) it is in, can impact a site's vulnerability in various ways, as further detailed in Section 4.4. The information and data pertaining to the site's contamination is typically obtained from site environmental investigations.

4.4 Potential Climate Change Impacts on Contaminated Sites

Besides the site-specific characteristics discussed in Section 4.2 above, impacts of climate change on contaminated sites will depend on multiple aspects of the contamination, including:

- type of constituents of concern (e.g., metals vs petroleum hydrocarbons);
- location of contamination (i.e., depth, location relative to water table, etc.);
- contaminant's phase (NAPL, solid, vapour or aqueous);
- affected media (sediment, groundwater, surface water, soil, vapour);
- extent of the contaminant plumes including soil, groundwater, vapour and LNAPL plumes;
- biological and physico-chemical properties of the constituents of concern (often in relation with the soil lithology); and
- toxicity of the constituents of concern.

A non-exhaustive list of potential physical effects of climate change hazards on affected media (groundwater, soil, vapour, surface water) and examples of subsequent effects on site contamination are presented in **Tables 3A** and **3B**, for inorganic and petroleum hydrocarbon constituents of concern, respectively. Note that some effects of climate change on site contamination are negative while some effects can be positive, and a number of those effects may be occurring at the same time but to different degrees. It is up to the practitioner's professional judgement to consider which effects are most likely to occur at the site in the future and to which degree, based on their knowledge of the site (obtained through site investigation) and understanding of climate change impacts (obtained through the previous sections of this guidance document).

4.4.1 Inorganic Constituents of Concern

Climate change can have an impact on the fate and transport of inorganic constituents, particularly through changes in the groundwater level (Jarsjö, 2020). Different climate change effects may influence key processes that affect inorganic constituent mobility, such as solubility, pH, and redox conditions, which in some cases may result in natural attenuation, dilution, or increased solubility and desorption.

For example, in areas with shallow groundwater table, an increase in precipitation can lead to rising groundwater water table position affecting the ambient geochemical conditions such as redox potential, pH or temperature. This could mobilize certain inorganic constituents sensitive to these geochemical changes (e.g. iron and arsenic are sensitive to redox conditions).

Increased precipitation can also lead to plume expansion due to increased water infiltration and contaminant leaching from the vadose zone to the saturated zone. However, cumulative effects should be considered. For example, a heavy rainfall event may result in less infiltration after a period of drought that would cause the soil to become more hydrophobic (unsaturated hydraulic conductivity decreases with decreasing soil moisture) and would reduce its capacity to absorb water quickly, hence being more impermeable.

Examples in **Table 3A** highlight the complex and site-specific nature of the impacts of climate change on inorganic fate and transport. Detailed information on inorganic constituents' fate and transport processes can be found in literature, such as USGS (1985) or US EPA (2007).

4.4.2 Petroleum Hydrocarbon Constituents of Concern

Climate change can directly affect the fate and transport of petroleum hydrocarbons by changing the physical site conditions (e.g., groundwater table position, soil moisture, etc.) or indirectly by changing the physico-chemical conditions of the subsurface (e.g., pH, redox potential, temperature) affecting the microorganisms responsible for their biodegradation. For example, changes in temperature and redox potential (e.g. aerobic to anerobic) can affect the rate of biodegradation of hydrocarbons by microorganisms.

Droughts typically lower the water table which increases the vadose zone. This may lead to an increase in aerobic biodegradation by microorganisms present in the vadose zone. Conversely, the lowering of the water table may increase the potential for volatile constituents that were previously submerged, to partition into the vapour phase. Additionally, a lower water table may result in thicker LNAPL smear zone (which may immobilize the LNAPL or result in not measuring it in the affected well) or increased zone of residual saturation. Similar to inorganic constituents, increased precipitation may result in greater contaminant dissolution from the unsaturated zone and greater contaminant mass addition to the dissolved phase causing the dissolved plume to expand and/or migrate further. However, it may also result in an increased dilution of dissolved constituents.

Additional examples of potential physical effects of climate change hazards on site petroleum hydrocarbon contamination are presented in **Table 3B.**

CASE STUDY: Climate Hazard Impacts on Contaminated Sites

Given the site conditions (including its location, geology, etc.) and contamination, the practitioner concluded that the site was mostly vulnerable to two main climate change hazards: river flooding in spring and droughts in the summer. As such, the following potential climate change effects on the case study site's contamination can be expected, based on information provided by **Table 3B**.

During summer drought and increased temperatures

- Decrease in water table elevation below previous range of seasonal fluctuation may increase the smearing of LNAPL within the expanded vadose zone or could in fact immobilize LNAPL.
- The increased temperatures and aerobic conditions within the expanded vadose zone may increase the biodegradation of contaminants.
- The expansion of the vadose zone, as well as the increase in temperatures, may cause additional volatilization of volatile compounds present in the dissolved phase, LNAPL and soil, hence decreasing the contaminants concentrations in those media, but increasing the contaminants concentrations in the vapour phase.

During spring river flooding

- Increased water infiltration and contaminants leaching through the vadose zone can lead to contaminant mass addition to the dissolved phase. This could increase the dissolved contaminant concentrations in groundwater, as well as the dissolved contaminant plume extent. The current front edge of the plume is approximately 3 m from the site boundary, in the direction of groundwater flow. An increase in the dissolved plume extent would mean that the plume is no longer stable and is advancing, with a potential to impact the adjacent property.
- The influx of freshwater may shift the redox conditions and increase aerobic conditions (due to the addition of freshwater with high oxygen content) and increase the microbial activity while the increase in soil moisture can hinder microbial activity, hence affecting the biodegradation of the contaminants.
- Additional groundwater recharge may result in the dilution of the dissolved plume, and could balance, to a certain extent, the increased dissolved concentrations due to dissolution.
- A sudden increase in water table elevation could trap the LNAPL plume below the water table and immobilize it temporarily.
- The increase in water table elevation may reduce the partitioning to the vapour phase of contaminants present at residual levels in soil that become saturated. The partitioning would only occur from the aqueous phase (i.e. dissolved contaminants plume) which is relatively lower.

Once the potential impacts of climate change on the site contamination have been evaluated, a conceptual site model based on future conditions will be developed. Section 5 of this document discusses how to build a CSM to best represent the current and future conditions of the site.

To further investigate the potential impacts of climate change on the site's contamination, the practitioner decides to complete additional work, including:

- Conduct additional groundwater sampling after an extreme rainfall event to assess whether it added contaminants mass to the dissolved plume and the plume has advanced, even temporarily.
- Conduct seasonal groundwater monitoring and sampling to assess changes in plume extent under various seasonal water table elevation.
- Conduct additional vapour sampling during summer, at the lowest seasonal water table.
- If contaminants concentrations in groundwater and/or vapour have increased, drilling of additional boreholes and installation of groundwater monitoring wells between the site boundary and the leading edge of the dissolved plume, to intercept any advancement of the plume before it migrates off-site.
- Update CSM as new information becomes available.

4.5 Data Gaps and Uncertainties

Evaluating vulnerability of a site to climate change involves a certain level of uncertainty. It is important to consider approaches for acknowledging and communicating uncertainty. However, uncertainty should not limit or discourage assessments of vulnerability (CCME, 2015). Ongoing research and continuous advances in climate science, as well as a better understanding of the effects of climate change will contribute to a reduction in uncertainty in the future.

4.5.1 Uncertainties of Climate Change Projections

According to ClimateData.ca (2023), there are three main sources of uncertainty in climate projections. The first source is natural internal climate variability, which refers to the unpredictable fluctuations in the climate system that occur without any change in GHG concentrations. These fluctuations include phenomena such as El Niño and North Atlantic Oscillation which are largely unpredictable. Other external and unpredictable factors such as volcanic activity and solar output can also not be accounted for in the simulations.

The second source of uncertainty is model uncertainty which refers to climate models being based on the laws of physics which represent our current understanding of the climate system which can differ from reality. Models also vary in their level of simplification, grid size, and the way they represent physical aspects such as clouds and soil, and therefore will provide slightly different projections. To address this uncertainty, sets of climate change models are often used for a calibration of sorts and show a range of possible features.

The third source of uncertainty pertains to GHG emissions as it is not possible to determine what future emissions will be. This is the reason why different trajectories of emissions are included in the models and are known, as the previously referred to in Section 2.2, as RCPs or SSPs which are based on variables such as technological change, demographic and socioeconomic development, and land use.

4.5.2 Cumulative Effects of Climate Change

Shared climate conditions can cause various hazards that can trigger each other through landscape precondition. The compounding hazards are interconnected and can lead to more severe consequences. For example, a drought can make the landscape more vulnerable to wildfires by making them more likely to occur. In turn, wildfires can lead to landslides by burning vegetation, creating hydrophobic soils, and increasing runoff during rainfall events. The landscape preconditioning changed by one hazard can reduce the threshold for other hazards, making them more likely to occur. The cumulative effects of climate change hazards were not further assessed in this document but should be considered by practitioners when conducting a climate change vulnerability assessment for a contaminated site.

4.5.3 Variability of Climate Change Impacts

The fate and transport processes of contaminants are complex and site-specific and can vary based on the nature and variability of the climate change hazards. For this reason, climate change hazards can have positive and / or negative effect on constituents of concern, as noted in the examples listed under Section 4.4. It is, therefore, important to take into account any potential climate related impacts to the site that may be temporary or could negate any adverse effects on the site's constituents of concern. To mitigate the uncertainty related to the variability of climate change impacts, regular site monitoring is recommended to physically assess how the site conditions and contamination change due to climate change hazards as they occur.

4.5.4 Other Data Gaps

A major data gap that exists currently within BC for the potential to plan and mitigate potential climate change impacts is the non-existing or insufficient climate change adaptation strategies for municipalities. As previously mentioned, it is imperative that climate change impacts be approached on a more detailed, site-specific scale and therefore, it is important for municipalities to adapt their own, comprehensive adaptation strategies. These strategies can be used by various professionals to aid in their own climate change evaluations.

