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Roadmap to Enable Climate Resilient Adaptation Retrofits

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Executive Summary

Many structures across Canada were designed and constructed in accordance with earlier versions of the building code, based on the assumption that climatic loads would remain stationary over the service life of the building. However, due to Greenhouse Gas (GHG) emissions, Canada's climate has become increasingly variable, and this trend is expected to continue. The frequency and intensity of natural hazard events are rising and regions previously unaffected by certain climate events may now experience them for the first time. In addition, many Canadian jurisdictions are likely to face multiple competing or compounding climate hazards, including concurrent events. These evolving conditions are already placing pressure on building owners, who are now required to undertake more frequent, unanticipated, repairs and invest in climate resilient upgrades, a demand that is projected to grow as climate impacts intensify. As more occupants and building owners pursue adaptation strategies to enhance the climate resiliency of their properties, there becomes a growing need for clear, evidence-based guidance. Such guidance must ensure that the selected measures do not result in unintended consequences or maladaptation, particularly in the context of competing hazards.

To address this need, a roadmap is proposed, which outlines the key steps required between hazard identification to adaptation implementation. This roadmap also serves as the organizational framework for this report, which reviews the information available to individuals and professionals seeking to design for a changing climate. This report focuses on the risks and vulnerabilities of buildings and their occupants to hazards such as wildfire, wind, extreme heat, flooding, and multi-hazard scenarios. The report also emphasizes individual building-level retrofits, including upgrades to the building envelope, mechanical, electrical, and plumbing systems, as well as improvements to the immediate surrounding property, rather than strategies that are to be implemented on a broader community scale. The insights and recommendations in this report can inform the future development of best practice guidelines, enabling individuals and professionals to navigate the full adaptation process, from identifying relevant hazards to implementing tailored retrofit solutions based on the specific needs of their building and location.

Introduction

According to National Resources Canada – Office of Energy Efficiency: Housing Stock by Building Type and Vintage, as of 2022 the total housing stock in Canada was approximately 16.5 million dwellings, with approximately 40% of those being constructed before 1983 [1]. These older structures were designed following previous versions of building codes that assumed stationary climatic data and fixed loads to act upon the structures over their service life. However, it is understood that Canada's climate is not stationary and subject to variability due to the effects of Green House Gas (GHG) emissions acting on earths atmosphere [2]. Due to climate change, it is anticipated that our future climate will become more variable, with an increase in both the frequency and intensity (duration and severity) of extreme climate events, including, but not limited to: heat waves, droughts, wild fires, snow, ice and hail storms, precipitation leading to flooding and wind storms [3]. In addition to the increased frequency and intensity of events, it is anticipated that events may be experienced in areas that have not previously experienced such conditions before. Although climate change progresses slowly and is often seen as a minor concern, the long service life of buildings means that the climate conditions at the time of their construction will likely differ significantly from those at the time of their demolition [4]. During climate change, it is unlikely that new mechanisms of degradation affecting structural durability will emerge, but probable that buildings will be subjected to greater climate loads for longer periods, leading to an accelerated rate of degradation in building components [5].

Climate events are already putting pressure on building owners to undertake more frequent or unanticipated repairs, maintenance, and climate resilient upgrades, and affecting their finances through changes to the cost of insurance, fuel, and utilities. On top of all of this, it is likely that many Canadian jurisdictions will be vulnerable to multiple climate hazards, and be exposed to concurrent events that have competing or compounding risks to the building and or occupants [6]. As such, when looking to determine what measures to implement and when to implement them, a process must be followed to ensure that the measure selected to address the risks associated with one climate hazard do not negatively interact or produce unintended consequences or maladaptation's for another hazard [7].

In order to design for resiliency or to assess if a structure may be resilient to a changing climate, a systematic approach for determining the climate loads that a structure could be exposed to, to the implementation of adaptation measure, should be taken. As such, a roadmap was proposed which outlines the potential steps required to go from hazard identification to adaptation implementation. The proposed steps of the roadmap also serve to organize the sections of this report. A review was caried out to determine what information and decisions are needed throughout the process of retrofitting a home to increase its resilience to climate change and to help identify any gaps in information and/or barriers that exist in developing a resilient retrofit guide for individuals or professionals looking to design for a changing climate.

This report will focus on the risks and vulnerabilities of buildings and their occupants to hazards such as wildfire, wind, extreme heat and flooding, as well as the challenges posed by multi hazards. The report will also emphasize building level retrofits that can be implemented on the building envelope, mechanical, electrical, and plumbing systems, and the immediate surrounding property to enhance the structure's resilience, rather than strategies that are to be implemented on a broader community scale. The information in this report could be used to develop retrofit or best practice guidelines for individuals and professionals aiming to enhance climate resiliency in their design. This report covers the entire process from hazard identification to recommended retrofits, tailored to the specific needs of each building and location.

Proposed Roadmap to Enable Adaptation Retrofits

As the issue of resilience becomes increasingly urgent, the number of groups and organizations developing guidelines, tools for assessment, climate loads projections, and educational resources has increased. This surge has led to an increase in research which can be classified under the following themes: hazard and exposure mapping, vulnerability assessment for buildings and occupants, identification of appropriate adaptation measures, evaluation methods for the effectiveness of resilience measures, implementation of adaptation measures through pilot studies and de-risking strategies, and information dissemination [8]. A roadmap which can be seen in Figure 1, has been proposed to organize and interpret ongoing efforts by illustrating how each research themes interact with one another, showcasing the overall flow of information required to develop science-based guidelines for resiliency. The proposed roadmap has also been used as the framework for this review of existing and ongoing work in the resilience sector, in order to begin identify any gaps in information or barriers to creating resilient retrofit guides.

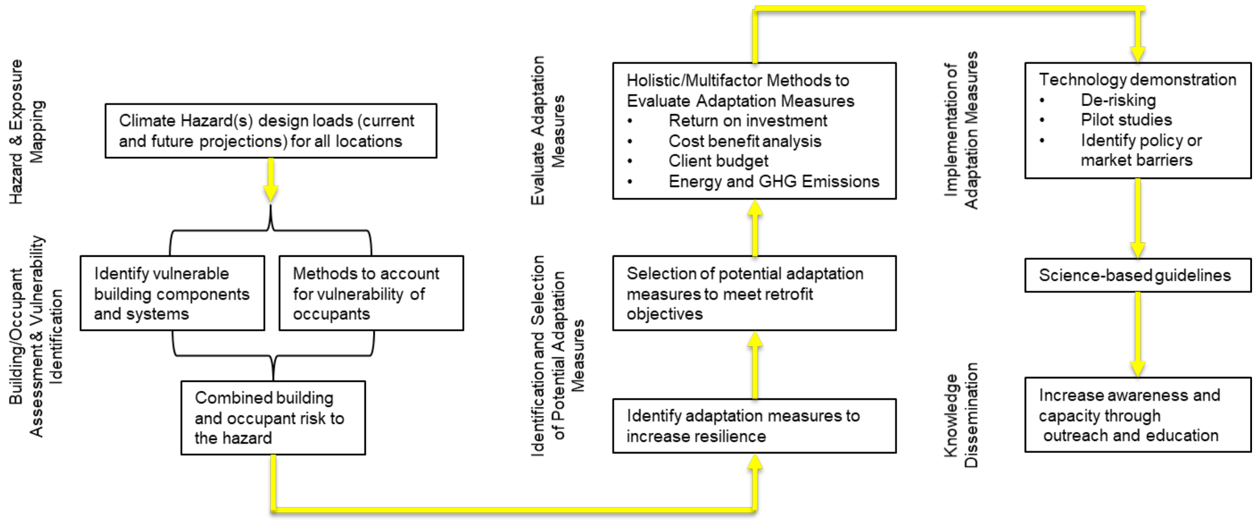


Figure 1: Proposed roadmap to enabling adaptation retrofits

The first area of focus is **hazard and exposure mapping**, where the objective of this section is to identify what information exists on current and future climate design loads in a specific location, as well as to identify what climate exposure maps may exist. The information gathered in this section helps those looking to identify what climate hazards are currently present or may become present in a geographic area, and may help assess the current and future vulnerability of buildings and occupants in areas identified as having exposure to climate hazards.

The intent of the second section, **building/occupant assessment and vulnerability identification** is to gather information on what information is needed in order to assess buildings and their occupants for vulnerability. Research will be summarized to identify why some buildings may be inherently more vulnerable to current and future climate loads due to parameters such as, but not limited to: age, construction practices, source of energy, or their maintenance strategies. Additionally, an understanding of what vulnerability means for building occupants will be documented. The information gathered within this section could help in the development of checklists for practitioners during site visits, and in the development of any weighting or evaluating system to assign a level of risk to a building and or its occupant(s) based on their vulnerability and probability of the hazard occurring.

The third section of the report titled **identification and selection of potential adaptation measures** focused on gathering information about what resources are available to those seeking to implement resiliency retrofits and any information on how to prioritize retrofits under a multi-hazard scenario. An outcome of this effort could be the development of a database that compiles recommended practices and adaptation measures aimed to decrease vulnerability of buildings and their occupants to climate-related risks. In addition to understanding the available adaptation measures, information on how these measures may interact in locations prone to multiple or competing hazards was gathered. The information on how measures may interact in locations prone to multiple or competing hazards may help identify complementary, coordinated and conflicting adaptation options for specific buildings and occupants facing one or more competing climate hazard(s). Conflicting adaptation measures may achieve a positive result for one or more hazards while inadvertently increasing vulnerability or unintentional risk for others. In contrast, complementary strategies are when a recommended practice or adaptation measure can decrease vulnerability and risk in a multi hazard scenario. Coordinated strategies leverage the characteristics of various adaptation measure to achieve a desired outcome.

The objective of the fourth section of the report was to document tools or procedures that could be used to **evaluate the adaptation measures** for their effectiveness against multiple criteria, including but not limited to, cost benefit analysis, return on investment, client budget, energy consumption and or GHG emissions associated with the retrofit. The information gathered from this section could be used in the development of holistic tools and procedures to be able to evaluating adaptation measures for their effectiveness when there are competing interests and or objectives.

The fifth section of the report, summarizes groups working on the **implementation of adaptation measures**, either through pilot studies to validate or de-risk strategies, or by increasing the adoption of strategies through grants and funding. Additionally, information is provided in the sixth section, on how current **knowledge** is being **disseminated** to those at risk or seeking to reduce their vulnerability. The final section of the report highlights any gaps in information or barriers limiting the uptake of climate resilient retrofit measures, and offers suggestions for future research areas.

1 Hazard and Exposure Mapping

Maps are often used to highlight and visualize areas of importance, where in terms of climate hazards, maps may be used to present information on parameters such as climate loads, vulnerability, exposure, sensitivity, and adaptive capacity. The information obtained from these maps and data sets can be used in the completion of risk assessments, or used to estimate the damage, injury, and economic losses that could be attributed to a hazards' occurrence and severity in a given area [9]. The information can also be used to identify regions and or populations at risk, or which may one day be at risk of climate-related hazards, where a summary of general resources used to help identify areas and populations at risk of climate hazards can be found in Table 1.

In order to anticipate the potential loads associated with future climate events, future climate data is needed, such as that developed at NRC under a range of forcing scenarios [2]. Data generated under these scenarios can be used to determine the possible range of loads a building may be exposed to throughout its service life and used in investigations to determine how long materials and assemblies may be resilient to changing conditions. Long-term climate predictions are especially needed for smaller cities that generally lack the ability to collect and maintain these data sets [10].

The national physical exposure model (CanEM) is a framework for integrated risk assessment which is presented in a report published by the Geological Survey of Canada [9]. The approach sought to establish a framework of tools, methods and knowledge to support the assessment of exposure and susceptibility to significant natural hazard threats at both local and regional levels across Canada. In order to quantify the level of threat associated with a hazard, the authors combine parameters for the physical exposure of a location with the susceptibility or damage potential that could be caused by the hazard in that location. Physical exposure maps are created, through a combination of land-use layers and climate loads to highlight where climate events may interact with populations and infrastructure. Land use maps are developed by overlaying building layers of the urban footprint with census data in mapping tools, highlighting where buildings, people and assets are located. The damage potential of an area, can be estimated by combining land use maps, climate load maps and local structural damage curves and or content damage curves.

The government of Canada hosts a webpage that provides information on natural hazards and their associated risks across Canada [11]. The website provides hazard specific information from mapping to emergency preparation techniques for avalanches, earthquakes, floods, hurricanes, landslides, severe storms, storm surges, tornadoes, tsunamis and wildfires. The website also provides links to both short and long-term forecasts for locations across Canada as well as severe weather warnings. Carleton University's MacOdrum Library hosts a database of historical and future climate hazard maps and climate load maps across Canada. Websites and databases such as these can provide an excellent first resource for any interested party to become familiar with the climate hazards within their area.

Table 1: Resources for climate data and exposure mapping

Resource Title	Description	Reference
National Research Council of Canada	An initiative to prepare climate data needed for building simulations for 564 locations across Canada.	[2]
Geological Survey of Canada	Physical exposure to natural hazards in Canada: Developing a method to assess the form and function of a built-up area to support the risk assessment of communities to climate hazards.	[9]
Government of Canada	A website that provides hazard specific information from mapping to emergency preparation techniques for multi-hazards	[11]
Geological Survey of Canada	Social vulnerability to natural hazards in Canada:	[12]
Carleton University – MacOdrum Library	A compilation of links to both historical and future climate GIS data and maps for Canada.	[13]

1.1 Wildfires

Wildfire events are becoming more prevalent across the country due to global and local rising temperatures, a decrease in soil moisture content and general lack of water availability, an accumulation of organic fuels and a shift in landscaping to drought-resistant vegetation [14] [15]. These factors are contributing to an increase in the number of wildfires by extending the length of the fire season and increasing the exposure area due to an increase in available fuels. It is predicted that the numbers of lightning caused wildfires will increase by 50% between 2050 and 2100, respectively, due to the changes in both climate and fuel [16]. This section of the report describes the tools used to assess whether a structure is located in an area at risk to wildfires occurring, resources that help identify areas where fires are actively occurring and where wildfire smoke is present. A summary of these resources can be seen in Table 3.