Currently there is little to no information on how extreme weather events affect sites with existing contamination and how resilient (or stable) the contamination is after such an event. This information would be helpful for practitioners predicting site resiliency in future climate change hazards.

The resiliency of the soil, vapour and groundwater standards/guidelines to the hazards of climate change has not been well studied. Guidelines/standards have been developed under conservative scenarios to be protective, encompassing protection for human health and the environment over large geographical areas. This degree of conservatism could by itself have resiliency built in and lessen the need for climate adaptation assessment.

There are many variables that cannot always be accounted for in climate change projections and may change the hazard impacts as it pertains to a regional or local scale. Some of these variables include the effects of carbon storage and release from deforestation, wildfires, and permafrost thawing; ocean acidification and warming; and the impacts to contaminant fate and transport due to geochemical and redox conditions.

It is therefore important to incorporate any changes in climate data or new information that becomes available as climate change science and tools develop.

5 CLIMATE CHANGE CONCEPTUAL SITE MODELS

To assist practitioners assessing the potential impacts of climate change on contaminated sites in BC, it is recommended to develop a future conceptual site model (CSM) for a given site. A climate change CSM takes the components of a traditional contaminated site CSM (i.e., sources, pathways and receptors) which represents the current site conditions and overlay the identified climate change hazards and associated potential impacts. The CSMs presented in the sub-sections below illustrate examples of how to show potential climate change hazards that can be expected at hypothetical sites located in different regions of BC and the impacts they may have on inorganic and petroleum hydrocarbon constituents of concern.

5.1 Building a Future Conceptual Site Model

A CSM is a fundamental tool for clarifying the relationships between contaminant sources, pathways, and receptors. It brings together essential information about the site's contamination sources, how contaminants move through the environment, and how they may affect a given receptor. The CSM is an iterative and dynamic document, continuously updated as new information becomes available, either confirming or refuting previous iterations and ensuring a comprehensive and defensible CSM is established. It can be supplemented with additional details about contaminants, their forms in different media, and effects on receptors. Understanding the physical, biological, and chemical systems of a site is critical to developing a good CSM. The CSM can be represented in various formats, such as pictorial diagrams for simpler communication to non-technical audiences and box-diagrams for more comprehensive and rigorous analysis. Software options like spreadsheets, presentation packages, and graphic software are available to create CSMs, depending on the required presentation format, details and ease of use. There are various guidelines and tools to assist with conceptualizing a site, including the FCSAP (2022), BC Guidance for Risk Assessment, BC Protocols (e.g., P1, P13) as well as BC Technical Guidance (TG) documents (e.g., TG 4, 6, and 8).

After preparing a preliminary (during a Phase 2 PSI) and/or detailed CSM (during a DSI) illustrating the current site conditions, practitioners can create a new CSM illustrating the future climatic conditions that incorporate information on climate change projections and hazards under future time horizons, and how those hazards may influence the contaminants distribution, exposure, pathways and receptors (hereafter referred to as “future CSM”.

Climate change hazards and potential effects identified in this document (Tables 1, 2, 3a and 3b detailed in Section 4), together with site-specific data collected during site environmental investigations, can be used to compile a future CSM. The potential climate change impacts that may apply to the site should be clearly identified, as well as the potential effects on the site contamination, to inform decision making (e.g., remedial option evaluation or risk management). Any data gaps pertaining to the site’s vulnerability to climate change hazards should also be included in the future CSM (Washington State Department of Ecology, 2023). Such data gaps could be evaluated and prioritized during additional site investigation to determine how and whether the missing information (e.g., additional sampling to better understand the natural processes occurring at the site) would influence the selection of a remedial/risk management options for the site. It may not be possible to know the exact magnitude of changes to the contaminant distribution, exposure pathway and receptors due to climate change hazards during the development of the future CSM. However, it may be possible to know the direction of change at the conceptual level. This conceptualization establishes, for example, that certain pathways are not being eliminated without first considering whether they would be possible under future climate change scenarios (FCSAP, 2022).

The future CSM can help practitioners for different aspects of decision making, including:

- Design and plan additional site investigation to better understand the possible magnitude of future change;
- Select the appropriate timeframe of the remedial option;
- Assess the potential consequences of the remediation or risk management failure;
- Determine the need for long-term monitoring; and
- Assess the site risk classification, which is further discussed in Section 6.2.

The Washington State TCP document (2023) and FCSAP (2022) provide more information for the development of future CSMs.

5.2 Coastal Region Examples

The CSM in **Figure B** represents the current conditions of a site contaminated with metal and petroleum hydrocarbon (PHC) constituents of concern, located on top of an unconfined aquifer that is hydraulically connected to the ocean or Fraser River delta, for example in the South and West Coast region. **Figures C** and **D** below illustrate some potential impacts of climate change to the site when exposed to sea level rise, extreme precipitation and flooding.

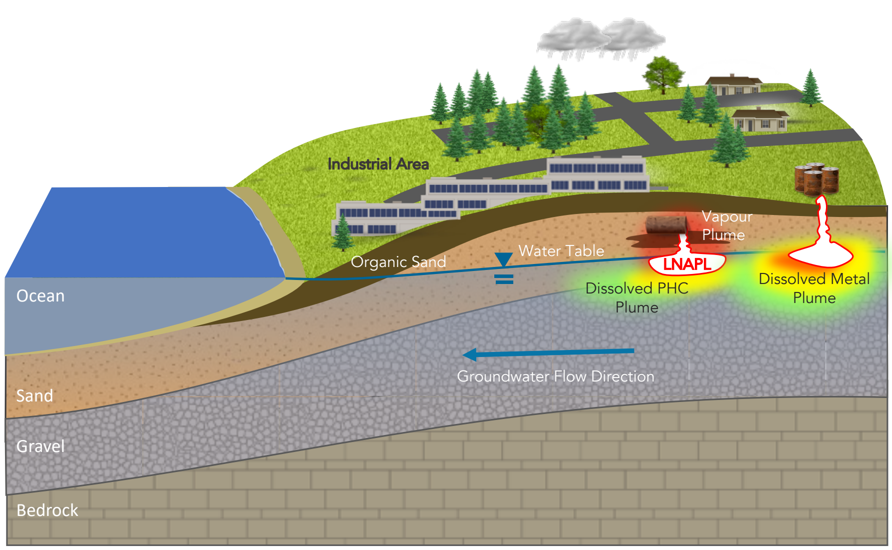


Figure B: CSM of current conditions of a coastal site with inorganics and petroleum hydrocarbons contamination.
Created from the Health Canada CSM Builder Tool (eSolutionsGroup Ltd., 2015)

5.2.1 Inorganics Constituents of Concern

Sea level rise will lead to further saltwater intrusion into coastal aquifers. This could change the applicable standards at a given site (e.g. drinking water standards may no longer be applicable in the future). This could lessen the need for remediation in the future. At the saltwater-freshwater interface, ion exchange can occur resulting in mobilization of some inorganic constituents while immobilization of others. This could result in the increase of some dissolved inorganic constituents while a decrease in others. At existing groundwater extraction wells (e.g., an in-situ pump and treat system), the extracted groundwater may become brackish or even saline due to the increased saltwater intrusion caused by pumping, hence affecting the efficacity of the water treatment.

As sea level rises, the saltwater wedge moves inland, and the vertical position of the local water table will rise, due to both the difference in density and the higher hydraulic head at sea level. The rise in water table elevation will increase the saturated zone and reduce the vadose zone. For soil constituents of concern that were in the vadose zone and become saturated, this may lead to a change in redox, temperature and pH conditions which may result in the mobilization of certain inorganic constituents from soil to groundwater, or immobilization of other constituents from groundwater to soil.

Similarly, an increase in precipitation and flooding of low-lying areas will also contribute to a rise in the water table as well as increased leaching of metals from source areas through infiltration into the vadose zone. Although leaching may cause an increase in dissolved contaminants concentration in pore-water, increased groundwater recharge may dilute the dissolved contaminants due to the addition of fresh non-contaminated water. Depending on the geology underlying the site, it may also result in a plume "diving" deeper due to the "flushing" effect of additional fresh non-contaminated groundwater.

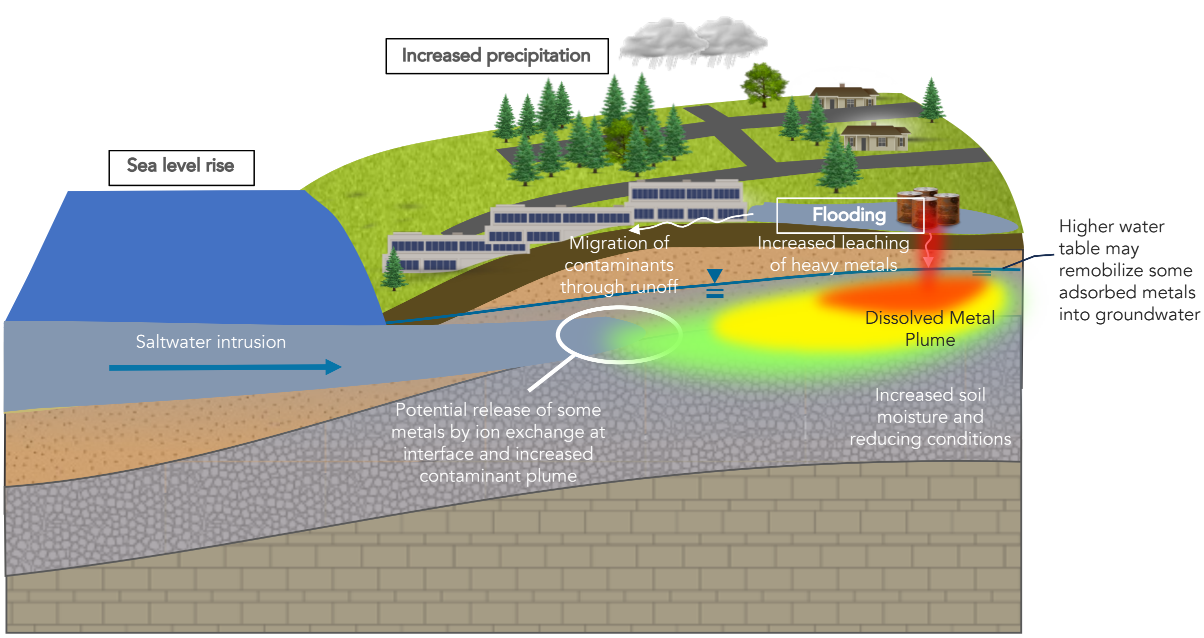


Figure C: CSM illustrating potential climate change impacts to a coastal site with metal contamination.
Created from the Health Canada CSM Builder Tool (eSolutionsGroup Ltd., 2015)

Finally, if a shallow contamination is present at or near ground surface, there is a potential for the contamination to be entrained and transported from a contaminated area to a non-contaminated area, via overland flow, runoff or erosion. This could result in the contamination of otherwise non-contaminated areas.