The National Guide for Wildland-Urban Interface (WUI) Fires hereafter referred to as the "WUI Guide" [17], outlines a process to determine if a structure may be located in an area that is at risk of a wildfire occurring as represented in the flowchart in Figure 2. The assessment process is comprised of three parts: i. determining the structures proximity to the WUI or sources of fuel; ii. determining the level of hazard of the surrounding area; and, iii. performing an exposure assessment of the structure and its immediate surroundings [17]. The WUI Guide starts with a high-level analysis by evaluating whether there are any structures located within a 500 m radius of the WUI which will determine the need for any additional assessment. This high-level assessment can be completed at a community level by overlaying building layer maps with forestry maps, or at a local level by measuring the distance between structures and the surrounding WUI. If structures are identified as being within 500 m of the WUI, further assessment must be conducted or a further assessment is required if an inspection has not been completed within the last 5 years for the location.

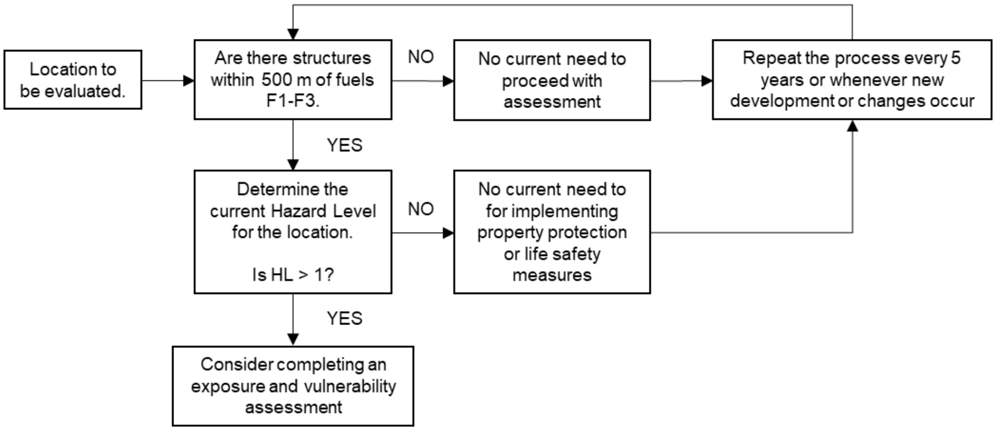


Figure 2: Wildfire assessment flowchart, adapted from [17]

The second step of the wildfire assessment flowchart is to determine the areas Hazard Level (HL) on a scale of 1 (Nil- Very Low) to 4 (High). Hazard levels can be used as an indicator of the likelihood that a large intense fire, which has the potential to cause widespread damage, may occur. HLs are based on regional topography, fuel type, weather conditions and the history of wildfires in the area. An area’s HL is reported on a daily basis through Fire Weather and Fire Behaviour maps available on the Canadian Wildland Fire Information System (CWFIS) and Natural Resources Canada webpage [18].

Parameters reported in these Fire behavior maps include the Fire Weather Index (FWI) and the Fire Danger (FD). Fire weather index is a forecasted numeric rating of fire intensity based on consecutive previously recorded daily temperatures, relative humidity, wind speeds and precipitation levels within previous 24-hour periods. Fire danger is a relative index indicating how easily vegetation can ignite, how difficult a fire may be to control and the potential damage a fire may cause. It is reported on a scale of nil to extreme, with definitions for each level provided in Table 2. If an area’s HL is greater than one, further exposure assessments should be completed by an expert in order to inspect and confirm the surrounding fuel type and its susceptibility to transferring and spreading wildfires. More details on what is required during an exposure assessment for an individual property will be covered in Section 2.1.

Table 2: Fire Danger (FD) rating levels as defined on the Canadian Wildland Fire Information System (CWFIS) and Natural Resources Canada webpage [18].

Fire Danger Level	Description of Fire Danger Level
Nil	Currently no information available for the area.
Low	Any current fires are likely to be self-extinguishing and new ignitions are unlikely. Any current fires are limited to smoldering.
Moderate	Surface fires that are slow moving and easily contained by groundcrews with pumps and hand tools.
High	Moderate to vigorous surface fire with intermittent crown involvement. Challenging for ground crews to handle; heavy equipment (bulldozers, tanker trucks, aircraft) often required to contain the fire.
Very High	High-intensity fire with partial to full crown involvement. Head fire conditions beyond the ability of ground crews; air attack with retardant required to effectively attack fire's head.
Extreme	Fast-spreading, high-intensity crown fire. Very difficult to control. Suppression actions limited to flanks, with only indirect actions possible against the fire's head.

Under certain cases, the loss of electrical power to a home as a result of loss or damage to surrounding electrical infrastructure can cause a secondary hazard to occur [19]. As wildfires usually occur during warmer summer periods, and can cause periods of heavy smoke, the loss of electrical services can result in periods of overheating, or hazardous indoor air quality to occur within buildings that normally rely on mechanical cooling or filtration to maintain their indoor air quality.

In addition to reporting an area's fire weather index and danger level, groups are working to forecast and report the potential spread of resulting wildfire smoke. The smoke released by wildfires in Canada are a significant source of air pollution and can be a serious health concern for even those living thousands of kilometres from the wildfire. Environment and Climate Change Canada (ECCC) has created a system which provides animated hourly emissions maps over a 72 hours period for all of North America [20]. The maps show the dispersion of wildfire smoke, the total levels of fine particulate matter ($PM_{2.5}$), ground level ozone (O_3) and nitrogen dioxide (NO_2) hourly concentrations [21]. These pollutants are used to calculate the Air Quality Health Index (AQHI), which is reported on a scale from 1 to 10+; where the higher the index, the greater the health risk associated with the air quality [22]. Another interactive map showing the anticipated trajectory and concentration of $PM_{2.5}$ can be accessed though FireSmoke.ca [23]. Both of these sources report the movement of particulate matter which measure less than 2.5 micrometers in diameter otherwise known as $PM_{2.5}$ as these particles pose a health risk as they can travel deep into lungs if inhaled. As $PM_{2.5}$ describes the size of a particle and not the composition, there can be any number of sources contributing to the mix of particles in the air and during a wildfire event, especially if a wildfire makes contact with a developed area [24]. By estimating and reporting the resulting AQHI, and movement of $PM_{2.5}$ during a wildfire event, citizens can be warned of periods when potentially hazardous air quality may affect their area.

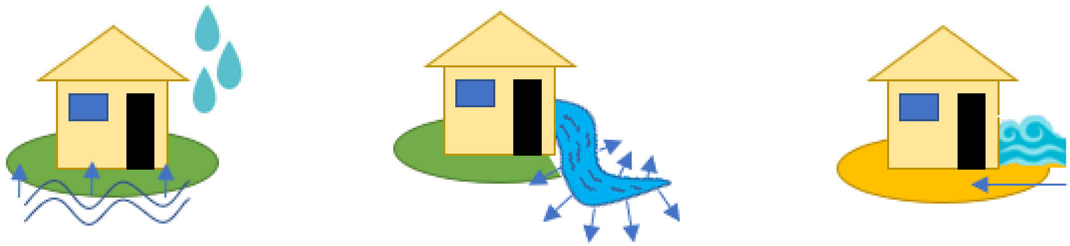
BC interior health has also published wildfire smoke vulnerability maps where exposure is measured by the number of days with elevated $PM_{2.5}$ concentrations during severe wildfire seasons [25]. Sensitivity of an area is estimated by using Census data and the likelihood of respiratory conditions and age-related vulnerabilities. The adaptive capacity maps from BC Interior health highlight communities with fewer resources and lower socio-economic status, indicating a reduced ability to cope with smoke events. This layered approach provides a detailed picture of how different communities in BC may be affected by wildfire smoke. [25]. Another resource is Crown-Indigenous Relations and Northern Affairs Canada which hosts the First Nation Adapt (FNA) program. The program works to provide First Nation communities the support needed to assess their community for vulnerability before a climate event and resources to respond to the impacts of climate change. The program works with the communities to increase climate resilience against priority issues including wildfire risk management, that have been previously identified through discussions with these communities.

Table 3: Summary of wildfire and wildfire smoke mapping resources

Resource Title	Description	Reference
Natural Resources Canada	The Canadian Wildland Fire Information System (CWFIS) creates daily fire weather and fire behavior maps year-round and hot spot maps throughout the forest fire season, generally between May and September.	[18]
Environment and Climate Change Canada	Interactive maps showing the dispersion of wildfire smoke, the total levels of fine particulate matter ($PM_{2.5}$), ground level ozone (O3) and nitrogen dioxide (NO2) over the next 72 hours.	[20]
FireSmoke Canada	Interactive forecasts of hourly, daily average and daily maximum concentrations of $PM_{2.5}$ smoke particles at ground level from wildfires.	[23]
Government of British Columbia	Provides access to WUI risk class maps for communities across British Columbia.	[26]
Crown-Indigenous Relations and Northern Affairs Canada	Hosts the First Nation Adapt (FNA) program, which provides support to First Nation communities and organizations located south of the 60th parallel to assess and respond to the impacts of climate change, in order to increase their climate resilience.	[27]

1.2 Flooding

Flooding is currently one of the costliest and most frequently occurring natural hazards in Canada, where approximately 80% of major Canadian cities are to some degree exposed to flooding [28] [29]. Flood events are typically reported in terms of flood depth or return periods, such as 1 in 100 years. A 100-year return period does not mean that an area will only flood once in 100 years; rather, it indicates a 1% probability of flooding in any given year. Of the 15.4 million residential addresses in Canada, over twelve percent are modeled to be in a 1 in 100-year return period, and eight precent are modeled to be in a 1 in 20-year return period. The type of flooding that is expected to occur in these locations can be classified into three broad categories: pluvial (groundwater or surface flooding), fluvial (or riverine flooding), and coastal flooding, as seen in Figure 3. However, it should be noted that floods often result from a combination of factors, where a single climatic event may cause multiple flood types to occur simultaneously.



Pluvial or
(Groundwater or Surface flooding)

Fluvial or
(Riverine flooding)

Coastal flooding

Figure 3: Graphical representation of the three main types of flooding

Pluvial floods result from extreme rainfall amounts that cause an area to exceed its drainage capacity and can occur in both urban and rural areas. In urban areas, flooding from pluvial events generally results from water backing up due to undersized or poorly maintained drainage systems, or as a result of water not being able to infiltrate non permeable surfaces [30]. Infiltration is a function of the soil type, compaction levels, vegetation cover, and the soil's initial moisture content and can mitigate flooding by reducing the amount of runoff. Fluvial/Riverine flooding (freshet) occurs when rivers, streams, or creeks overflow due to heavy precipitation, snow melt, ice jams or as a result of a controlled holdback of water upstream of a dam during spring melt holding water back from more populated areas. The resulting depth of water from a fluvial flood is dependant on parameters such as local topography and the severity of the climate event. Coastal flooding occurs when normally dry, low-lying areas next to large waterbodies are partially or fully flooded. Factors that can influence the amount of coastal flooding include, but are not limited to: storm surges, tsunamis and rising water levels. Strom surges occur when strong onshore winds drive surface water toward land causing waves to push further onto shore. In the case of a coastal area, the timing of a storm surge can be of particular concern if it coincides with a tidal event, where combined events can cause water to be driven further inland. Another factor that could induce coastal flooding is the rising water levels due to melting glaciers and seawater thermal expansion, where global sea levels have risen by around 8 inches in the past century [30].

Flood hazard maps are used to highlight areas which have a higher probability of flood occurrence and can be used in both mitigation planning and emergency management. On flood maps, flood boundary lines are typically used to delineate the extent of an area that would be inundated by water and the elevation that the water may reach during a specified event. These flood boundary lines are linked to Design Flood Levels (DFL), which are calculated through hydrologic and hydraulic modeling that considers many local parameters [31] [30].

The DFL specifies the depth of flood water referenced from the normal or still water level (SWL), which is the level of the river or water body in the absence of waves as shown in Figure 4 and Figure 5. The Design Flood Depth (d_f) describes the depth of the flood waters, relative to the ground level (G) and the DFL. The depth of water during a flood directly influences the forces that are enacted on a structure, and the flood forces are used in calculations to ensure that structures are resilient to these flood forces. Once an area's flood risk has been determined, parameters for safe construction setbacks can be calculated. These setbacks can be used in new developments to ensure that new structures are constructed out of the flood zone, and during the inspection of current structures to assess their risk level.

In a coastal setting, in addition to the depth of the flood, the height of waves beyond the shoreline needs to be taken into consideration, described as wave setup or wave runup as seen in Figure 5 [31]. The wave setup can be affected by additional parameters such as tides, winds and storm surges. In a riverine context, wave actions are either absent or too insignificant in magnitude to consider. Riverine specific parameters include the floodway and the flood fringe. The floodway is known as the part of the floodplain with the highest velocity and flood flow, and in the majority of Canadian provinces, is defined as the river channel that will be produced from a 1 in 20-year flood. The flood fringe is the remaining part of the flood plain that does not include the floodway.