5.2.2 Petroleum Hydrocarbons Constituents of Concern

The rise in water table associated with sea level rise and/or increased precipitation and flooding will increase the vertical thickness of the saturated zone and reduce the vertical thickness of the vadose zone. If a vapour plume is present in the vadose zone, it could reduce in extent if sourced from residual soil contamination or potentially expand if sourced from the aqueous phase due to less vertical attenuation.

Although increased precipitation and flooding could result in an increase of aqueous phase constituents of concern, it also has the potential to reduce their relative concentration due to dilution. Also, similar to inorganics, the addition of fresh non-contaminated groundwater (owing to increase infiltration during increased precipitation and flooding) may resulting in a "flushing" effect, resulting in a diving plume. The higher groundwater table could also affect the redox conditions due to the different vertical position of the saturated zone and variation in dissolved oxygen levels. As a result, petroleum hydrocarbon biodegradation rates could change; as well as, the general natural attenuation processes which were previously controlling constituent concentrations at the site.

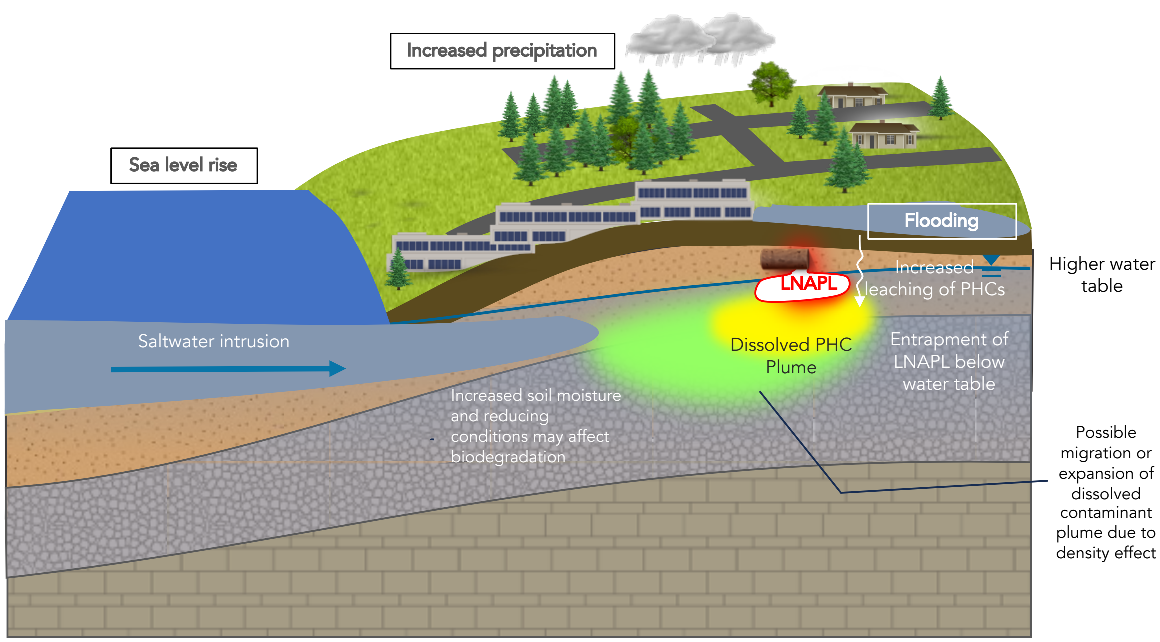


Figure D: CSM illustrating potential climate change impacts to a coastal site with petroleum hydrocarbon contamination.

Created from the Health Canada CSM Builder Tool (eSolutionsGroup Ltd., 2015)

The sudden rise in water table associated with extreme precipitation and flooding has the potential to temporarily trap the LNAPL plume below the water table. On the other hand, water table rise owing to sea level rise would be a slower and more permanent effect, and could result in the LNAPL to move up with the water table and closer to the surface. Finally, sea level rise has the potential to cause the migration or expansion of the dissolved contaminants plume due to the density effect of saltwater causing groundwater table to rise and the thickness of freshwater lens to decrease (Masterson J. P. & Garabedian S. P., 2007).

5.3 Interior Region Examples

The CSM in **Figure E** represents the current conditions of a contaminated site with metal and petroleum hydrocarbon constituents of concern, located on top of an unconfined aquifer, in an interior region, such as the Okanagan. **Figure F** below shows some potential impacts of climate change to the site when exposed to drought, increased temperatures and wildfires.

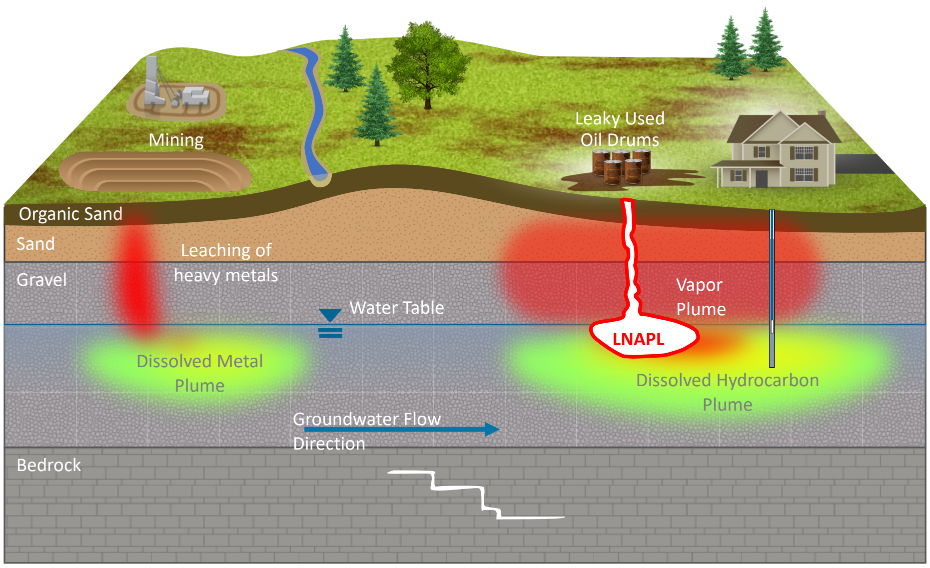


Figure E: CSM of current conditions of a site in the interior of BC with metal and LNAPL contamination.
Created from the Health Canada CSM Builder Tool (eSolutionsGroup Ltd., 2015)

Research has shown that, independently of the emission scenario considered or the soil type, the increase in air temperature will lead to an increase in soil temperatures, to various degrees depending on the scenario (Bradford J.B. et al., 2019). The effects of an increase in soil temperature due to climate change on contaminated sites has not been well studied yet. However, based on technical knowledge of petroleum hydrocarbons and inorganics geochemistry and fate and transport, it is possible to anticipate some potential effects. For example, an increase in soil temperatures can increase the volatility and biodegradation rates of certain petroleum hydrocarbon compounds, and increase some inorganic constituent reactions (e.g., dissolution / precipitation and adsorption / desorption). These effects may accelerate natural source zone depletion, reducing the mass of LNAPL while increasing dissolved and vapour phase constituent concentrations.

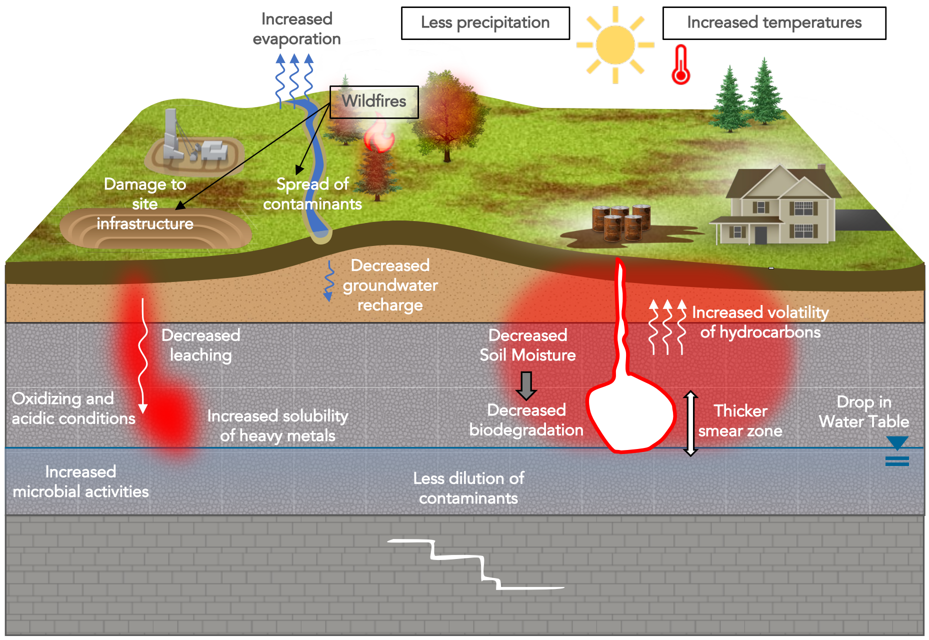


Figure F: CSM illustrating potential climate change impacts to a site in the interior of BC with metal and LNAPL contamination.