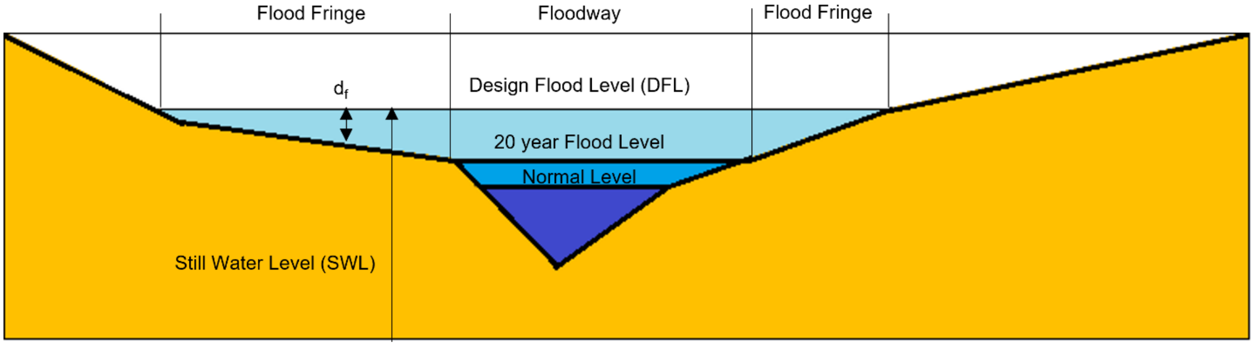


Figure 4. Riverine Flood Design Parameters. Image inspired by [31]

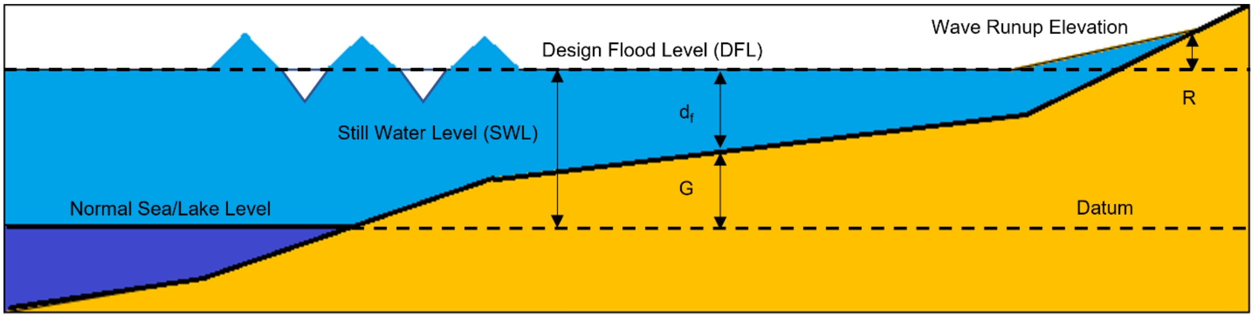


Figure 5 Coastal Flood Design Parameters. Image inspired by [31]

Due to the uncertainties associated with still water levels and flood depth calculations, there is a margin of error in DFL values. Therefore, when reporting flood depths or specifying building setbacks on Flood Construction Level (FCL) maps, an additional safety factor, known as freeboard, is sometimes added to the DFL. The depth of freeboard values specified and whether to include one or not on FCL maps varies by province and territory [32]. If a freeboard is used, a typical value is 0.6 m. The Flood Construction Level (FCL) is a regulatory-defined parameter for flood elevation and construction standards and is the addition of the DFL and the freeboard values. The FCL is a value above the still water level that should ensure that new buildings are constructed above potential flood levels, incorporating current and future conditions [31].

An area's flood history, or “complaints record”, is another metric used in the development of flood risk maps. An area's complaints record is calculated by dividing the total number of reported flood events or insurance claims in an area by the total number of houses in the community, where repeated events for the same dwelling is treated as a distinct event [33]. Recording the number of complaints and claims can help identify risk areas that may have been overlooked in elevation or precipitation-based flood mapping exercises. These high-complaints areas can then be further investigated to determine the causes of the events.

Table 4 provides a summary of flood mapping, flood safety and flood preparedness resources. FloodSmart Canada and Natural Resources Canada provide resources and databases that can be used to identify potential areas where flooding may occur, while Public Safety and Environment and Climate Change Canada provide information on how to prepare for a flood, including what to do before, during and after a flood. Environment and Climate Change Canada also hosts a coastal flooding prediction and alerting program, to issue coastal flooding alerts and forecasts across the country. Crown-Indigenous Relations and Northern Affairs Canada hosts the First Nation Adapt (FNA) program, which provides First Nation communities the support needed to assess the community for vulnerability before a climate event and resources to respond to the impacts of climate change. The program works with the communities to increase climate resilience against priority issues that have been previously identified through discussions with these communities. In terms of flooding, priority climate issues include sea level rise, flooding, risks to archeological and cultural sites, fishery management and water source vulnerabilities. Indigenous Services Canada, is another resource that helps indigenous communities ensure that emergency preparedness and response plans are in place before flooding events, as well as providing information on the funding available for eligible flood mitigation preparedness and response measures.

Table 4: Summary of flood mapping and safety resources

Resource Title	**Description**	**Reference**
Crown-Indigenous Relations and Northern Affairs Canada	Hosts the First Nation Adapt (FNA) program, which provides support to First Nation communities and organizations located south of the 60th parallel to assess and respond to the impacts of climate change, in order to increase their climate resilience.	[27]
FloodSmart Canada, Know your Risks	A list of Canadian flood maps organized by provinces, territories and municipalities.	[34]
Natural Resources Canada	Natural Resources Canada has launched the Flood Hazard Identification and Mapping Program, in order to update existing flood hazard maps of higher-risk areas across Canada, through partnership with provincial and territorial governments.	[35]
Public Safety Canada	Provides information on how to prepare for a flood, including what to do before, during and after.	[36]
Environment and Climate Change Canada	Provides information regarding the causes and costs of flooding, measures to reduce flood damage, and summary of some of the major flood events in Canadian history.	[37]
Environment and Climate Change Canada	Implemented a coastal flooding prediction and alerting program, in order to issue coastal flooding alerts and forecasts across the country, using both the probability and expected impact of an event.	[38]
Indigenous Services Canada	Provides information needed to ensure that emergency preparedness and response plans are in place, as well as providing information on the funding available for eligible flood mitigation preparedness and response measures.	[39]

1.3 Extreme Wind

High wind events including storms, tornadoes and hurricanes are becoming more frequent across Canada, causing a significant risk to structures and their inhabitants [40]. Wind pressure is reported in kilopascals (kPa) and wind speed is reported in kilometer per hour (Km/hr) or meter per second (m/s). These metrics are used to quantify extreme wind events and are used in the design calculations for resilient structures. Currently the

National Building Code of Canada provides prescriptive measures for resiliency in residential buildings against high to extreme wind pressures greater than 0.8 kPa but less than 1.2 kPa. For an area to be classified as being affected by high to extreme winds, the location must have a 2% probability (or 1-in-50 year return) or experience hourly wind pressures within the range of 0.8 kPa to 1.2 kPa in any given year. Only a small number of Canadian cities are classified as regions which may experience wind pressure values within these ranges. Despite this classification, many other regions within Canada experience extreme wind events from hazards such as, but not limited to, chinooks, tornadoes, hurricanes, downbursts and derechos. Wind events such as these are usually described and classified based on their measured or estimated wind speeds, such as those measured from an approaching hurricane and reported using the Saffir Simpson Wind Scale, or estimated wind speeds after an event based on observed damage and reported using the Enhanced Fujita (EF) scale.

The Saffir Simpson hurricane wind scale is broken into five levels (Category 1 – 5), where each level is designated by wind speed ranges as seen in Table 5 [41] [42]. Environment and Natural Resources Canada, provides weather warnings, forecasts, up-to-date tropical conditions and hurricane track maps to help people prepare for developing or incoming systems [43], where Environment and Climate Change Canada through Public Safety Canada hosts a webpage of information on how to prepare both your home and yourself for a hurricane and what best practices to do during and after the storm [41] as seen in Table 8.

The EF scale on the other hand is divided into six levels (EF0-EF5), where each level is designated by wind speed ranges as seen in Table 6 [44]. The Government of Canada hosts “Get Prepared” a website dedicated to providing information to keep Canadians safe from hazards and risks in their area. The site provides links to weather alert services that share weather warnings, watches, advisories and statements, and links to information on how to prepare for tornados and what to do both during and after an event [45]. The Northern Tornadoes Project founded at Western University of London Ontario Canada is a team or researchers dedicated to improving predictions, and advanced warnings for severe and extreme weather events including tornado occurrence throughout Canada in order to reduce harm to people and property. The site also reports on previously investigated wind events, posting information including location, path length, path width and maximum wind speeds, where data such as this can be used to develop exposure and vulnerability maps for extreme wind events.

The EF classification of an extreme wind event is typically assigned after a post-event damage assessment is conducted. During a post-event assessment, damage indicators tables specific to the damaged infrastructure, such as the one seen in Table 7, which was developed for one to two story structures, are used to estimate the range of wind speeds that occurred. These tables can help estimate wind speeds after an event (evaluated during a post-event assessment), where the assigned wind speed category can guide the design and retrofit of structures to enhance resilience to expected wind speeds in the area, and or to classify the wind speeds that new structures may encounter. Since extreme wind events are difficult to predict, both the frequency and extent of historical events are considered in the development of exposure maps.

Table 5: Ranges of sustained wind speeds assigned to each level on the Saffir Simpson scale

Saffir Simpson Scale	**Sustained wind speed range (km/h)**
1	119-153 (64-82 knots)
2	154-177 (83-95 knots)
3	178-209 (96-113 knots)
4	210-249 (114-135 knots)
5	249 or higher (135 knots or higher)

Table 6: Ranges of 3 second wind gust speeds assigned to each level of the Enhanced Fujita scale

Enhanced Fujita Scale	3 second wind gust speed range at 10 m in open terrain (km/h)
0	90-130
1	135-175
2	180-220
3	225-265
4	270-310
5	315 or higher

Table 7: Example of Degree-of-damage (DOD) descriptions and reference wind speeds for the observed damage to one to two story structures. Table adapted from [46]

Degree of Damage	Description of Observed Damage	Expected wind speed (km/h)	Lower bound of wind speed (km/h)	Upper bound of wind speed (km/h)
1	Onset of visible damage	105	85	130
2	Loss of roof covering (less than 20%), gutters, awnings, and or siding	125	100	155
3	Glass broken in doors and or windows	155	125	185
4	Loss of roof covering (more than 20%), damage to chimney, collapse of garage door	155	130	185
5	Shift of house on foundation	195	165	225
6	Removal of large section of roof structure	195	165	230
7	Collapse of one of more exterior wall(s)	210	180	245
8	Collapse of most exterior walls	245	205	285
9	All walls exterior and interior collapsed	275	230	320
10	Destruction of well constructed residence; Slab swept clean	320	265	355

Table 8: Summary of resources for extreme wind

Resource Title	Description	Reference
Environment and Natural Resources	Provides weather warnings, forecasts, up-to-date tropical conditions and hurricane track maps.	[43]
Public Safety Canada	Provides information on how to prepare for a tornado, including what to do before, during and after.	[45]
Public Safety Canada	Provides information on how to prepare for a hurricane, including what to do before, during and after.	[47]
Western University - Northern Tornados Project (NTP)	Improving tornado alerting effectiveness for Canadians as well as reporting on extreme wind events across the country.	[48] [49]

1.4 Extreme Heat

High temperatures and frequent heat waves threaten human life and substantially increase the use of, and cost to health care systems [50]. Global statistics estimate that approximately 0.5 million deaths have occurred every year for the past two decades due to the effects of extreme heat [51]. Most (>98%) of these heat-related deaths have occurred in building interiors due to excessive space overheating, with the most affected populations being people over the age of 65 with compromised health conditions or living alone [52] [53]. A 2021 heat wave in British Columbia resulted in over 600 excess deaths over a week of extremely high temperatures, which soared to approximately 50°C; with approximately 73% of the deaths occurred in residences (a place normally considered safe) [54]. Similarly, the 2010 and 2018 summer heat waves in the Montreal Island area of Quebec resulted respectively in 106 and 66 excess deaths, among which 71% to 88% occurred in residences [55]; [56]; [57].

Reduction in the risk of heat-related deaths in buildings is possible by adequately designing new, or retrofitting old buildings, to reduce the risk of overheating. It is critical though that these actions are taken to protect the health of occupants, particularly those whom are most vulnerable to heat. However, gaining an understanding of the rate at which the climate is warming and where these extreme heat events may occur is the first step in being able to design homes that are a safe shelter and resilient to rising temperatures.

A study conducted by Laouadi, et al. sought to determine which factors of the built environment contribute to the risk of occupant overheating, and what factors make certain individuals more susceptible to health risks during extreme heat periods [58]. The study examined building parameters such as insulation levels, the presence of mechanical ventilation, occupant density, and the physical configuration of buildings. It also considered human factors like age and underlying health conditions to determine their impact on an occupant's ability to regulate core body temperature during extreme heat. The findings from this research can help building owners and occupants understand which building characteristics may increase the risk of overheating and identify the demographics most vulnerable to heat-related health issues. Using mapping programs that incorporate building information layers and census data, the vulnerable characteristics of buildings and occupants can be used as metrics to identify geographic areas where populations or buildings may be more sensitive to extreme heat events.

Regional projected climate data, such as the data developed by Gaur, et al., can be used to determine geographical areas prone to extreme heat events. The sensitivity layers and exposure layers can then be combined to determine the risk of overheating based on location [59]. As these layers are based on averaged data sets, the buildings and occupants that have been identified as being located within these high-risk areas should be further assessed to determine their actual adaptive capacity and vulnerability to extreme heat events.

Overheating vulnerability mapping is essential in urban settings, where heat-absorbing surfaces like concrete and asphalt prevail and green spaces are scarce. Maps from resources such as the one described in Table 9 can be used to help identify areas with heightened risks and populations sensitive to heat, such as the elderly and those with chronic conditions. Urban heat maps can be used to identify priority areas for intervention actions such as expanding green spaces, enhancing building insulation, and ensuring access to cooling centers [60]. In this case, vulnerability mapping to overheating in an urban setting is essential, as the phenomena of urban heat islands might raise temperatures considerably in urban settings relative to the surrounding rural areas.

Table 9: Summary of resources for extreme heat

Resource Title	Description	Reference
Mapping Spatial Patterns in Vulnerability to Climate Change-Related Health Hazards: 2020 Report	A set of interactive maps and accompanying report for communities across British Columbia that highlighting their level of risk to extreme heat events.	[25]
Mapping the vulnerability and exposure to extreme heat waves of populations living in housing in Canadian communities	An interactive map and accompanying report that highlights the level of risk of 156 urban regions across Canada to extreme heat events.	[59]
Climate Atlas of Canada	An interactive map which shows the number of extreme heat days across Canada under multiple climate change scenarios and time periods.	[61]

2 Building/Occupant Assessment and Vulnerability Identification

The first section of this report defined climate hazard exposure and explained how exposure to environmental climate hazards are determined. This section outlines the current state of knowledge regarding the identification of vulnerable building assemblies and systems, as well as methods to account for occupant vulnerability. In addition, a review of any methods being developed to assess the combined risk to buildings and occupants from the climate hazard will be provided. The intent of the second section is to summarize information on what vulnerability means to both buildings and their occupants.

Structural Vulnerability

There are numerous factors that can affect a structure's vulnerability to climate hazards, as such a thorough investigation should be completed to assess and determine its current condition. The assessment should aim to identify any components of the structure that may be susceptible to degradation and determine if any of the components have adaptive capacity and if any resilience measures have already been implemented. However, understanding what to assess during an inspection, for each hazard type, archetype, and location can be a challenging task.

The Institute for Catastrophic Loss Reduction (ICLR) has published a series of reports providing guidance on how to reduce the risk of damage to buildings due to climate hazards. These reports provide general guidance for extreme heat, flooding, hail, severe wind, snow and ice, wildfires and in some cases consideration for competing hazards.

Each ICLR report concludes with an inspection scorecard designed to provide home owners with a means of assessing their risk level for various climate hazards. However, a potential drawback arises if the current or future level of exposure to a hazard at the location to be assessed is not known or considered during the evaluation. For instance, a structure might receive an extreme risk score based on its current condition or construction to a climate hazard, prompting costly retrofits in an area with limited current or future projected exposure to that hazard, resulting in a low cost-benefit ratio. On the other hand, without knowledge of future hazard exposure levels that are not presently evident, an appropriate evaluation may be missed, putting occupants and the structure at future risk.

Tools such as Risk Factor Pro have been developed to articulate the current and future risk of climate events for specific locations across the United States [62]. This tool provides representative scores out of ten (10) as well as a written summary describing the anticipated hazards, loads, and the probability of an event occurring to help define what might be expected if an event were to occur. Information from these tools can be invaluable for anyone looking to integrate resilient measures into their design.

Inspection checklists and/or scorecards can provide a useful starting reference for identifying items to consider when assessing a structure's vulnerability during site visits or inspection. However, due to the qualitative nature of most scorecards and/or checklists, which often feature “yes”, “no” or “not applicable' answer options, the initial assessment may fall short of accurately establishing the true condition or performance level of a building pre-retrofit. A detailed condition assessment of a structure should be performed before any retrofits or actions are carried out. Information collected during early assessments can enhance understanding of its current condition and performance level to serve as a reference for any future analysis performed and after intervention to determine the success of the intervention. Failure to collect or quantify certain information early on may result in hazards or loads being overlooked. The importance of performing a detailed condition assessment of a structure before intervening was highlighted in a report by Moore, et al., (2023), which made use of the three phases of rehabilitation when rehabilitating heritage mass masonry buildings against freeze-thaw damage [63]. The three phases of rehabilitation consist of Understanding, Planning and Intervening, which are presented in The

Standards and Guidelines for the Conservation of Historic Places in Canada report [64]. In the understanding phase, quantitative performance metrics should be recorded before intervention to help determine how the structure responds to the intervention(s), allowing for the identification of any maladaptation before it leads to damage. Moore, et al., (2023) also stressed the importance of establishing retrofit objectives early in the process, in order to have metrics in which to evaluate the effectiveness of adaptation strategies against. Through analysis and modeling, strategies can be selected by understanding the trade-offs between multiple retrofit objectives such as cost, energy savings, and thermal or hygrothermal performance. In the case of multi-hazard scenarios, several analyses may need to be performed in order to determine how a single adaptation measure may affect multiple objective parameters. To truly understand what resiliency strategies should be implemented at a location, home and building owners need to have access to qualified contractors who can perform detailed condition assessments, site-specific climate risk analyses and design appropriately for multi-hazard adaptation, [10].

During a site level inspection, the dollar value of the structure and its contents should be assessed, as these evaluations feed directly into any cost benefit or return on investment analysis. This assessment helps determine the acceptable risk level for protecting the structure. If a visual assessment of the structure and its contents cannot be performed, the structure's replacement cost can be estimated using the property's assessed or insured value under normal market conditions (excluding land value) and adding the total insured value of the contents. These estimates may be normalized to a per-square-meter value to facilitate further analyses and the development of standardized damage functions for both content and structural components of the building [30].

When developing content damage curves for a location, comprehensive sampling of homes must be conducted to establish a representative value for the area. In areas where higher-value structures represent less than 1% of the homes, the value of these higher-end homes may be undervalued based on the average. Therefore, an additional multiplier may be needed to obtain a more representative value for select higher-valued structures [30]. For flooding, content damage curves can be further broken down or expressed on a per-story basis to account for the depth of the flood.

Structural damage curves reflect the financial damage to a building and its stationary components, such as water heaters and furnaces, relative to the depth of flood water. As discussed in the federal flood damage estimation guidelines for buildings and infrastructure report by Natural Resources Canada and Public Safety, the financial damage to a structural can be estimated based on 300 mm increments of flood depth. The development of a structural damage curve begins with a field assessment to determine the characteristics of structures within each construction class, such as multi-unit residential buildings or single detached homes. The structural damage curve should account for all costs associated with cleanups, replacements, and repairs required for a structure after a flooding event. The estimates should reflect the costs of repair or restoration based on present-day regional material and labor costs [30]. To ensure that both content and structural damage curves are up to date and represent the true value of structures within a geographic area, continuous monitoring and inspections are required. Regular updating of standardized damage functions to represent current-year dollars and taking inflation into account is also important, as past damage-curve estimates may not be directly applicable to future flood events.

Evaluating the surrounding property is also a crucial component of a vulnerability assessment, as the condition of the surrounding property can increase a building’s vulnerability to multiple hazards. One factor that should be considered for all hazards is the presence of debris on or surrounding a structure. In the case of wildfires, debris can be considered a source of fuel, increasing the structure’s risk of catching fire. Conversely, during flooding, debris can obstruct drainage systems, increasing the risk of overland flooding, or be carried by flood waters, causing severe impact damage to buildings. As the size and weight of debris can vary, along with its potential to be a source of fuel, creating an exhaustive list of debris to assess can be a significant challenge which makes retrofitting a building against this hazard relatively difficult [31]. Therefore, many infographics or resiliency guides, such as the Intact Centre’s three steps to a cost effective “FireSmart Home” or their three steps to cost effective

“Home Flood Protection” suggest general maintenance and upkeep of the property as a resiliency measure against debris [65].

Occupant Vulnerability

In the context of natural climate hazards, the consequences of exposure to these hazards on human life can vary. Occupant vulnerability is defined as their susceptibility to harm relative to their ability to cope and recover from the effects of a hazard [25]. Sensitivity to natural hazards can be defined as the degree to which a population or system can be affected by exposure to the hazard, while adaptive capacity is the ability of a population or system to adjust, recover, or react to potential harms and damages. Table 10 provides a short summary of some of the resources available that may be used to identify potential vulnerabilities in populations, and physical exposure of populations relative to natural hazards.

Sensitivity and adaptive capacity are unique to each individual, meaning that the experience of a hazardous event can vary greatly from person to person, where not all people are equally affected by the same hazard. For some, the results of exposure could be severe enough to result in mortality, while for others, the same hazard could only result in mild discomfort. Factors such as age, mobility and underlying health conditions can all contribute to a person’s sensitivity and adaptive capacity. Populations at the extremes of age are more vulnerable to hazards because of their increased physiological and logistical needs in emergencies. Similarly, individuals with disabilities or chronic health conditions may face higher risks in natural disasters due to limitations in mobility or access to care during a hazardous event. These demographic and health factors are crucial considerations for inclusive planning to address the challenges faced by these particular groups [9]. In addition, the effects of exposure can go beyond one's physical health; targeting one's mental health or economic situation [12].

Climate hazards have been shown to impact mental health, with the effects of these events often being both severe and long-lasting, resulting in challenges such as anxiety, depression, and post-traumatic stress disorder (PTSD) [66]. Communities that have been repeatedly impacted by climatic events, those who have been displaced from homes, or those being subjected to extended or delayed recovery processes, are particularly vulnerable to such psychological issues. Therefore, assessing whether proper health support networks are in place is a necessary part of disaster recovery [66].

In addition to heath networks, the social and communication networks of a community can contribute to its resilience and adaptive capacity. These networks become important during and after disasters as they determine the extent to which a community can rely on one another for support and resources to reduce individual and collective vulnerability. Communities with strong social networks often demonstrate more resiliency by establishing action plans before climate events, ensuring they have organized evacuation and recovery processes. Moreover, developing and maintaining communication networks is especially important for the evacuation of individuals with limited mobility and warning those living in isolation or remote communities [12]. Ensuring that these networks are established for remote communities is critical to guarantee access to food, water, medical attention, and resources during hazardous events. [67].

The economic status of a community, household or individual can influence their vulnerability and susceptibility to the negative consequences of climate hazards [66]. Those with lower economic status may have a more challenging recovery process, if they do not have the financial means to rebuild or relocate, potentially resulting in prolonged displacement and further economic hardship. In addition, communities with lower economic status may have limited access to healthcare resources during and after climatic events. The HealthADAPT program is a multi-year initiative managed by Health Canada, designed to help the health sector prepare for and respond to the impacts of climate change. The program aims to increase understanding of climate change impacts on the health of Canadians and healthcare systems, identify vulnerable populations, and develop climate change and health adaptation plans [68].

Table 10: Resources on occupant vulnerability

Resource Title	Description	Reference
Physical exposure to natural hazards in Canada	Provides in depth analysis of the physical exposure to the Canadian population to natural hazards, based on factors relating to the built human environment and human settlement patterns.	[9]
Social Vulnerability to Natural Hazards in Canada	Identifies disparities in vulnerabilities among different groups of people and populations in Canada, based on the social and physical aspects.	[12]
Health of Canadians in a Changing Climate (Chapter 3: Natural Hazards)	Assesses health consequences of natural-weather-related hazards due to climate change, emphasizing protective measures and identifying vulnerable populations.	[66]

2.1 Wildfire

A detailed exposure and vulnerability assessment for wildfires is recommended for a home when a high-level analysis has identified that the surrounding area's hazard level exceeds 1 and the structure is located within 500 meters of the WUI. Detailed exposure and vulnerability assessments are conducted to determine the actual sources of fuel that may be present in the surrounding area, the potential sources of ignition a structure might be exposed to and any components of the building that may be susceptible to ignition.

Property level assessments are conducted to identify potential ignition sources that a structure might be exposed to, including flying embers within 500 meters, flame radiation within 30 meters, and direct contact between the structure and the flame front. The likelihood of exposure varies based on the distribution and properties of the fuels surrounding the structure. The distance between the structure and the fuel source is categorized into five zones, also known as the Priority Zones [17] [69] as seen in Figure 6.

The WUI Guide outlines both simplified and detailed methods for conducting exposure assessments. The simplified method estimates a structure's exposure level to flying embers and heat radiation based solely on the type of fuel present within 500 meters of the structure. In contrast, the detailed method considers both topography and fuels within a 2-kilometer radius [17]. By calculating the exposure level, the recommended level of fire resilient construction practices, or "Construction Class" can be obtained, for each priority zone.

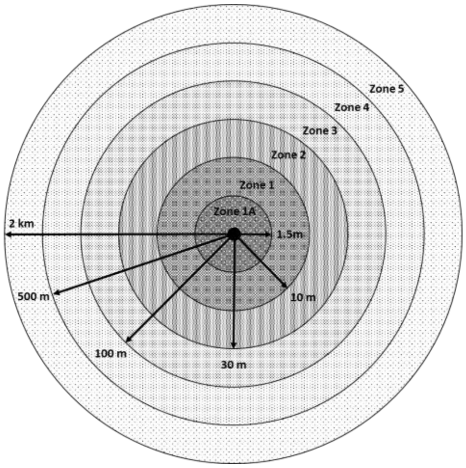


Figure 6: Visual of Priority Zones surrounding a structure, adapted from [17]

Once the recommended construction classes for all components of a structure have been determined, a physical assessment can be conducted to determine the structure's level of compliance and subsequent vulnerability. The

WUI Guide by Bénichou, et al., 2021, outlines multiple methods in which to assess a structure's compliance to the WUI Guide. One such method takes a prescriptive approach, simplifying a structure's vulnerability to a function of the ignition probability and loss value as a ratio of the exposed value [70]. Other methods take a more performance-based approach, taking into consideration all observed materials and assemblies, allowing for an analysis of each component to understand its susceptibility to ignition in order to determine a structure's vulnerability against wildfires [70].

To help complete a detailed assessment of a structure, FireSmart Canada has published a wildfire-resilience best-practice checklist that can be used during both new construction and renovation projects and to help assess landscaping for compliance [71]. The goal of the checklist is to encourage the uptake of landscape maintenance that complies with the WUI Guide [17]. In addition to the checklists, the Appendix provides examples of acceptable wildfire-resilient building materials and practices for many components of a structure along with the appropriate test standards these components must meet.

In addition to assessing a structure's vulnerability to wildfires, it is critical to understand the impacts on occupants' physical and mental health. Both the flame front and released smoke can affect occupants [66] [72]. The released emissions from wildfires contain a significant amount of fine, coarse, and chemically complex particulate matter, such as carbon monoxide, nitrogen oxides, volatile organic compounds, and traces of metal [73]. The emissions from wildfires if inhaled into a person's lungs, can cause severe damage, where persons with underlying respiration and cardiovascular diseases such as asthma and rheumatic heart disease may be at greater risk during these events [66]. Physical mobility issues can also hinder an occupant's ability to evacuate or relocate during a wildfire, potentially exposing them to greater physical danger of developing respiratory issues and or heat-related conditions such as heat exhaustion. Studies note that children, primarily infants, are more susceptible to poor air quality, which can trigger asthma attacks or other breathing issues. [66]. Mental wellbeing of those living in wildfire prone areas may also be affected, where anxiety, depression, insomnia and PTSD symptoms have been witnessed, especially in those who were forced to evacuate their residences. The traumatic experience of a wildfire, coupled with the possibility of leaving one's home, could amplify pre-existing mental health and socio-economic issues. It is crucial to understand the negative impacts on the occupants' mental health and provide the necessary support, especially when they endure losses that worsen pre-existing socio-economic conditions and inequities [67].