Created from the Health Canada CSM Builder Tool (eSolutionsGroup Ltd., 2015)

Rising temperatures would also escalate the evaporation of surface water bodies, coupled with reduced precipitation, leading to a decrease in infiltration and groundwater recharge, which would result in a drop in the groundwater table. Consequently, the vertical smear zone of LNAPL may increase below the typical seasonal low water table, under drought conditions. This in turn may result in increased volatile petroleum hydrocarbon partitioning to the vapour phase, within the vadose zone. The decrease in soil moisture content could also diminish the population of aerobic microorganisms resulting in a decrease of petroleum hydrocarbon biodegradation in soil.

A decline in the groundwater table could affect the redox conditions in the vadose and saturated zones (i.e., increased oxidizing conditions) and therefore could change groundwater geochemistry, resulting in the mobilization or immobilization of certain inorganic constituents, depending on their speciation.

Lastly, wildfires may disseminate pollutants from contaminated areas to uncontaminated zones and damage some site's infrastructure, including remediation systems.

6 CLIMATE CHANGE VULNERABILITY ASSESSMENT OF CONTAMINATED SITES

This section details different available methodologies to aid practitioners to conduct a climate change vulnerability assessment of a given contaminated site. It builds on the tools (tables) developed in Section 4 and the CSMs detailed in Section 5. The vulnerability assessment will identify whether a contaminated site would be considered "highly vulnerable" to climate change hazards. This section provides information on how to determine when a site would be considered "highly vulnerable" with respect to climate change and for which particular hazard(s), while evaluating the potential consequences of these hazards on the site's contamination.

6.1 When to Conduct a Vulnerability Assessment

Currently, there is no legislative or regulatory requirement to conduct a climate change vulnerability assessment of contaminated sites in BC and no guidance has been developed by the provincial government to assist environmental practitioners with this process. As a result, a vulnerability assessment of a given contaminated site will be conducted only if a client or stakeholders require it. Potential impacts of climate change on contaminated sites where there is a limited contaminated source present, and low potential for contaminant remobilization need not to be evaluated. Potential scenarios where a climate change vulnerability assessment could be considered include (list is non-exhaustive):

- Contamination at the site is complex (e.g. with multiple sources, multiple contaminant plumes, complex hydrogeology, etc.);
- The site has been classified as a "high-risk site" or "risk managed high-risk site" under Protocol 12 of the BC CSR;
- Remediation of the site is believed to take several years to be completed (e.g. monitored natural attenuation sites);
- Indigenous sites or concerns, e.g. culturally significant or sensitive sites;
- Select portion of sites where a performance verification plan (PVP) is in place. Should be considered where the PVP is likely to be ineffective given climate change projections.

6.2 Definitions

6.2.1 Vulnerability

In order to inform the development of adaptation solutions to reduce future climate change impacts, it is important to understand how the contaminated sites is currently vulnerable to the climate change hazards. Various definitions of vulnerability are present in the climate change adaptation literature. Some examples include:

- CCME (2021) defines vulnerability as "*the degree to which a system or jurisdiction is susceptible to harm arising from climate change impacts. It is a function of a system or community's sensitivity to climate change and its capacity to adapt to climate change impacts*". This definition was also used by FCSAP (2022).
- AR4 of the IPCC defines vulnerability as "*the degree to which a system is susceptible to, or unable to cope with, adverse impacts of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity and its adaptive capacity*". This definition is also used by BC ENV (2022) and US EPA.

Based on the definitions provided above, the vulnerability of a site is determined by assessing the potential for its exposure to identified climate change hazards, its sensitivity to those hazards, as well as its ability to adapt to mitigate those hazards, as illustrated on **Figure G**. For the purpose of this framework, the "system" is represented by the contaminated site, its location, specific characteristics (e.g., its geology, infrastructure present, etc.), contamination and existing natural processes.

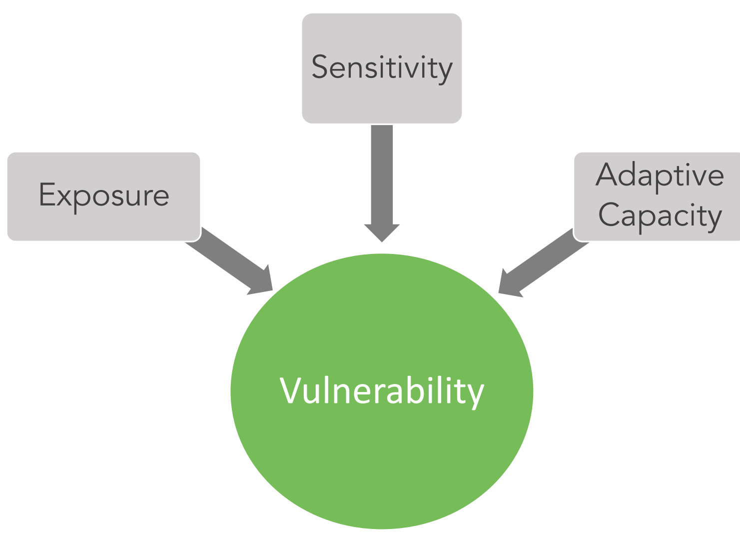


Figure G: Key Aspects of a Vulnerability Assessment

6.2.2 Vulnerability Assessment

The purpose of a vulnerability assessment is to identify climate change hazards that have the most potential to adversely affect a contaminated site. The goals and scope of vulnerability assessments are site-specific and are defined with input from the future CSM. The boundaries of the assessment are also important to define and may depend on the type of project and the hazard being addressed (ITRC, 2020). The outcomes of the vulnerability assessment will help practitioners understand to which climate change hazard(s) the site is the most vulnerable, and prioritize adaptation measures and resources accordingly. These outcomes include:

- An assessment of the sensitivity and exposure of the site to climate change hazards;
- A broad understanding of the adaptive capacity of the contaminated site; and
- A list of vulnerabilities of the site.

The flow diagram below (**Figure H**) shows the process of assessing a site's vulnerability using the tools (tables) developed in Section 4 of this report as well as the future CSM discussed in Section 5. There are no particular equations to assess a site's vulnerability. It is the combination of all three components (exposure assessment, sensitivity assessment and adaptive capacity assessment) that results in the overall site's vulnerability to a given climate hazard.

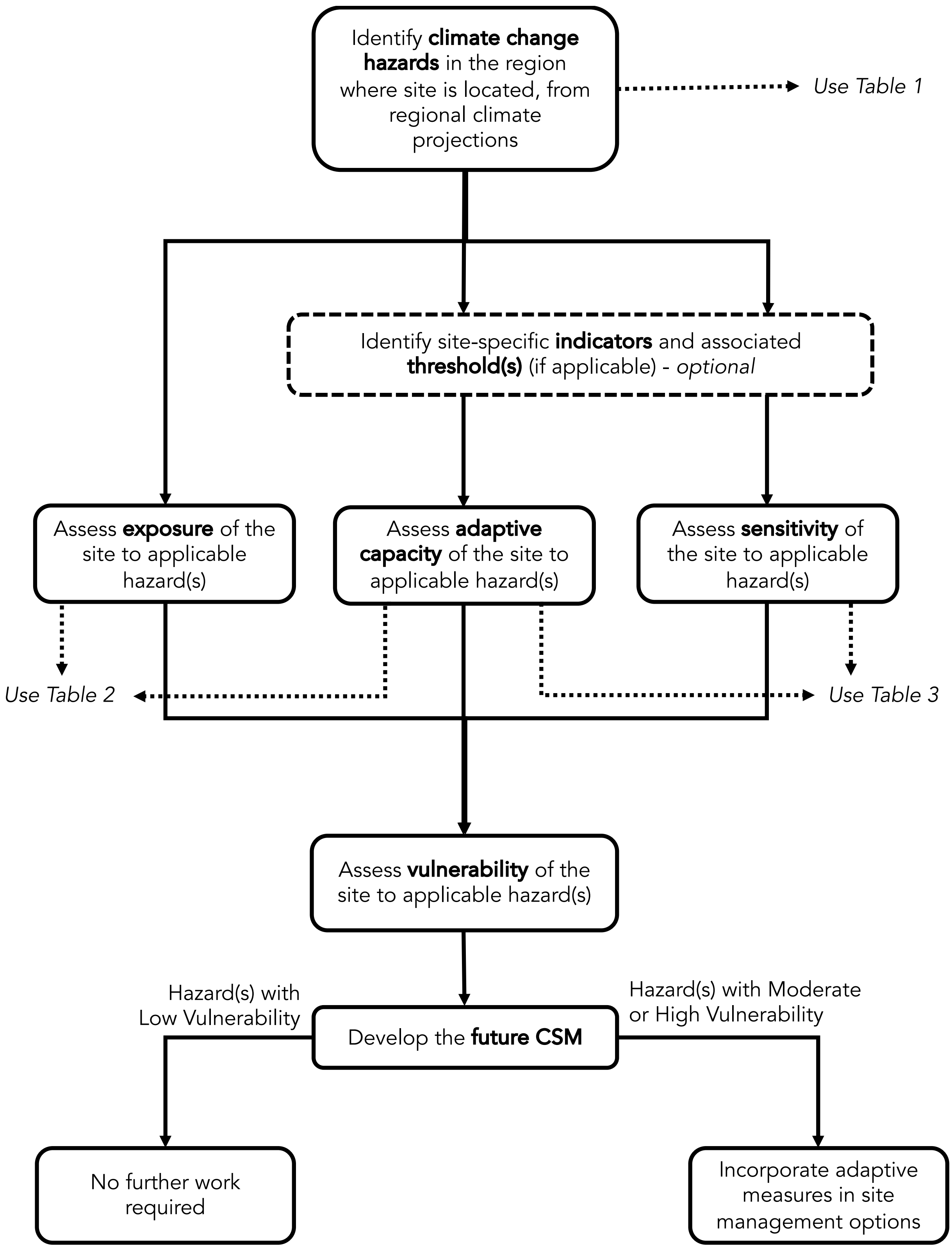


Figure H: Vulnerability Assessment Flow Chart

6.3 Vulnerability Assessment Components

A site's vulnerability can be assessed through the use of indicators that measure physical, chemical and biological characteristics of the system (FCSAP, 2019). Once exposure, sensitivity, and adaptive capacity have been identified, the results are combined and the overall vulnerability of the system is determined.