The economic status of a population also affects their adaptive capacity to wildfires. For example, individuals living in social housing may not have access to air conditioning or adequate ventilation during periods of extreme heat and or wildfire smoke, putting them at greater physical risk compared to others. Remote, or fly in communities may also experience barriers during wildfire and smoke events due to limited access to emergency services or evacuations measures. Many Indigenous communities have been evacuated time after time in the past decades; exacerbating existing socio-economic inequities including inadequate housing infrastructure, crowded accommodations, and culturally insensitive emergency responses. [66].

2.2 Flooding

Once the probability of a flood occurring within a geographic location is known, a site inspection can be tailored to include flood specific items, based on the predicted type of flood and anticipated depth of water. Using the anticipated water depth, structural damage curves can be referenced to estimate the potential financial damages that may occur to a structure and its contents. The estimated value of the structure before damage can be confirmed during inspection. Historical flood damage records may help develop an understanding of local archetypes that may be at greater risk to flooding based on local building techniques, traditions or styles, further emphasizing the need for a site-specific inspection [28].

The site-level inspection should include an assessment of the structure, immediate topography and landscaping, local infrastructure and whether the area has any advanced warning system [33]. Inspection checklists, such as the one published by the Government of New South Wales of Australia, can serve as a reference for components within and surrounding a home that should be assessed during a visit [74]. The Government of New South Wales checklist starts by having the user confirm the location for which the assessment will be performed, such that flood construction level (FCL) maps can be consulted, and local flood history confirmed. FCL maps can help confirm if the asset is located within the design flood level (DFL) or if a freeboard value was taken into consideration when the asset was constructed. The checklist then lists potential components of buildings that may be more susceptible to damage during a flood based on estimated depth.

After conducting an inspection of the structure, aspects of the immediate topography and landscape which may not be evident from high-level flood prediction analysis should be assessed. Parameters such as, but not limited to, grading, landscaping permeability, general property maintenance (including presence of debris), and the condition of the eaves and downspouts can all affect the vulnerability of a structure. The grading of the landscaping dictates how water flows on the property, with low-lying areas being susceptible to pooling water. Pooling of water occurs when water accumulates at a rate faster than it can drain away or infiltrate into the groun, where in slopped areas, water that does not infiltrate the surface is carried to low-lying areas (Moudrak & Feltmate, 2019). Another parameter to consider when inspecting a property is the presence of any material that could become loose during a flood event. Debris carried by flood events can cause severe damage to a building depending on its size, weight and shape. As such, generically retrofitting a structure to be resilient to the impact of debris can be challenging; therefore, reducing risk by removing or securing potential debris is recommended [31].

The third assessment during a site visit involves evaluating and confirming the local infrastructure, specifically the type of sewer and foundation drainage system in use. Generally, sewer systems are one of three types:

1. Combined system; A single pipe carries both sanitary effluent and stormwaters flow
2. Separated system: Two distinct pipes handle sanitary and stormwater flows separately
3. Partially separated systems; These systems keep sanitary and stormwater flows separate until they merge at the treatment facility [33].

Combined systems have the highest risk of causing backups resulting in damage to homes, as storm water and black water flow through the same pipe. During intense rainfall events these systems can become overloaded causing backups to occur. Beyond a home's connection to the sewer system, the inspection should check for the presence of a backup valve, which can greatly reduce a homes susceptibility to backups and flooding. This inspection should also verify if a sump pump is necessity and if so is installed. A sump pump collects and then drains water from the lowest part of a home and discharges it away from the structure's foundation. This device's functionality requires both power and maintenance, and in cases where its operation is critical to keep water out of the structure, a secondary sump pump and/or backup power supply is recommended to increase resiliency.

Beyond the vulnerability posed to a structure, occupants living in flood-prone areas are susceptible to both physical and mental health challenges due to flooding and its aftermath. Therefore, flood risk assessments must also consider the broader health and socioeconomic impacts on occupants and communities. Addressing these factors requires analyzing demographic characteristics, housing conditions, and access to critical resources like mental health support and secure food and water supplies.

The physical health of occupants living in flood prone areas can be at risk, if clear escape plans and early warning systems are not in place. Individuals with mobility issues or those living in social isolation can be at greater risk if they are unable to vacate their premises in a timely manner [66]. Flood events can cause water security issues when contaminated floodwaters carrying pathogens come in contact with municipal systems. If this occurs, occupants can be at risk of contracting gastrointestinal illnesses such as Escherichia coli and Giardia infections, as well as skin allergies or respiratory problems. Flood events may also cause food security issues through the destruction of crops and infrastructure required for supply chains. The disruption of supply chains can be extremely detrimental to those living in isolated communities that rely on external assistance or resources; these issues can persist long after the floodwaters have receded [66].

The socioeconomic status of a community often correlates with its vulnerability to flooding, as lower socioeconomic communities may reside in flood-prone areas, such as natural floodplains or poorly drained urban regions. These communities frequently lack the financial means to invest in flood prevention or to recover after a flood. Further vulnerability may arise if these communities are denied access to insurance based on their location, making rebuilding after a flood difficult to accomplish [66].

2.3 Extreme wind

A site-level inspection is often completed to determine a structure's vulnerability to extreme wind events. These inspections often begin by assessing the current condition and maintenance of a building and surrounding property. By accessing predicted climate data, and historical records, an assessment list can be generated based the type of wind events that the structure may be exposed to [75].

A 2019 report by FEMA outlined two levels of assessment that could be used to determine the wind resilience of a building [76]. Although the FEMA report focuses on critical facilities such as hospitals, the assessment procedures and criteria can be applied to other structures. The assessment process starts by confirming the level of exposure, including the local EF rating or estimated wind speeds the building may be exposed to, in order to establish the level of resiliency the building would need to be designed or evaluated against. Using this exposure information, if the building is located in a wind-prone area or if more than five years have passed since the last inspection, a preliminary or high-level risk assessment should be carried out to determine the structure's current vulnerability against wind damage [76].

The preliminary or high-level evaluation provides general information pertaining to the building's vulnerability to wind damage and offers general recommendations for mitigation or repair. The goal of the preliminary assessment is to conduct a review of the original construction drawings, if available, to determine the original wind design load of the building. It also includes a visual inspection of critical building components, including roof, windows, doors, and exterior-mounted equipment, to identify obvious or surface-level vulnerabilities in the building structure or envelope. These assessments are used to estimate the approximate remaining service life of the structure. In most cases, these initial assessments are non-invasive and not characterized by thorough analysis, and as a result can only estimate remaining service life. In the case where the initial assessment indicates that there could be potential issues requiring further investigation, or if the expected wind speeds in the area are predicted to be greater than 120 mph (193 km/h), a more thorough secondary analysis must be completed by a qualified team of either engineers or architects, experienced with the type of architecture being evaluated [76]. This secondary assessment aims to further establish the structural integrity of the building through a detailed more intrusive inspection and follow up analysis.

The forces generated during extreme wind events can interact with buildings in many ways, where positive pressure may work to push a structure off its foundation, while negative pressure may attempt to lift the roof off. One of the best ways to reduce the risk of structural damage is to ensure that a continuous vertical load path is established through the structure, transferring any uplift or lateral forces to the foundation, as seen in Figure 7. Continuous vertical load paths are created by ensuring strong connections between roofs, load-bearing walls, floors and the foundation [40]. A visual inspection within a home's attic can confirm if sufficient fasteners have been used to secure the roof and wall sheathing to the underlying framing, assess the condition of the roof sheathing and determine the level of bracing required for specific roof styles. A building inspector can also evaluate the condition and bracing of large openings in the building such as double entry doors, large picture windows, and garage doors, which if damaged, could cause pressurization and subsequent failure of the internal structure [40].

In 2009 multiple tornadoes were reported to have touched down in Vaughan, Ontario. Western University of London Ontario, conducted a survey of 92 homes damaged as a result of these tornados. It was estimated that 40 of the 92 homes experienced severe structural damage to masonry walls and wood-framed roofs [40]. Damage to thirty of these homes likely occurred as a result of failure of the roof to wall connection (RTWC), where 27 of the 30 homes experienced losses to major portions of their roofs. The wind speeds responsible for such catastrophic destruction was estimated to be 200km/h, or an EF2 tornado. The study went on to investigate how two houses of similar shape located next to one another experienced drastically different degrees of damage. From discussions with owners and inspections of the damage, the team determined that the front door of the damaged building gave in and the roof trusses had fewer toe-nails than required by code. These factors lead to the significantly different damage between the homes. The assessment concluded that damage may have been reduced in all of the severely damaged homes if the RTWC had been improved and large openings such as garage doors were strengthened. The authors present a tiered approach for application of resiliency measures based on exposure, where basic measures such as improving RTWC and taking steps to ensuring roof coverings remain in place are suggested for all regions across Canada, while more advanced strategies which are detailed within Appendix A of their report are specified by increasing exposure.

Historical damage records from wind events such as hurricanes and tornados, can also be used by insurance companies or those performing cost benefit analysis for the implementation of resiliency measures. By knowing the average area of damage resulting from a hurricane or tornado and the average market values of buildings within a community, potential financial losses for specific neighbourhoods or whole communities can be estimated [77].

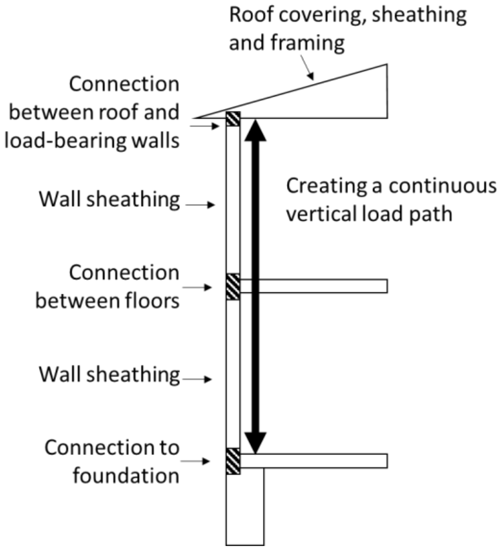


Figure 7: Illustrating a continuous vertical load path. Image inspired by [40]

2.4 Extreme Heat

This rise in global and urban temperature has led to a surge in extreme heat events, posing significant health and economic threats for Canadian occupants. Studies have revealed that these heat events accounted for 0.53% of all-cause mortality (a measure of the total number of deaths from any cause) between 1986 and 2010 and 6% of the total hospitalizations in that period [66]. Periods of overheating generally occur during extreme heat events and in cities where urban temperatures are higher than their surrounding rural landscape, otherwise known as the Urban heat Island effect. Overheating often occurs in older free running buildings (Buildings that rely on natural ventilation versus controlled ventilation), which can sometimes be correlated to multi-unit residential buildings in lower income areas [50], but can also be found in over insulated and well air sealed buildings during periods of power failure. A report by Yin Siu, et al. highlights how wording within building codes, may result in unsafe conditions occurring within buildings. Their report highlights the fact that occupant overheating is tied to the amount of thermal energy that builds up within a structure, and that when designing with only energy efficiency in a heating dominated climate in mind, there is potential that unsafe conditions may occur in any building as a result of a changing climate. As such, the only way to assess whether a structure has the potential to cause periods of internal overheating would be to perform a detailed inspection of building assemblies, its systems and backup systems, in order to conduct an energy balance. Only after results of the energy balance are analysed and an assessment of the health of the residents is performed, can a risk factor be assigned [58].

The first step of the assessment process consists of developing a building energy model using available data on building geometry, orientation, and envelope properties. Unfortunately, there are many cases for older buildings where it is not possible to know all the parameters precisely. As these parameters can have a large effect on the resulting energy balance, it is often recommended that a visual inspection be performed in order to confirm factors such as the presence/absence of air conditioning, insulation levels, the insulating quality of the windows, and the presence of shading elements. Ideally, additional details including whether the building has any common areas that can provide occupants access to cooling, whether the building has any communication network to warn residents of upcoming heat waves, and if the building has any backup to maintain operations of any ventilation systems would further aid the risk assessment process. In addition to the visual inspection, it is often recommended to perform a physical test such as a blower door test to determine the air tightness or infiltration rate of the envelope [60]. Quantifying the level of air tightness of a structure is important, as older buildings may benefit from their draftiness to remove excess heat at night, but also be negatively affected by that same air movement during periods of heat or when air quality is poor. The high air tightness of newer buildings may reduce the amount of energy lost during the heating season and lead to better indoor air quality, but trap heat from escaping during periods of power loss. Once these parameters are confirmed, an energy balance can be completed, and an overheating risk assessment can be conducted.

Information on the health of the occupants residing within a building is also used to determine vulnerability. If occupant specific detains are unknown or unavailable, generic predictions based on building archetype can alert building owners that their building may be at risk of creating conditions where overheating can occur. Building owners can then alert their tenants, and watch out for individuals who may be at higher risk of overheating, including older adults, infants, young children, people with chronic illnesses or disabilities, and those who live alone [78] [58]. By learning that their building has the potential to overheat and that vulnerable populations may be at risk, building owners should implement strategies such as communications networks to warn residents of potentially hazardous conditions and establish communal places to find relief [79].

3 Identification of Adaptation Measures

Understanding the available adaptation options, selecting the most effective strategies, and determining the optimal timing for implementation to enhance resilience against climate hazards can be a challenging task. Therefore, this section of the report focuses on gathering resources that outline recommended practices and adaptation measures that could be used to reduce the vulnerability of buildings and their occupants. Table 11 provides a short summary of a few resources that can be used to help identify adaptation measures under a multi-hazard scenario. Additionally, this section introduces resources that could be used to help in the decision-making process for prioritizing and recommending retrofits in areas exposed to multiple hazards.

The Government of British Columbia has published a report outlining climate-resilient standards for public sector buildings [80]. A table within the report outlines the minimum climate standards and requirements for both new and existing buildings. For each of the requirements the authors have provided a description of the required actions along with links to the relevant sections of the National Building Code, standards, or supporting references for design and implementation of the strategy. Although the table is not intended to be used by individual home owners, the information provides an excellent starting point for consideration in the design or redesign of NBC Part 9 residential building construction.

Partners for Climate Action at the University of Waterloo have compiled a database of example retrofits that target increasing the resilience of residential structures exposed to one or more climate hazards [81]. The database addresses climate hazards such as floods/extreme precipitation, heat, wildfire, wind, and snow/ice. Users can filter adaptation options based on specific hazards, challenges resulting from these hazards, or by the structural components where the retrofits are applied. Each retrofit or adaption measure includes a description of how the retrofit addresses the climate challenge, along with estimates for the time or effort to install, cost, and level of experience required for implementation.

The Tribal Climate Adaptation Menu [82] was developed as a resource of climate change adaptation actions for managing resources through natural processes. The menu emphasises the importance of taking the time to observe, listen, and learn, in order to develop a thorough understanding of the problem and its root cause(s) before attempting to find a solution. These initial investigations serve as an opportunity to seek guidance from knowledge keepers on historical lessons learned and any location specific strategies or preferences. It is also an opportunity to hold open discussions with all affected parties to develop a holistic strategy that seeks to avoid maladaptation to others. The guidance shared in the menu aligns with the idea that adaptation efforts can be conflicting, complementary, or coordinated with other efforts and that a holistic approach can reduce the likelihood of unintended consequences appearing.

Table 11: Resources for resiliency under a multi-hazard scenario

Resource Title	Description	Reference
Climate Resilience Framework & Standards for Public Buildings	Contains a table of proposed minimum climate standards and requirements for both new and existing buildings. A description is provided for each action and technique listed, along with a link to the relevant codes, standards or supporting references that would be required during the design or implementation of the strategy.	[80]
Climate Resilient Retrofits – Partners for Action and University of Waterloo	A database of retrofits that targets increasing the resilience of residential structures that may be exposed to one or more competing climate hazards.	[81]
Dibaginjigaadeg Anishinaabe Ezhitwaad: A Tribal Climate Adaptation Menu	Provides a framework to integrate indigenous and traditional knowledge, culture, language and history into the climate adaptation planning process as well as climate change adaptation actions for natural resource management.	[82]

3.1 Wildfire

When looking for ways to decrease the potential wildfire damage to a property, many sources such as those listed in Table 13, suggest an order of operations approach. The order of operations approach starts by first implementing changes to the structure and the immediate surrounding area before working outwards, as these strategies have been found to have the greatest impact on reducing the risk of wildfire damage [17] [69] [83]. Guides such as the WUI Guide published by the National Research Council of Canada [17] and wildfire-resilience best-practice checklist for home construction published by FireSmart Canada [71], provide detailed information on adaptation techniques that can be implemented within each of the surrounding priority zones based on the anticipated exposure level. Both reports outline the standards or guidelines that resiliency measures must meet (an example of which can be seen in Table 12). Additionally, infographics and summary reports such as those published by the ICLR [69] and Intact Centre on Climate Adaptation [65] offer concise summaries of complex information.

Table 12: Example of acceptable wildfire-resilient building components – Adapted from [71]

Building Assembly	Suggested adaptation	Standards and Guidelines
Roof Covering	Asphalt fiberglass composition shingles, clay tiles, slate, (non-aluminum) metal roofs, concrete tiles, Ethylene Propylene Diene Monomer roofing.	ASTM E108 Standard Test Methods for Fire Tests of Roof Coverings ULC S107 Fire Tests of Roof Coverings – “Class A” rating.

Since the smoke from wildfires can pose significant health risks, it is crucial to understand the available adaptation measures to decrease smoke infiltration into structures and techniques that can be used to remove particulates from indoor spaces. A report by Health Canada, provides detailed information on the risks of wildfire smoke to human health as well as ways to both monitor the indoor air quality and decrease one’s exposure to it [84].

Table 13: Resources for resiliency against wildfires and wildfire smoke

Resource Title	Description	Reference
National Guide for Wildland-Urban Interface Fires	Provides guidance on hazard and exposure assessment, property protection, community resilience and emergency planning to minimize the impact of WUI fires.	[17]
Intact Centre on climate Adaptation – Climate-Ready infographics	Three steps to a cost-effective FireSmart Home & Three features of a wildfire-ready community: A series of infographics that outline adaptation options from low-cost/Do-it-yourself to more complex upgrades.	[65]
Institute for Catastrophic Loss Reduction: protecting your home from wildfire	Outline of steps that can be taken to decrease the vulnerability of a home to wildfires, from inspection to action.	[69]
Wildfire-Resilience Best-Practice Checklist for Home Construction, Renovation and Landscaping	Information to encourage the uptake and implantation of adaption measures to decrease risk of damage resulting from wildfires.	[71]

3.2 Flooding

Similar to the approach for increasing wildfire resilience, many sources recommend an order of operations approach to decrease the potential flood damage. This involves first eliminating exposure to the hazard before implementing strategies to fortify against damage [85] [74] [86]. Upon learning the local Flood Construction Levels (FCL), one could eliminate exposure to flooding by relocating to an area outside of the FCL [85] [31]. Relocation might involve moving the entire structure outside the predicted floodplain, or abandoning and demolishing the structure, with occupants relocating to a new area. There are many challenges associated with the relocation or complete abandonment of a structure, along with the fact that these strategies cannot be classified a retrofit measure, yet in some cases these options may yield the highest benefit- cost ratio of all adaptation options.

Depending on the anticipated depth of the water, relative to the lowest story in the house, secondary strategies such as full or partial abandonment of the lowest level or elevation of the structure and or its contents above the FCL, may be viable options. The strategies of partial abandonment or elevation may be preferable to those who have a strong connection with their environment as they increase resilience while allowing the occupants to remain in their current location. In the case of partial abandonment, fortification techniques can be employed to strengthen assemblies through material substitution or resilient design techniques to be less susceptible to damage and make it easier to rebuild or replace if they become wet [86] [74]. An example of a fortification retrofit can be seen in Figure 8, where loose insulation that is normally encased within a wall cavity is replaced with rigid closed cell insulation that does not adsorb or retain moisture, allowing the wall to dry faster after wetting.

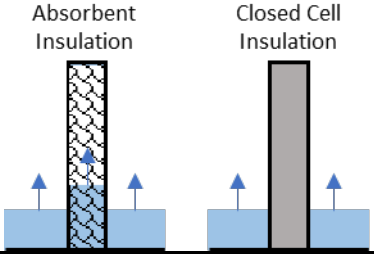
Recommended Practice	Visual Representaiton
Consider replacing loose-fill insulation within ridged or closed cell insulation as loose-fill insulation within wall cavities may absorb moisture during a flood and develop mould.	

Figure 8:Example of a material substitution/resilient design, adapted from the checklist published by the Government of New South Wales of Australia [74]

Adaptation techniques for flooding can also be implemented to decrease a structure's risk of damage due to precipitation events, overland water, and sewer backups. As flooding is currently one of the costliest and most frequently occurring natural hazards in Canada [28] [29], there are a number of resources that provide information on both design and adaptation measures to increase the resilience of a structure to flooding, a summary of which can be seen in Table 14. References such as "Protecting your home from basement flooding" published by the Institute for Catastrophic Loss Reduction [87], provide step by step guidance and best practices for these challenges while many subsidy and grant programs exist to help reduce the cost of impending these measures [88].

Table 14: Resources for resiliency against flooding

Resource Title	**Description**	**Reference**
National Research Council of Canada	Guide for design of flood-resistant buildings – an approach that can be used during the design of new buildings to decrease their vulnerability to flood damage.	[31]
Flood Resilient Design Framework	A resource that provides examples of flood resilient design approaches for different home archetypes, along with a design checklist.	[74]
National Research Council of Canada	Guidelines for improving flood-resistance for existing buildings – outlines adaptation options specifically developed for existing buildings.	[85]
Habitations + Inondations Mesures D'adaptation Résidentielle	Provides a table of fortification techniques and design strategies for residential homes to increase their resilience to flooding. The table classifies the strategies as key measures, adaptation measures and avoidance measures.	[86]
Institute for Catastrophic Loss Reduction: protecting your home from basement flooding	Outline of steps that can be taken to decrease the vulnerability of a home to flooding, from inspection to action.	[87]
Intact Centre on climate Adaptation	Canadian Provincial and Municipal Flood Protection Subsidy/Grant Programs: List of grant and subsidy programs across the country intended to increase the uptake of adaptation actions.	[88]
Intact Centre on climate Adaptation	Three steps to cost-effective home flood protection: An infographic that outline adaptation options from low-cost/Do-it-yourself to more complex upgrades.	[89]
Floodsmart Canada – Helping Canadians Prepare for Floods	Provides a list of resources organized by province and territory, for Flood/Emergency preparedness, Guides, toolkits and maps, Emergency notifications and alerts as well as any available incentives and or grants.	[90]

3.3 Extreme Wind

The Institute for Catastrophic Loss Reduction has published a foundational document for low-rise residential homes which outlines adaptation measures organized by building assembly, including: roof and framing, walls, anchoring the building and building openings. This report emphasizes the importance of establishing a continuous vertical load path between the roof and the foundation and describes several adaptation options that can be used to decrease the risk of roof lift-off and building damage [40] [91]. A similar report published by FEMA focuses on adaptation measures for improving the resiliency of homes to damage associated with tornadoes with a rating of EF2 or less [92]. A summary of the resources to decrease the risk of damage resulting from extreme wind are provided in Table 15.

Table 15: Resources for resiliency against extreme wind

Resource Title	Description	Reference
Institute for Catastrophic Loss Reduction: Increasing High Wind Safety for Canadian Homes: A Foundational Document for Low-Rise Residential and Small Buildings	Provides a list of wind risk reduction measures that can be implanted for both new and existing buildings to improve the continuous load path between roof and foundation.	[40]
Institute for Catastrophic Loss Reduction: protecting your home from severe wind	Outline of steps that can be taken to decrease the vulnerability of a home to severe wind, from inspection to action.	[91]
Improving windstorm and tornado resilience	An overview of building envelope and load path improvements that can be used to increase the resilience of wood-framed, one- and two- family residential structures.	[92]

3.4 Extreme Heat

Reducing the risk of occupant overheating in buildings is possible by adequately designing new or retrofitting old buildings to protect the health of occupants, particularly those whom are most vulnerable to heat such as children, the sick, and the elderly. There are many ways to design new buildings so that their indoor environmental conditions are more stable and less susceptible to external loads; however, as occupant overheating mainly occurs in older free running buildings subject to high external thermal loads, internal heat gains and limited space ventilation, finding appropriate retrofit strategies becomes the challenge. Table 16 provides a summary of some of the resources available to help identify signs and symptoms of overheating, as well as resources that suggest possible adaptation strategies that may be implemented to reduce the risk of overheating.

Building retrofit strategies to reduce the amount of thermal energy that is transferred into the interior environment of a building can be grouped into passive or active strategies. Passive strategies require little to no energy to function, whereas active strategies require some level of energy to operate. Strategies such as building orientation, insulating levels and window configuration are examples of passive strategies that can be effective at controlling the amount of thermal energy this is transferred into the interior environment; however, due to how some of these strategies are integrated into the building structure, they are difficult to implement into existing buildings. Other passive strategies including overhangs, operable windows and shading devices are strategies that may be more easily integrated into an existing structure. Prioritizing a passive first approach before installing active systems is beneficial, as it decreases both the cooling capacity (size) and one's reliance on active strategies, increasing the resilience of the design to power fluctuations and reducing the overall cost to operate, increasing social equity [50].

Laouadi et ai., (2021) assessed multiple adaptation solutions for their potential to reduce occupant's risk of overheating. The solutions analysed in the report included: varying levels of window insulation, passive and adaptive window technologies for reducing soler heat gain coefficients, exterior window shading systems as well as natural and adaptive ventilation strategies [58]. The authors quantified the effectiveness of each adaptation option for multiple building archetypes, through computer simulation. The results provide reference values for anyone looking to determine what adaptation strategy may be most effective at reducing their vulnerability based on their archetype. However, the actual effectiveness of any one strategy at mitigating overheating can be affected by many parameters including but not limited to occupant density, building construction, orientation, maintenance and, regional climate, and should be assessed on a case-by-case basis as highlighted by the authors.

One of the most effective active strategies to maintain interior thermal conditions is to make use of mechanical air conditioning systems. Despite this, there are approximately 40% of buildings Canada-wide [93] that do not use “air-conditioning” as the cooling of air within a building is not currently mandated by the National Model Building Code [94]. The drawback to the use of conventional air conditioning systems is that they can contribute to the total operational energy use of the building, and expel waste heat to the urban environment, where in dense urban centers this excess heat contributes negatively to the urban heat island effect. As such, finding retrofit strategies to adapt buildings to reduce risk to overheating while also reducing operational energy use has been the focus of several groups.

A report by Eyquem and Feltmate outlines a list of actions that that can be taken in preparation for extreme heat events, to help buildings and occupants adapt [95]. The authors classified the adaptation options into three categories including building retrofits, nature-based solutions (NbS) and behavioral changes. Each suggested adaptation option includes a detailed description for the strategy along with key benefits and potential limitations. Many of the recommended building specific retrofit strategies can be assessed for their effectiveness or ability to maintain safe indoor conditions for occupants using building energy models. NbS, often applied to the building envelope or surrounding landscape [96], have the potential to adapt buildings to a changing climate and contribute to climate change mitigation, where a review by Hayes, et al., 2022 found that NbS have the potential to reduce ambient air temperatures above urban surfaces by approximately 1°C [97].

Since occupant health is the primary concern, behavioral adaptation options or personal strategies should also be considered. Online resources such as “Staying Healthy in the Heat” published by Health Canada [98], and ”Preparing for Summer Weather” published by Provincial Health Services Authority [52] provide information to residents on heat illness, symptoms, demographics at greater risk to the effects of extreme heat and adaptive strategies to reduce one’s exposure and risk.