6.3.1 Exposure Assessment

Exposure is the only component directly linked to climate parameters (i.e., character, magnitude and rate of climate change and variation) (BMZ, 2014). An exposure assessment is performed to understand the site's history and location and identify the specific site's potential exposure to each climate change hazard (US EPA). For each hazard, the exposure assessment should consider the magnitude, extent (spatial and/or temporal), and frequency that the system will be exposed to the climate change hazard within the relevant time horizons (FCSAP, 2022). Typical exposure parameters include temperature, precipitation, evapotranspiration and climatic water balance. The exposure assessment consists in two parts. First, **Table 1** is used to identify which climate change hazards are relevant to the site. The next step consists in determining which of the identified hazards apply to the site using **Table 2**. The data is then analyzed to assess the exposure of each climate change hazard to the site (e.g., low, medium, or high exposure).

6.3.2 Sensitivity Assessment

FCSAP (2022) defines sensitivity as "*the degree to which a system is affected, either adversely or beneficially, by climate variability or change; a measure of how a system is likely to respond when exposed to induced stress*". Sensitivity is typically shaped by natural and/or physical attributes of the system such as topography, soil type, or land cover. But it also refers to the human activities which affect the physical constitution of a system such as contamination, water management, resource depletion, remediation systems, etc. As most systems have been adapted to the current climate (e.g., construction of dams and dikes, irrigation systems), sensitivity already include historic and recent adaptation (BMZ, 2014)

Box 1: *Examples of sensitivity indicators include:*
- *Groundwater table elevation*
- *Sea level change*
- *Position of saltwater wedge*
- *Distance between leading edge of dissolved plume and receptor*
- *Mean summer temperatures*
- *Maximum precipitation during a single rainfall event*
- *Type of soil*
- *Vegetation height or age*
- *Soil saturation*
- *Slope gradient*
- *Paved surface area*
- *Optimal range of operation for in-situ remedial system*
- *Contaminants concentrations*

Site-specific indicators can be identified to evaluate a site's sensitivity to climate change and will vary with each site. An indicator is a qualitative or quantitative variable component of a site-specific factor as detailed in Section 4.2. Examples of indicators are presented in Box 1. Additional indicator examples can be found in State of Washington (2023) and CCME (2021), and BMZ (2014) have a whole module dedicated to the selection of indicators. Practitioners should use their specific knowledge of the site and their professional judgement to select the appropriate site-specific indicators for their vulnerability assessment.

One or more thresholds may be assigned to a quantitative indicator, especially if the indicator is characterizing an ongoing climate hazard (e.g., sea level rise). A threshold is an indicator value which, if reached or crossed, would make the site moderately to highly sensitive to the climate change hazard (i.e., moderate sensitivity threshold and high sensitivity threshold).

Questions that practitioners can ask themselves to assess the site's sensitivity include (CCME, 2021 and FCSAP, 2022):

- What indicators can be used to quantify sensitivity? Are there any associated thresholds?
- Is the system already subject to existing stress?
- How are the indicators likely to respond when exposed to the climate change hazard(s)?
- What is the potential for the indicators to be adversely affected by the climate change hazard(s)?
- What is the potential for the indicators' threshold to be exceeded due to the climate change hazard(s)? Will there be a negative change, a positive change, or no change?

Based on the climate change hazard effects on the indicators and thresholds, and the site sensitivity questions above, the practitioner can assess the site sensitivity (e.g., low, moderate, high).

6.3.3 Adaptive Capacity Assessment

Adaptive capacity is referred by IPCC in AR4 as "*the ability of a system to adjust to climate change (including climate variability and extremes), to moderate the potential damages, to take advantage of opportunities and/or to cope with the consequences*". Adaptive capacity is sometimes also referred to as resilience (CCME, 2021). It is usually evaluated through the use of indicators of adaptive capacity. These indicators may represent the inherent characteristics of the system or natural processes that influences their ability to adapt to the climate change hazards. These indicators could also include existing infrastructure or activities utilized as adaptive measures. Some examples of adaptive capacity indicators are presented in Box 2, additional examples can be found in the CCME (2022) report. In addition, BMZ (2014) have a whole module dedicated to the selection of indicators. By identifying these indicators, practitioners can assess the level of adaptive capacity (i.e. low, medium or high), using their knowledge of the site, understanding of climate change hazards and professional judgement to answer the following questions:

> ***Box 2**: Examples of adaptive capacity indicators include:*
> - *Presence/absence of dikes (protecting from flooding)*
> - *Artificial groundwater recharge (mitigating flooding and drought)*
> - *Vegetation maintenance prior to wildfire season*
> - *Increased planting of climate change tolerant plants vegetation*
> - *Wetland maintenance or restoration*
> - *Improved drainage (mitigating landslide, erosion and flooding)*
> - *Runoff control (mitigating erosion and flooding)*
> - *Biodiversity of microorganisms responsible for natural attenuation*
> - *Presence/absence of back-up generator for pump and treat system*

- Can the site handle the predicted changes in climate?
- Are there barriers to the site's ability to accommodate changes in climate?
- Are efforts already underway to address the impacts of the climate change hazard?
- Is the rate of predicted climate change likely to be faster than adaptability?

6.4 Vulnerability Assessment Methodologies

The data collected through the review of **Tables 1** to **3** will help practitioners to assess the vulnerability of the site to climate change hazards. To do so, practitioners can ask themselves the following questions to evaluate the risk that climate change may have on the contaminated site (FCSAP, 2022):

- What changes in contaminants and contaminant concentrations, distribution, migration pathways and affected media are likely to occur at the site for the applicable time horizon, in the absence of active remediation, and if no adaptation measures are implemented against the identified climate change hazard(s)?
- What changes in human and ecological receptors, and their exposure pathways are likely to occur at the site, for the applicable time horizon, in the absence of active remediation, and if no adaptation measures are implemented against the identified climate change hazards?

The response to these questions will also inform the development of the future CSM. They will help practitioners understand and prioritize the site risks associated with climate change and select an appropriate site risk management or remedial approach resilient to future climatic conditions.

6.4.1 Top-Down and Bottom-Up Approaches

CCME (2015) and CCME (2021) documents provide a good description of the difference between a top-down and bottom-up approach to climate change adaptation. The objectives, time horizon, drivers and financial resources of the vulnerability assessment will determine which approach will be used.

A bottom-up approach is considered participatory and relies on knowledge and expertise from local stakeholders, and instead of using climate models for looking into the future, it examines vulnerability to current climate. This approach often considers past examples of response to climate change impacts, assuming that adapting to current climate variability or change is an appropriate way of assessing for near term climate change, given the uncertainties associated with most climate projections. Examples of bottom-up approach frameworks include BARC Milestone 2 (ICLEI Canada, 2020) and Climate Change Planning Tools for First Nations (CIER, 2020)

A top-down approach is more technical and science driven. It is a desktop study that relies on scientific research and climate model projections of future climate change to assess the risks associated with future climatic conditions. It is typically carried out by an individual or a small group of individuals internal to an organization (or externally via a third-party partner or consultant). This approach can however be combined with stakeholders engagement or consultation, and interviews of knowledge holders. The top-down approach is mostly driven by federal or provincial legislation. It has the capability to focus on near-term but also mid- and long-term horizons. This approach takes the human and social aspect of climate change less into account than the bottom-up approach. Typically, the results of this approach is an inventory of known climate-related issues (e.g., impacts, risks, vulnerabilities resulting from the changing climate). Examples of top-down assessment frameworks include ISO 31000: 2018 Ontario Climate Change and Health Toolkit and PIEVC Engineering Protocol. (CCME, 2021). This approach is more applicable to contaminated sites.

6.4.2 Qualitative Vulnerability Assessment

The choice of vulnerability assessment approach depends on the availability of data, the level of complexity required, and the resources available for conducting the assessment. A qualitative assessment is the simplest approach that favours narrative and thematic evaluations leveraged from perceptions and lived experience (CCME, 2021). The goal of a qualitative risk assessment is to provide a comprehensive overview of the site vulnerabilities and their implications without relying on specific numerical data. It relies instead on the practitioner's knowledge of the site and professional judgement to evaluate the potential risks associated with climate change hazards on a contaminated site. This approach involves identifying the climate change hazards applicable to the site, understanding the site's sensitivity to those hazards, and qualitatively describing the potential consequences of these hazards on the site's contamination and surrounding environment without assigning specific numerical values or probabilities to the risks. It is typically based on professional judgement, literature reviews, and qualitative data gathered from site history.

Qualitative terms (such as "increase", "decrease", "alteration", "degradation", "changes", "more" or "less") may be used to describe how climate change may exacerbate contamination issues on a site due to changes in fate and transport of contaminants. It is also useful to identify potential adaptation strategies that could be employed to reduce or negate a site's vulnerability to climate change. This approach may provide a broad overview of the risks but lacks the precision and quantification of a more data-driven method. However, it is easier to manage uncertainties in qualitative assessments, as it is not limited to the confines of numerical allocations of risks. The Climate Change Planning Tools for First Nations provides an example of qualitative vulnerability assessment (CCME, 2021).