Table 16: Resources for resiliency against extreme heat

Resource Title	Description	Reference
Provincial Health Services Authority – Preparing for summer weather	An online resource that outlines signs and symptoms of heat illness and information on demographics that might be at greater risk to the effects of extreme heat.	[52]
National Research Council of Canada – Climate Resilient Buildings: Guideline for management of overheating risk in residential buildings	A list of passive and active adaptation solutions along with results from computer simulation quantifying their potential to reduce occupant's risk of overheating for multiple building archetypes.	[58]
Intact Centre on Climate Adaptation	Irreversible Extreme Heat: Protecting Canadians and communities from a lethal future. A list of adaptation options and their key benefits or potential limitations.	[95]
Health Canada - Staying Healthy in the Heat	An infographic to help convey the risks associated with extreme heat on humans, and outline key adaptation measures one can do to reduce body temperatures and stay safe during periods of extreme heat. The infographic also provides a summary of the health concerns, signs and symptoms of heat related illness, a summary of those who are most at risk of heat related health effects.	[98]
Intact Centre on Climate Adaptation	Three steps to cost-effective home heat protection & apartment and condo heat protection: A series of infographics that outline adaptation options from low-cost/Do-it-yourself to more complex upgrades.	[99] [100]

4 Evaluate Adaptation Measures

There are many ways to define what success or failure means in regards to a retrofit and just as many parameters that could be used in the evaluation of the design, including, but not limited to: budget, operational energy/GHG emissions use, cost-benefit analysis, return on investment, and embodied GHG emissions associated with the retrofit. However, energy efficiency and operational costs have generally been the driving factor for initiating home improvements over the last several decades [101]. Energy retrofits are often initiated after a certain threshold has been reached in terms of operating energy costs. Retrofits are also initiated when the costs associated with repairing or maintaining systems or assemblies has surpassed a threshold and/or after an inspection and analysis has determined that current systems or components could be replaced by newer, more efficient technology(ies) to meet the needs of the building.

Climate adaptation retrofits address the changing conditions and frequency of events that a building is exposed to and have the potential to alter both the operational energy costs and maintenance/repair frequency. When building systems can no longer recover from climatic events to which they are exposed, meet their design service life requirements, or maintain a safe indoor environment for occupants, a climate change retrofit may be required. While the previous section of the report focused on identifying adaptation measures to decrease the vulnerability of occupants or structures to climate hazards, this section has compiled information on how to select or rank adaptation options and evaluate the effectiveness of the retrofits after implementation.

Climate retrofits can be undertaken proactively in anticipation of an event or retroactively after an event. The benefits associated with completing the retrofits before or after an event are variable based on the type of hazard, likelihood of the hazard occurring, the frequency of occurrence, the exposure to the hazard, the severity of the outcome if the hazard was to occur and the timeline over which design service life is considered (Lepage, 2021). Lepage (Lepage, 2021) describes a "risk assessment matrix" that can be used to prioritize hazards when faced with multiple threats in one area. The matrix uses the expected frequency of an event (likelihood) and the level of impact (severity) to describe the risk associated with a particular hazard. Tools such as the risk assessment matrix may be especially useful in an area experiencing multiple hazards and when allocated funding or resources are limited.

As not all climate resilient retrofits will impact the operational energy use of a building or be effective against all hazards, a common metric in which to compare the effectiveness of a given retrofit strategy is needed. One way to estimate the effectiveness of climate-resilient retrofits is by reviewing their benefit-cost ratio (BCR) values. BCR is an indicator to show the relationship between the potential economic savings (loss reduction) resulting from having the adaptation measure installed before a climate event relative to the cost of implementing the retrofit. When the BCR values exceed 1, the suggested retrofit is considered cost-effective [70]. Parameters such as the average value of homes in an area, estimated damage costs caused by events and the effectiveness of adaptation measures at preventing damage are used in the development of BCR values. There are many additional parameters that could be considered in a holistic BCR value associated with implementing a climate resilient retrofit measure. Additional parameters could include the costs associated with the health of the occupants [102] and the cost benefits associated with improvements to the surrounding environment such as enhanced biodiversity and improved air and water quality [103].

A report commissioned by The National Research Council of Canada (NRC) sought to estimate the benefits associated with the of implementation of the climate retrofits identified from the Climate Resilient Buildings and Core Public Infrastructure (CRBCPI) initiative at NRC [104]. The authors used a prior study by the Multihazard Mitigation Council (MMC) of the National Institute of Building Science (NIBS) as a reference to complete the analysis by transferring economic value from USD to Canadian dollars based on material and labour costs [105]. In the report, RSMeans was used to estimate both the material and labour costs required to install the recommended resiliency measures into new homes under construction. Data for the cost of residential construction along with the cost estimates on a per square foot basis can be found in RSMeans [106] [107], while contractor labour pricing can be estimated from the RSMeans Contractor's Pricing Guide for Residential Repair & Remodeling [108]. The study found that for new construction, the added cost per home (Unit cost) to implement the recommendations outlined within the Fire and Flood guides would be approximately $7,500 and $5,000 respectively, with estimated benefits of $45,000 and $30,000 respectively if an event were to occur during the service life of the house. The benefits resulting from implementing resilience measures for overheating could not be valued on a per house basis as the value was estimated based on total number of deaths avoided for Canadians. The study then used a projection for the total number of new homes that may be built in both WUI areas and known flood zones, along with the value of deaths avoided to estimate a total cost to construct new homes to these standards and a total benefit that may be achieved if an event were to occur over the service life of these homes.

Table 17: Estimated benefit to cost ratio (BCR) values for implementing resilience measures Summary from [105]

CRBCPI Guideline	**Unit cost**	**Unit benefit**	**Benefit-cost ratio (BCR)**	**Cost ($ millions)**	**Benefit ($ millions)**
National Wildland Urban Interface Guideline & Standard	$7,500	$45,000	6:1	$150	$900
National Guidelines for the Flood Resilience of Buildings	$5,000	$30,000	11:1	$250	$2,750
Overheating Tool	N/A	N/A	N/A	N/A	$1,000
National annual total cost and benefit (rounded)			12:1	$400	$4,700

Following their 2020 study, an analysis was conducted for NRC by Porter et al., (2021) to determine the BCR of applying adaptation measures outlined within the WUI Guide on different reference archetypes. Their analysis considered strategies for both individual homes and community-level implementations. RSMeans data was used to generate estimate costs for;

1. The current replacement cost of the new home archetype,
2. The change in replacement cost of the same home designed to satisfy the WUI Guide,
3. Renovation cost of an existing home archetype to fully satisfy the WUI Guide and,
4. Renovation cost of an existing home archetype to partially satisfy the WUI Guide, excluding impractical or non-cost-effective modifications.

The authors calculated the cost to retrofit homes to satisfy the WUI Guide in both low and moderate-to-high hazard areas. These retrofit costs were compared to the cost of building a new home to satisfy the WUI Guide in both moderate-to-high and low hazard areas. The study analyzed 102 houses across nine communities, including three communities each in low-, moderate-, and high-hazard areas [70] [109]. The results suggest that it is more costly to retrofit an existing home ($16 per square foot) than to build a new home to satisfy the WUI Guide ($6 per square foot). The higher retrofit cost was the result of replacing vinyl siding with non-combustible cladding and replacing windows with tempered outer panes. The retrofit costs could be reduced to $7 per square foot if vegetation within 10 to 30 meters of the home could be controlled. Once built to meet the WUI Guidelines, the BCR was calculated to be 34:1 and 14:1 for new construction and retrofit work, respectively, within the high hazard areas. The BCR decreased to 5:1 for new homes and 2:1 for retrofit work in moderate hazard regions. In low-hazard locations, it is not cost-effective to perform retrofit work, yet a 5:1 BCR exists for new construction, based on lower costs and longer service life period of the selected substitute materials. The BCR for investing in immediate landscaping efforts was 93:1 for new construction and 32:1 for existing homes.

A study was carried out by The Pembina Institute and Introba, in order to determine what resources were available for, and what challenges may be in the way of, retrofitting Multi Unit Residential Buildings (MURB's) in Alberta for climate resiliency [10]. The investigation found that despite there being guides and best practices available for single detached homes, there was little guidance or financial support available for MURB's to become more resilient. The authors concluded that in order to make resilient communities a reality, future efforts should be made to identify retrofit options and best practices for MURB's as well as find ways to incentivise building to levels beyond code-minimum specifications. To determine where spending should be made to incentivize resiliency efforts, the authors suggested that more effort should be made to fully quantify and demonstrate the installation costs and avoided costs associated with retrofitting structures against one or more climate hazards. In order to guide future efforts, the authors suggest to quantify the financial benefits associated with resilient retrofits, such as increasing property value and possibly reducing insurance premiums.

The Intact Centre on Climate Adaptation partnered with the University of Waterloo to develop a table of estimated cost ranges for residential flood protection projects for single family homes [110]. The table provides a range of prices from do-it-yourself options to hiring a qualified professional, along with an estimate on service life for some of the projects. The table also includes information as to whether the flood protection strategy is likely to qualify for any government subsidies or insurance discounts. A comprehensive list of Canadian provincial and municipal flood protection subsidies and grants can be found online at FloodSmart Canada [88].

In addition to potential economic savings resulting from increasing resilience, some adaptation measures have the potential to alter the operational energy requirements of the home. The operational energy usage associated with various residential retrofits was investigated by Prabath et al., 2020 using a HOT2000 energy simulation [101]. Their investigation analysed the potential for retrofits to improve the energy performance of two reference buildings considering varying future climatic conditions and grid cleanliness levels. One reference building contained a natural gas furnace and hot water tank, while the other had electrical baseboard heating and an electrical hot water tank. The energy performance of both buildings was analysed before and after retrofits to showcase possible improvements. The authors used estimated life cycle energy values in their analysis to show how different retrofit solutions may be more or less appealing to different stakeholders across the country based on their initial investment, cost reduction over service life or the life cycle emissions reductions. This framework could be used in future studies to evaluate the energy savings associated with performing resiliency-based retrofits.

A report by Moore, et al., (2023) suggests that defining retrofit objectives early on facilitates for a better understanding of the parameters that need to be collected or used during the both the selection process and assessment process after implementation. With the proper metrics, analysis and modeling, strategies can be selected based on an understanding of the trade-offs between multiple parameters. In a multi-hazard scenario, several analyses may be required to determine how a singular adaptation measure affects multiple objective parameters. Future research should continue to investigate if there are negative consequences associated with addressing one climate hazard over another in multiple climate locations. One such example of an area where future research may wish to explore is the interaction between increasing a buildings envelope air tightness to protect occupants from wildfire smoke infiltrating the building, and the resulting risk or maladaptation to occupant overheating.

Designing for a changing climate can be more than just adapting to current and future climate hazards. Climate-focused retrofits also have the potential to mitigate future climate change by reducing the amount of lifecycle greenhouse gas emissions associated with adaptation [111] [19]. There is growing need in including the embodied carbon emissions associated with building materials in the decision-making process when selecting materials to improve resiliency against climate change. With the decarbonization of energy supplies, and homes becoming more energy efficient, the proportion of embodied emissions associated with the materials used in their construction increases [112]. One strategy that can be used to decrease the embodied carbon within a building is to consciously substitute components with those made from natural materials, local sources, and/or materials that have longer service lives. Determining how the service life of materials, components and/ or assemblies may be affected by changing climate loads may be the subject of future investigations. By including the metric of embodied carbon into the BCR value, the costs associated with selecting retrofit strategies that can both adapt to a changing climate and mitigate the effects of climate change may start to be captured.

The concept that retrofit strategies can enhance both building resiliency and climate mitigation was explored in a report by Mantle Developments for the Standards Council of Canada and The Institute for Catastrophic Loss Reduction [113]. The report presented a methodology to assess the embodied carbon associated with adaptation measures, providing individuals or practitioners with an additional metric to evaluate or rank solutions. The report suggests that when multiple adaptation measures can be implemented to decrease the risks associated with a specific climate hazard, the embodied carbon from the manufacturing and delivery stages (LCA stages A1 - A5) and the operation and maintenance stages (LCA stages B1 – B6) should be considered. This approach allows for material substitutions that not only increase the structure's resilience but also helps mitigate the effects of climate change [113]. By using a tool such as the one developed by Mantle Developments in conjunction with an adaptation pathway or resilient retrofit methodology that analyses adaptation measures for complementary or competing relationships under multi-hazard scenarios, adaptation measures that are both climate-resilient and climate-conscious may begin to be identified.

5 Implementation of Adaptation Measures

Demonstration projects are often used to determine the effectiveness of adaptation measures, and as a means of identifying any challenges that may arise during their implementation in the field. Demonstration projects provide opportunities to validate or de-risk strategies under real world conditions in a low to no risk environment. Results from these studies can help both manufacturers and consumers build confidence in the technologies or strategies increasing their uptake. Other methods including grants and subsidies are also used to encourage the uptake of adaptation measures. The lessons learned and information gained from demonstration projects and pilot studies could then be used in the development of best practices guidelines outlining ways to correctly implement adaptation options across a range of archetypes. These guides could then be used by industry to ensure that adaptation options are being installed consistently across the country and during any inspection process that may be required for insurance purposes. As such Table 18 of this report provides a snapshot of existing demonstration projects and or available sources of funding that may help encourage the implementation of resilient retrofits across Canada.

Table 18: Snapshot of existing Canadian climate resiliency initiatives, incentives and programs for climate resiliency retrofits.