The presentation of the qualitative vulnerability assessment results should be accessible and focused on conveying the information in a way that can be easily understood and acted upon by decision-makers and stakeholders. The outcome of a qualitative assessment can take multiple form, some examples include:

- **Future CSMs**: As described in Section 5, future CSMs are great tools to illustrate the interactions between climate change hazards and the contaminated site, showing potential future contaminants pathways, and potential impacts on contaminants sources and receptors.
- **Tables**: Listing the identified site risks to climate change in a table format, with their description and any relevant qualitative information about their consequences and vulnerability is another option of qualitative vulnerability assessment outcome.
- **Geographic Information System (GIS) Maps**: GPS utilize maps can display the location of the contaminated site and highlight potential areas of concern in relation to climate change hazards.
- **Narrative description**: Provide clear and concise written explanations of the identified risks and their significance, using language that is easily understood by non-technical audiences. They can be supported by visual aids such as photographs, or illustration.

6.4.3 Semi-Quantitative Vulnerability Assessment

A semi-quantitative vulnerability assessment incorporates some quantitative elements but still relies on qualitative professional judgments to a significant extent. It involves assigning relative scales or scores to the likelihood of climate change hazards occurring at the site (i.e. exposure), the consequences on the site's contamination (i.e. sensitivity), and the site's adaptive capacity. While numerical values are used, they are not as precise as those in a fully quantitative assessment, or do not correspond to site-specific values but rather an arbitrary number to illustrate a range of possibilities. A scoring system helps in ranking the hazards by comparing their effects on the site's contamination and prioritizing actions for risk management, making it a more structured approach than a purely qualitative assessment.

The outcomes of semi-quantitative assessments typically use numerical scales or scores to compare and rank different risk factors and evaluate their relative significance in terms of potential impacts on the contaminated site and surrounding areas. This allows decision-makers to prioritize actions and allocate resources based on the level of risk posed by climate change. The outcome of a semi-quantitative vulnerability assessment can take multiple forms, some examples include:

- **Risk Matrix**: The risk matrix assesses the likelihood and consequences of various climate change impacts on a contaminated site. **Figure I** below present an example of a risk matrix developed for a vulnerability assessment.

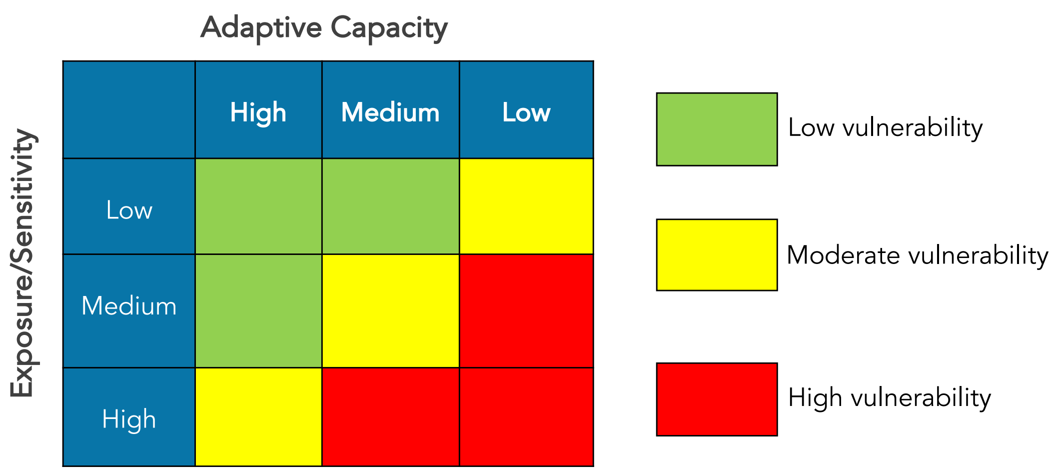
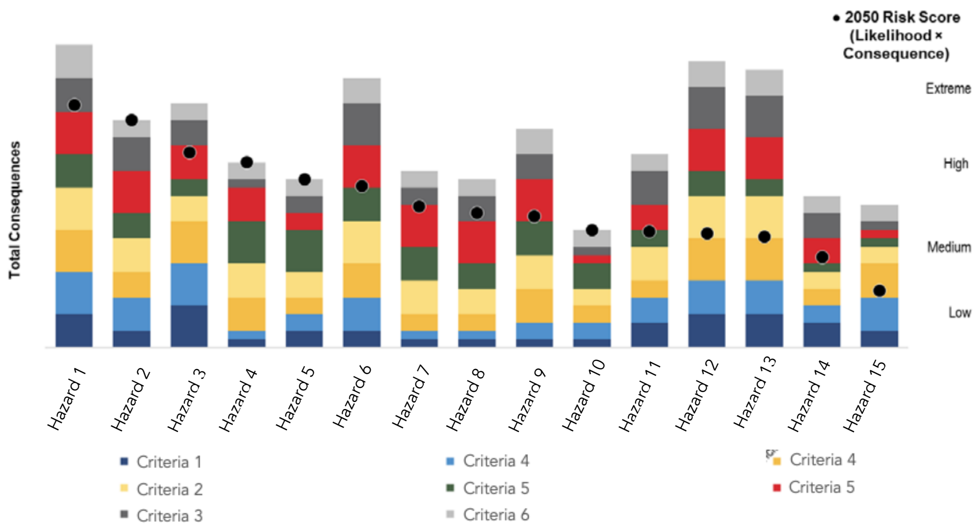


Figure I: Example of Vulnerability Assessment Risk Matrix

- **Relative ranking**: climate change hazards are listed and ranked in order of their potential impact on the site's contamination, based on their overall score. This can be presented in a tabulated format.
- **Consequence rating:** the potential consequences of climate change hazards on the site's contamination are assessed using a rating scale (e.g., low. moderate, high). For example, **Figure J** present the consequences rating in a column chart which can show the cumulative effects of different hazards. In this example the criteria are the various factors describing the consequences.



Source: Ministry of Environment and Climate Change Strategy, 2019

Figure J: Example of a Visual Representation of Overall Consequences and Risk Score.

6.4.4 Quantitative Vulnerability Assessment

A quantitative vulnerability assessment involves rigorous data analysis, probability calculations, and numerical models to estimate the impacts of one or more climate change hazards on the site's contamination, i.e. the sensitivity of a contaminated site to those hazards. It requires extensive climate data (historical data, modelled climate projections and downscaled projections), site characteristics (including geological, topographic, hydrogeological data), contamination data (e.g. type of contaminants, affected media, concentration, extent, etc.), and other relevant factors. It would also include detailed modeling of contaminant fate and transport under different climate conditions, as well as the potential exposure pathways and impacts on human health and ecosystems. This approach provides the most precise and comprehensive understanding of the potential risks and their probabilities and support the design of adaptation strategies, but it is also the most time consuming and requires subject-matter experts. This is usually used for very complex sites (e.g., multiple contaminants sources, complex hydrogeology, etc.). Examples of quantitative vulnerability assessment frameworks include PIEVC Engineering Protocol and BARC Milestone 2 (CCME, 2021).

7 CONCLUSIONS

Potential impacts of climate change on contaminated sites in BC are complex, difficult to predict and highly site-specific. Several climate change hazards have been identified for the different regions of BC, including flooding, sea level rise, drought, increased temperatures, increased extreme storms/precipitation, erosion and landslide, and wildfires.

There is currently in BC no legislative or regulatory requirements, or any guidance to help environmental practitioners determine when and how to assess potential climate change impacts on contaminated sites. This document is intended to aid practitioners with carrying out this work, when a client or stakeholders request it. The framework was designed to be iterative and can be revisited for future site vulnerability assessment, to incorporate changes in climate data or new information that becomes available as climate change science and tools develop. It will also need to be revised if legislative or regulatory updates are released by the provincial government.

A climate change vulnerability assessment framework is provided in this document to help environmental practitioners assess the potential impacts of climate change on a given contaminated site. It involves evaluating the exposure of the site to one or more climate change hazard(s), the sensitivity (or impacts) of the these hazards on site's contamination, and the existing adaptive capacity of the site. A good understanding of the site conditions, including the existing contamination and site history; as well as, knowledge of climate change predictions are necessary to implement this framework document. Different methodologies of vulnerability assessment (qualitative, semi-quantitative or quantitative) are available and depend on the availability of site-specific data, the complexity of the site, and the resources available, as well as the client or stakeholders requirements. The outcome of the assessment, including future site conceptual models incorporating climate change impacts, will assist practitioners in prioritizing remedial options or site risk management and on assessing the need for long-term monitoring.

8 CLOSING

We appreciate the opportunity to assist you with this project. If you have any questions or would like to discuss the report in more detail, please do not hesitate to contact the undersigned.

Yours sincerely,

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FIGURES

Figure 1: British Columbia Regions

TABLES

Table 1: Identified Climate Change Hazards and Associated Regional Projections
Climate Change Impacts on Contaminated Sites
CSAP Society

Hazard	Region 1 Projections South + West Coast	Region 2 Projections Skeena	Region 3 Projections Okanagan + Boundary	Region 4 Projections Northeast, Omineca, Cariboo
Flooding (8)	• Today's 500- year Fraser River flood up to five times more likely by 2050 (1) • Increased frequency (and risk) of moderate and major flooding events in the 2050s • By the 2050s, moderate flood events once every 11 to 50 years (1) • Increased damages from river and coastal urban floods (8)	• Increased frequency (and risk) of moderate and major events in the 2050s (1) • By the 2050s, moderate flood events once every 11 to 50 years (1) • Increased seasonal soil moisture (amount of water held in soil), contributing to increased flood potential and severity (7) • Increased storm surge events by the 2050s (7) • Increased damages from river and coastal urban floods (8)	• Increased frequency (and risk) of moderate and major events in the 2050s (1) • By the 2050s, moderate flood events once every 11 to 50 years (1) • Increased damages from river and coastal urban floods (8)	• Increased frequency (and risk) of moderate and major events in the 2050s (1) • By the 2050s, moderate flood events once every 11 to 50 years (1) • Increased damages from river and coastal urban floods (8)
Drought (8)	• Increased frequency and duration of summer water shortage in the 2050s (1) • Increased drought stress on forests by the 2050s (9)	• Increased frequency and duration of summer water shortage in the 2050s (1) • Increased summer drought (7) • Increased drought stress on forests by the 2050s (9)	• Increased soil impermeability (1) • Increased frequency and duration of summer water shortage in the 2050s (1) • Compromised groundwater and aquifer recharge (5)	• Increased frequency and duration of summer water shortage in the 2050s (1) • Increased drought stress on forests by the 2050s (9)

Table 1: Identified Climate Change Hazards and Associated Regional Projections

Climate Change Impacts on Contaminated Sites

CSAP Society

Hazard	Region 1 Projections South + West Coast	Region 2 Projections Skeena	Region 3 Projections Okanagan + Boundary	Region 4 Projections Northeast, Omineca, Cariboo
			• Increased drought stress on forests by the 2050s (9)	
Wildfires (8)	• 4% increase annual area burned by the 2050s [1] • Amplified severity of wildfires in the 2050s [1]	• 4% increase annual area burned by the 2050s [1] • Amplified severity of wildfires in the 2050s [1] • Longer fire season [7]	• 4% increase annual area burned by the 2050s [1] • Amplified severity of wildfires in the 2050s [1] • More smoke days [5]	• 4% increase annual area burned by the 2050s [1] • Amplified severity of wildfires in the 2050s [1] • Increased risk of wildfire and associated health risks [4]
Extreme weather/ Precipitation [8]	• By 2050, 15% less summer rain, 10% more rain in the fall [2] • More intense and frequent extreme weather events by 2050 and, [1] • Increased inundation in storm water systems [1]	• By 2050, -7% increase annual precipitation, with 15% more rain in fall by 2050 [7] • More intense and frequent extreme weather events • with Increased heavy precipitation and winds by 2050 [1]	• By 2050, 10% less summer rain, 15% more rain in spring, 10% increase wettest day precipitation [5] • More intense and frequent extreme weather events by 2050 [1]	• By 2050, 15 - 30% more rain fall and spring and 18% increase wettest day precipitation [4] • More intense and frequent extreme weather events by 2050 [1] •
Erosion/ Landslides [8]	• More frequent landslides triggered by precipitation by the 2050s [1]	• More frequent landslides triggered by precipitation by the 2050s [1]	• More frequent landslides triggered by precipitation by the 2050s [1]	• More frequent landslides triggered by precipitation by the 2050s [1]
Species distributions invasive/non native [8]	• Increased loss in forest resources to pests by the 2050s [1]	• Increased loss in forest resources to pests by the 2050s [1]	• Increased loss in forest resources to pests by the 2050s [1]	• Increased loss in forest resources to pests by the 2050s [1]

Table 1: Identified Climate Change Hazards and Associated Regional Projections
Climate Change Impacts on Contaminated Sites
CSAP Society

Hazard	Region 1 Projections South + West Coast	Region 2 Projections Skeena	Region 3 Projections Okanagan + Boundary	Region 4 Projections Northeast, Omineca, Cariboo
	• Expanded geographical ranges of invasive species by the 2050s [(1)] • Decreased abundance native species by the 2050s [(1)]	• Expanded geographical ranges of invasive species by the 2050s [(1)] • Decreased abundance native species by the 2050s [(1)] • Expanded mountain pine beetle outbreaks [(7)] • Increased numbers of spruce beetles [(7)]	• Expanded geographical ranges of invasive species by the 2050s [(1)] • Decreased abundance and ability of native species by the 2050s [(1)]	• Expanded geographical ranges of invasive species by the 2050s [(1)] • Decreased abundance native species by the 2050s [(1)] • Increased invasive species and pests [(4)]
Increased temperatures/ heat waves [(8)]	• 2.5 to 3 times as many days over 25°C by 2050 [(2)] • Increased evaporation and water shortages by the 2050s [(1)] • Increased tree mortality due to atmospheric warming [(8)]	• 8 times as many days over 25°C by the 2050s [(1)] • Increased evaporation and water shortages in the 2050s [(1)] • Increased annual warming of 1.8°C [(6)] • Increased frequency and intensity of heat waves in the 2050s [(6)] • Increased tree mortality due to atmospheric warming [(8)]	• 3 times as many days over 30°C by the 2050s [(1)] • Increased evaporation and water shortages in the 2050s [(1)] • Growing season increase by over a month [(5)] • Increased tree mortality due to atmospheric warming [(8)]	• 2 to 3 times as many days over 25°C by the 2050s [(1)] • Increased evaporation and water shortages in the 2050s [(1)] • Warmer temperatures across all seasons by 2050, with 28% fewer frost days, 37% longer growing seasons [(4)] • Increased tree mortality due to atmospheric warming [(8)]
Glacier/snow pack loss [(8)]	• By the 2050s, 25% decline in provincial glacial area [(1)]	• By the 2050s, 25% decline in provincial glacial area [(1)] • Decreased streamflow by the 2050s [(1)]	• By the 2050s, 25% decline in provincial glacial area [(1)] • Decreased streamflow by the 2050s [(1)]	• By the 2050s, 25% decline in provincial glacial area [(1)] • Decreased streamflow by the 2050s [(1)]

Table 1: Identified Climate Change Hazards and Associated Regional Projections

Climate Change Impacts on Contaminated Sites

CSAP Society

Hazard	Region 1 Projections South + West Coast	Region 2 Projections Skeena	Region 3 Projections Okanagan + Boundary	Region 4 Projections Northeast, Omineca, Cariboo
	• Decreased streamflow by the 2050s [1] • 56% decrease in snowpack by the 2050s [3]	• Earlier, more rapid snowmelt [7]	• Less snow accumulation [5]	• Additional freeze-thaw cycles by the 2050s, decreasing the snowpack [4]
Sea level rise [8]	• 0.5m of sea level rise by the 2050s [1] • In the 2050s, increased saltwater intrusion of groundwater and freshwater aquifers [1] • Decrease in irrigation water availability by the 2050s [1]	• 0.5m of sea level rise by the 2050s [1] • In the 2050s, Increased saltwater intrusion of groundwater and freshwater aquifers [1] • Decrease in irrigation water availability by the 2050s [1]	• Not applicable, region is not located on coast	• Not applicable, region is not located on coast

Table 2: Climate Change Hazard Identification Guide

Climate Change Impacts on Contaminated Sites

CSAP Society

Climate Change Hazard	Site Specific Factors	Considerations	Resources*
Flooding And Increased Precipitation	Location	Is the site located: • within a 50-, 100-, or 500-year floodplain? • downstream from a dam (incl. mine tailings dam)? • along river/stream or alluvial fan? • along the oceanfront? • In an area predicted to have increased/heavy precipitation events as a result of climate change?	• BC floodplain maps by region[1] • Retooling for Climate Change[2] • Climate Data website[3] • Climate Atlas website[4]
	Topography	Is site situated in a low-lying area such as a valley or along floodplain?	iMapBC[5]
	Geology	• Does the lithology below the site consist of fine-grained soil that can retard infiltration? • Are the soils permeable to support an unconfined aquifer or perched water table that can reach saturation quickly?	• Geological maps[6] • iMapBC[5] – soil/geology layers • Borehole logs from site assessments
	Physical hydrogeology	• Where is the water table? • Where does groundwater recharge and discharge? • What is the general groundwater flow direction? • Is the site overlying a regionally mapped aquifer?	• iMapBC[5] • BC Water Resources Atlas[7] • Historical data
	Infrastructure	• Is there sufficient drainage on the site in case of heavy precipitation? • If the site is situated along the shoreline, are there adequate barriers/dykes in case of flooding?	• Site engineering drawings indicating drainage, city resources (GIS, maps etc.) • iMapBC[5] – Flood protection structural layer
	Contaminants	• What are the contaminants present? • Where are the contaminants located at the site (e.g. above water table or below, within area sensitive to flooding)?	• Environmental site investigations

Table 2: Climate Change Hazard Identification Guide

Climate Change Impacts on Contaminated Sites

CSAP Society

Climate Change Hazard	Site Specific Factors	Considerations	Resources*
Drought	Location	Is the site located in an area currently or predicted to be subject to drought?	• Retooling for Climate Change[2] • Climate Data website[3] • Climate Atlas website[4] • BC Drought Information Portal[8]
	Physical hydrogeology	• Where is the water table? • Where does groundwater recharge and discharge? • What is the general groundwater flow direction? • Is the site overlying a regionally mapped aquifer?	• iMapBC[5] • BC Water Resources Atlas[7]
	Contaminants	• What are the contaminants present? • Where are the contaminants located at the site?	• Environmental site investigations
Wildfires	Location	• Is the site located in an area currently or predicted to be subject to drought? • Is the site a landfill, or situated close to a landfill which could produce landfill gas, with vegetation?	• Retooling for Climate Change[2] • Climate Data website[3] • Climate Atlas website[4]
	Vegetation	• Does the site have or is the site surrounded by a significant amount of grass or trees (forests or grasslands)?	
	Contaminants	• What are the contaminants present? • Where are the contaminants located at the site?	Environmental site investigations
Storm events	Location	Is the site located: • Located in a low-lying area? • Along a shoreline that are vulnerable to erosion?	• Retooling for Climate Change[2] • Climate Data website[3] • Climate Atlas website[4]
	Physical hydrogeology	• Where is the water table? • Where does groundwater recharge and discharge? • What is the general groundwater flow direction? • Is the site overlying a regionally mapped aquifer?	• iMapBC[5] • BC Water Resources Atlas[7]
	Infrastructure	If the site is located along the shoreline, does it have adequate infrastructure, such as dykes or rip rap, to prevent effects of wave action during storm surges?	• iMapBC[5] – Flood protection structural layer

Table 2: Climate Change Hazard Identification Guide

Climate Change Impacts on Contaminated Sites

CSAP Society

Climate Change Hazard	Site Specific Factors	Considerations	Resources*
			• Engineering assessment drawings
	Contaminants	• What are the contaminants present? • Where are the contaminants located at the site?	• Environmental site investigations
Erosion / landslides	Location	Is the site located: • On a sandy or marshy shoreline? • On a slope? • In an area where wildfires and heavy rainfall occur?	Landslide Susceptibility Map of Canada[9]
	Infrastructure	Does the site or surrounding area have infrastructure, such as adequate drainage and gabion structures, in place to prevent erosion?	Site engineering drawings indicating drainage
	Vegetation	Does the site have adequate vegetation to control erosion?	
Increased temperatures / heat waves	Location	Is the site located in an area where heat waves are predicted to occur?	• Retooling for Climate Change[2] • Climate Data website[3] • Climate Atlas website[4]
	Physical hydrogeology	• Where is the water table? • Where does groundwater recharge and discharge? • What is the general groundwater flow direction? • Is the site overlying a regionally mapped aquifer?	• iMapBC[5] • BC Water Resources Atlas[7]
	Contaminants	• What are the contaminants present? • Where are the contaminants located at the site?	• Environmental site investigations
Sea level rise	Location	Is the site located in a coastal area or within an area projected to be affected by sea level rise?	• Retooling for Climate Change[2] • Climate Data website[3] • Climate Atlas website[4] • Geological Society of Canada - Relative sea-level projections for Canada based on the IPCC

Table 2: Climate Change Hazard Identification Guide

Climate Change Impacts on Contaminated Sites

CSAP Society

Climate Change Hazard	Site Specific Factors	Considerations	Resources*
			Fifth Assessment Report and the NAD83v70VG national crustal velocity model[10] • Sea Level Rise Adaptation Primer[11] • Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT)[12] • Metro Vancouver Sea Level Rise[13]
	Physical hydrogeology	• Where is the water table? • What is the hydrostratigraphy of the site? • What is the general groundwater flow direction? • Is the site overlying a regionally mapped aquifer?	• iMapBC[5] • BC Water Resources Atlas[7]
	Infrastructure	If the site is situated along the shoreline, are there adequate dykes or other infrastructure to prevent effects of sea level rise?	• iMapBC[5] – Flood protection structural layer
	Contaminants	• What are the contaminants present? • Where are the contaminants located at the site?	• Environmental site investigations

***Not an exhaustive list. Municipal websites can also be a useful resource for more localized information and municipal climate change adaptation strategies.**

Table 3: Examples of Climate Change Effects on Contamination

Climate Change Impacts on Contaminated Sites

CSAP Society

METALS			
Climate Change Hazard	Physical Effects	Media Affected	Examples of Effects on Contamination
Flood And Increased Precipitation/ Storm Events	• Saturation of previously unsaturated soils (increased soil moisture) • Overland flow in flooded areas • Change in high water marks position of surface water body • Change in water table position • Increase water infiltration • Mixing of water chemistry (surface water and/or runoff mixing with groundwater)	• Soil (may become fully saturated) • Groundwater (increase of saturated thickness) • Soil vapour (may become non-existent)	• Increase in contaminant leaching from unsaturated zone during increased precipitation events. Could affect seasonal groundwater concentrations. • Potential shift in redox conditions (from aerobic to anaerobic) – could destabilize inorganic chemistry / contamination • Change in groundwater chemistry (pH, EC, DO) may mobilize or stabilize certain inorganic contaminants through precipitation/dissolution, adsorption/desorption. • Soil standards may no longer apply – sediment standards may become applicable under more permanent flooding conditions • Potential transport via overland flow of shallow surface contaminants (dissolved or in suspension) • Possible dissolved phase constituent dilution • Possible migration or expansion of dissolved contaminant plume due to "flush" effect
Drought And Increased temperatures / heat waves	• Change in water table position • Change in high water marks position of surface water body • Decrease in soil moisture • Increased evapotranspiration • Increased soil, soil vapour and water temperatures	• Soil (increased thickness of vadose zone) • Groundwater (decrease of saturated thickness) Soil vapour (increase in extent and concentration)	• Increased oxidizing conditions may affect geochemical conditions (increase or decrease in inorganic species mobility depending on the constituent) • Change in groundwater chemistry (pH, EC, DO) may mobilize or stabilize certain inorganic

Table 3: Examples of Climate Change Effects on Contamination

Climate Change Impacts on Contaminated Sites

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METALS			
Climate Change Hazard	Physical Effects	Media Affected	Examples of Effects on Contamination
			contaminants through precipitation/dissolution, adsorption/desorption. • Increased volatilization and vaporization of volatile compounds
Wildfires	• Compaction of upper portion of soil • Air movement of dust and ashes • Increased soil, soil vapour and water temperatures • Decrease in soil moisture	• Soil ('cracking' of upper layer) • Soil vapour	• Increased volatilization and vaporization of volatile compounds (e.g. mercury) • Change in metals speciation may mobilize or stabilize metal contaminants • Potential transport via air suspension (contaminants adsorbed onto soil particles)
Erosion/landslides	• Removal of a portion of the subsurface	• Soil (vadose zone may disappear) • Groundwater • Soil vapour (may become non-existent)	• Potential transport via overland flow of contaminants (dissolved phase, in suspension or on adsorbed soil particles) • Change in redox conditions may stabilize or mobilize metal contaminants • Potential elimination of soil vapour production
Sea Level Rise	• Seawater intrusion • Change in water table position • Shorter distance to high water	• Soil • Groundwater (change in saltwater wedge position and in saturated thickness) • Soil vapour	• Change in groundwater chemistry may mobilize or stabilize certain metals through precipitation/ dissolution, adsorption/desorption. • Ion exchange may mobilize or stabilize certain inorganic constituents • Saturated thickness may increase affecting soil and groundwater geochemistry (stabilize or mobilize certain inorganic constituents) • Sediment standards may apply instead of soil standards in areas permanently within intertidal zones.

METALS			
Climate Change Hazard	Physical Effects	Media Affected	Examples of Effects on Contamination
			• Surface water guidelines may apply to areas where groundwater standards previously applied (CSR Technical Guidance 15) • Soil vapour is closer to the surface and potential receptor(s).

Table 3: Examples of Climate Change Effects on Contamination

Climate Change Impacts on Contaminated Sites

CSAP Society

HYDROCARBONS			
Climate Change Hazard	Physical Effect	Media Affected	Effect on Contamination
Flood And Increased Precipitation	• Saturation of previously unsaturated soils (increased soil moisture) • Overland flow in flooded areas • Change in high water marks position of surface water body • Change in water table positions • Increased water infiltration • Mixing of water chemistry (surface water and/or runoff mixing with groundwater)	• Soil (may become fully saturated) • Groundwater (increase of saturated thickness) • Soil vapour (becomes non-existent)	• LNAPL smearing or immobilization • Possible dissolved phase constituent dilution • Potential shift in redox conditions (from aerobic to anaerobic) – could alter biodegradation • Increase in contaminant leaching from unsaturated zone during increased precipitation events. Could affect seasonal groundwater concentrations. • Decreased microbial activity due to very high soil moisture levels may affect biodegradation • Potential elimination of soil vapour production • Soil standards no longer in effect – sediment standards become applicable • Potential transport via overland flow of shallow surface contaminants (e.g. oil stains) • Possible migration or expansion of dissolved contaminant plume due to "flush" effect
Drought And Increased temperatures / heat waves	• Change in water table position • Change in high water marks position of surface water body • Decrease in soil moisture • Increased evapotranspiration • Increased soil, soil vapour and water temperatures	• Soil (increased thickness of vadose zone) • Groundwater (decrease of saturated thickness) • Soil vapour (increase in extent and concentration)	• Microbial activity increase due to high temperatures or decrease due to low moisture content may affect biodegradation • LNAPL smearing • Increased aerobic conditions may affect biodegradation • Increased volatilization and vaporization of volatile compounds
Wildfires	• Compaction of upper portion of soil	• Soil ('cracking' of upper layer) • Soil vapour	• Increased volatilization and vaporization of volatile compounds

Table 3: Examples of Climate Change Effects on Contamination

Climate Change Impacts on Contaminated Sites

CSAP Society

HYDROCARBONS			
Climate Change Hazard	Physical Effect	Media Affected	Effect on Contamination
	• Increased soil, soil vapour and water temperatures • Decrease in soil moisture • Air movement of dust and ashes		Potential transport via air suspension (residual contaminants adsorbed onto soil particles)
Erosion/landslides	• Removal of a portion of the subsurface	• Soil (vadose zone may disappear) • Groundwater • Soil vapour (may become non-existent)	• Potential transport via overland flow of contaminants (free product, dissolved phase or residual contaminant adsorbed onto soil particles) • Change in redox conditions may affect biodegradation • LNAPL smearing or immobilization • Potential elimination of soil vapour production
Sea Level Rise	• Seawater intrusion • Change in water table position • Shorter distance to high water	• Soil • Groundwater (change in saltwater wedge position and in saturated thickness)	• LNAPL smearing or immobilization • Possible migration or expansion of dissolved contaminant plume due to density effect • Potential decrease in microbial activity and reduce biodegradation due to change in soil moisture. • Sediment standards may apply instead of soil standards in areas permanently within intertidal zones. • Surface water guidelines may apply to areas where groundwater standards previously applied (CSR Technical Guidance 15)