Resource Title	Description	Reference
Grants/Incentives		
Intact Centre on climate Adaptation	Canadian Provincial and Municipal Flood Protection Subsidy/Grant Programs: List of grant and subsidy programs across the country intended to increase the uptake of adaptation actions.	[88]
Backwater Valve Subsidy Program	Aims to protect Edmonton homes from sewer line backups by offering financial assistance for installing backwater valves, targeting homes built before 1989, those with past basement flooding, and areas with a history of neighborhood flooding.	[114]
PacifiCan Fire-Resilient Construction Checklist	PacifiCan supports eligible homeowners who wish to rebuild. fire-resilient and Net Zero Homes through the Lytton Homeowner Resilient Rebuild Program.	[115]
Basement Flooding Protection Subsidy Program (City of Winsor)	Offers a financial subsidy to install a sump pump with sump pump overflow and/or backwater valve(s) and/or disconnect foundation drains from the floor drain to enhance flood resiliency of residential buildings.	[116]
City of Windsor Ontario - Home Food Protection Program (HFPP)	Windsor Backflow Valve Subsidy Program focuses on preventing sewer backup, which can be a resilience measure in flood-prone areas.	[117]
Initiatives/Programs		
Canada in a Changing Climate – Map of Adaptation Actions	Examples of communities and sectors adapting to a changing climate across Canada.	[118] [119]
Environment and Natural Resources – Climate action map	Examples of actions taken across Canada to adapt to a changing climate.	[120]
Climate Atlas of Canada	An interactive mapping tool that overlays climate loads under multiple climate scenarios with community initiatives working to adapt to and mitigate a changing climate.	[61]
Better Homes Ottawa	Reduce greenhouse gas emissions, lower energy costs, and improve home comfort and resilience for Ottawa residential buildings.	[121]
Clean Foundation's Resilient Retrofit Program	Address overland flood risks to homes in communities within the Halifax Regional Municipality (HRM) and the Town of New Glasgow.	[122]
City of Calgary Climate Implementation Plan	Reduce risk from river flooding by implementing community-level and property-level flood protection.	[123]
Climate Resilient Home	Helps stakeholders in the Greater Edmonton Region make decisions to enhance homes' ability to withstand climate change events (such as such as storms, floods, heatwaves, and extreme cold), reduce damages, save money, and ensure comfort and safety.	[124]
FireSmart Home Partners Program	Engage homeowners in voluntary wildfire mitigation activities by offering a professional home assessment with property-specific recommendations to enhance wildfire resilience.	[125]
Infrastructure Adaptation Program by Intact Centre on Climate Adaptation	Helps communities across Canada to reduce their risk of flooding and wildfire.	[126]
Home Flood Protection Program by Intact Centre on Climate Adaptation	Helps homeowners reduce the risk of basement flooding and minimize damage if flooding occurs by providing an on-site flood risk evaluation service.	[127]

City of Windsor Ontario - Home Food Protection Program (HFPP)	A flood protection pilot project being held in the city of Windsor as a flood prevention home check-up to inform residents of their household flood risks.	[117]
Reframed Initiative	Aims to transform Canada's retrofit sector by significantly reducing energy consumption and carbon emissions, enhancing climate resilience to extreme weather events (such as floods, wildfires, and extreme heat), improving occupant health, and making housing more affordable.	[128]
Mobilizing Building Adaptation and Resilience	Enhance the resilience of buildings to extreme weather events (such as heavier rainfall, overheating, wildfires, flooding, and windstorms), improve the safety and comfort of occupants, and provide resources and expertise for renovations and new designs.	[129]
Integrated Building Adaptation and Mitigation Assessment	Enhance building resilience and sustainability by integrating adaptation and mitigation strategies. It focuses on assessing vulnerabilities, developing comprehensive strategies, improving building performance, and promoting best practices.	[130]
Climate Resilient Burlington Plan	Aims to adapt to warmer, wetter, and wilder weather by focusing on five key themes: resilient built and natural infrastructure, thriving natural environment, health and well-being, disaster resilience, and a strong and resilient economy.	[131]
Cohabiter avec l'eau (Coexisting with water) by Architecture sans frontières Québec	Aims to enhance resilience to flooding by developing innovative architectural practices, improving adaptation options, and promoting awareness and training to better coexist with water	[86]
FloodSmart Canada	Aims to enhance flood resilience by raising awareness about flood risks, providing resources to reduce these risks, promoting proactive preparedness measures, and supporting effective recovery after flood events.	[90]
Housing, Infrastructure and Communities Canada (HICC)'s - Climate Help Desk	Support climate adaptation practitioners by providing technical resources, answering frequently asked questions, and offering expert assistance. Its objectives include helping users understand climate impacts, access local climate data and projections, and implement effective adaptation options	[132]
Canadian Red Cross & The Resilience Institute – Roots for Resilience	An initiative that aims to strengthen the climate resilience of small, rural, and Indigenous communities across Canada, while elevating diverse voices.	[133]

6 Knowledge Mobilization

After the science-based best practices guidelines have been created, understanding the methods available to disseminate the information to those who need it becomes the next logical step. Knowledge dissemination in respect to climate resilient retrofits means to design effective education materials tailored to the needs of audience (homeowner, builder, renovator, trades people, etc.) to enhance climate resiliency literacy, build capacity, motivate behaviour change, demonstrate the investment case, create connections between effectiveness and local relevance. This report has already discussed many sources, where climate resilient practices and adaptation options are being shared, including infographics, websites, databases technical guides and standards. Beyond the sources already discussed, information on current best practices is being shared through educational programs. Table 19 of this report has attempted to capture a snapshot of some of the educational programs currently working to increase the uptake of climate resilient design.

Table 19: Educational programs or courses in Canada focused on climate change adaptation

Resource Title	Description	Reference
Graduate Certificate in Managing Climate Risk and Resilience	Climate risk assessment and resilience planning	[134]

Climate Change Adaptation Resilience Training Program	Infrastructure, community planning, watershed management, and agriculture	[135]
Building Regional Adaptation Capacity and Expertise (BRACE) Program	Training, knowledge-exchange activities and practical action to increase the capacity to undertake climate change adaptation actions	[136]
Climate Adaptation, Resilience and Empowerment (CARE) Program	To equip future leaders with the skills and knowledge to address climate change, biodiversity loss, and pollution through cross-cultural education and sustainable development initiatives	[137]
Infrastructure Resilience Professional (IRP) designation	To equip engineers with the skills to plan, design, and manage resilient infrastructure in response to climate change. It enhances knowledge in asset management, risk management, climate science, and climate change law, promotes resilient practices, and supports professional development through structured courses and practical experience.	[138]
Residential Deep Energy Retrofit Fundamentals	Introduction to deep energy retrofits, cost-benefit analyses, and explore retrofit strategies focused on climate resilience and home electrification.	[139]

7 Summary and Future Work

This review was caried out to gain an understanding of what information is required and what decisions need to be made during the process of designing and preparing for home retrofits to increase resiliency to a changing climate and natural events. It also aimed to identify information gaps and/or barriers that may be in the way of developing a resilient retrofit guide. The focus was on risks and vulnerabilities affecting buildings and their occupants to hazards including wildfire, wind, extreme heat and flooding, as well as the challenges posed by multi hazard scenarios. In this report, adaptation and mitigation strategies were limited to those that could be implemented at the building level, and on the immediate surrounding property to enhance resilience, rather than interventions that are to be implemented on a broader community scale. Findings from a previous scientometric study by Riahinezhad and Hayes [8], revealed several recurring research themes, reflecting the growing number of groups and organizations developing guidelines, tools for assessment, climate loads projections, and educational resources for climate resilience. These themes include:

- Hazard and exposure mapping,
- Vulnerability assessment for buildings and occupants,
- Identification of appropriate adaptation measures,
- Evaluation methods for the effectiveness of resilience measures,
- Implementation of adaptation measures through pilot studies and de-risking strategies,
- Information dissemination.

To illustrate the interconnectedness of these research themes and the overall flow of information that may be required to develop science-based guidelines for resiliency, a roadmap linking research themes was proposed. This proposed roadmap served as the framework for the current review, highlighting how insights from one theme may benefit or influence another.

The first chapter of the report focuses on understanding the parameters that go into developing hazard loads and exposure maps, as well as compiling resources to identify exposure to the climate hazards targeted in this report. These hazard maps are valuable tools to identify areas of concern in terms of climate loads, vulnerability, exposure, and sensitivity. They can support risk assessments and help estimate potential damages, injuries, and economic losses associated with the occurrence and severity of specific hazard(s) in a given area. However, significant challenges exist in both the generation and upkeep of information for all populated areas across Canada despite their size or location. Additional challenges include ensuring that populations potentially exposed to climate hazards are aware of the loads they face, and recognize the fact that exposure does not necessarily equate to vulnerability. The interconnected nature of these challenges highlights that building climate resilience requires an iterative approach, involving continuous feedback and coordination across all actions outlined in the proposed flowchart.

The second chapter of the report explores the concept of vulnerability as it relates to both buildings and their occupants, along with a review of emerging methods to assess their vulnerability and their overall risk to climate hazards. The review identified several resources that provide hazard-specific inspection checklists and/or scorecards, to qualitatively assess the level of risk a structure may be susceptible to based on known weak points. However, there is a notable lack of tools capable of quantitatively measuring or evaluating vulnerability. Checklists/ scorecards can provide a useful reference for those looking to assess a structure's vulnerability to a climate hazard during site visits or inspections. However, their effectiveness depends on prior knowledge of current and/or future hazard exposure and without this context, vulnerability assessments may be misleading. For instance, a structure could be rated poorly for a hazard it is not even exposed to, or conversely, be at risk if exposure is overlooked. Being aware of one's current and future exposure level before performing a building assessment enables a more holistic, multi-hazard vulnerability assessment. Another potential limitation of scorecards and checklists may arise from their granularity, where if followed without performing more intrusive or quantitative investigations, an initial assessment for vulnerability may fall short of accurately establishing the remaining service life of buildings, or when/if they become vulnerable to climate loads. As early-stage assessments can influence decisions made during the design process, and serve as a baseline for evaluating the effectiveness of future interventions, assessing and quantifying the vulnerability of building systems may become an integral component of future building inspections. Future research could focus to identify key metrics for evaluating building performance and vulnerability, and on developing tools to quantify these metrics. In addition, future work may look to analyze previous building condition assessments and post-event reports to help identify if vulnerability may be linked to factors such as age, construction practices, energy sources, or management. This could also inform whether pre-emptive adaptation measures achieve their intended resilience outcomes.

The third chapter of this report focuses on the identification of adaptation measures. As communities across Canada can be exposed to a wide range of climate hazards, where both their level of exposure and vulnerability to the hazard(s) can vary significantly between communities, identifying appropriate resiliency strategies can be a challenge, even before taking building condition and occupant requirements into consideration. As such, a review was conducted of resources available to those seeking to implement resiliency retrofits and resources available to help determine which retrofits to prioritize under a multi-hazard scenario. The review found resources outlining adaptation measures to increase resiliency against a singular hazard, but only a handful of resources that provide guidance under a multi-hazard scenario. In addition, the suggested adaptation strategies from these resources tended to be extremely general, leaving out details on how these solutions might actually be implemented across different building archetypes or how effective they might be at decreasing risk based on location or building type. Future work is required to quantify the effectiveness of suggested adaptation strategies to decrease vulnerability across Canada's diverse climate zones, under multiple climate change scenarios and hazard loads. Further investigation into how adaptation measures interact, particularly in locations exposed to multiple or competing hazards, could help identify strategies that are complementary, coordinated, or potentially conflicting for specific buildings and occupants. Accessing information on how adaptation strategies may interact both now and under multiple climate projections during the design phase of a project could reduce future costs and effort by minimizing the risk of maladaptation or the likelihood that additional retrofits are needed in response to emerging climate hazards. Understanding how adaptation strategies perform under different climate projections will be key to ensuring long-term resilience.

The fourth chapter of the report focuses on identifying tools and resources that could be used to evaluate the effectiveness of climate resilient retrofits. Over the last several decades, energy efficiency and operational costs have generally been the driving factor for initiating home improvements. Success has typically been measured using parameters such as budget, operational energy consumption, cost-benefit analysis, and return on investment. While the resources highlighted in this chapter still emphasize cost savings and energy reductions as key performance indicators, the increasing frequency and severity of climate events have shifted the motivation for retrofits. Today, retrofits are often being initiated when building systems can no longer recover from climate-related impacts, meet their intended service life, or maintain a safe indoor environment for occupants. Tools such as the risk assessment matrix described by Lepage 2021, [19] may be particularly useful in helping to determine which adaptation strategy(ies) to implement in areas experiencing multiple hazards or where funding and resources are limited. Metrics such as benefit-cost ratio (BCR), offer insight into the economic value of an adaptation measure relative to its implementation cost. As highlighted in earlier chapters, there is a growing need to identify additional metrics that can quantify the effectiveness of retrofits in reducing vulnerability. Future research could investigate the relationship between vulnerability and indicators such as GHG emissions reductions, decreased use of sick days, and reduced insurance claims. Understanding these relationships could support more informed decision-making when selecting adaptation strategies and help ensure that retrofits deliver meaningful resilience outcomes.

Chapter 5 focuses on the implementation of adaptation measures. There are several methods that can be used to encourage the adoption or uptake of resilient technologies and practices. Demonstration projects are often used to validate or de-risk strategies in low-, or no-risk environments, in order to building confidence in effectiveness of a solution, while grants and subsidies are used to encourage the uptake of adaptation measures by making them financially more accessible and appealing. To support this, the chapter includes a summary table highlighting a range of existing demonstration projects and funding sources that may help encourage the implementation of resilient retrofits across Canada. Future research could explore the effectiveness of these support mechanisms in driving the uptake of resiliency measures. The information gathered could be used to help determine if further demonstration projects, or pilot studies are needed, to showcase strategies or if different incentives are required. Additionally, understanding how factors such as the level of intrusiveness or capital cost of a retrofit influence occupants willingness to adopt these resiliency measures would aid in the refinement of development of future sources of grants and subsidies, ensuring they are better aligned with user needs and barriers to implementation.

Finally, Chapter 6 focuses on knowledge dissemination. After the science-based best practice guidelines have been developed, multiple methods can be used to disseminate knowledge and findings through educational materials tailored to different audiences as needed. The potential audiences include but not limited to: homeowners, builders, renovators, trades people and government organizations. Throughout this report, various sources such as infographics, websites, databases, technical guides and standards, have been summarized to highlight the information available within each research theme. Beyond the sources already discussed, a snapshot of some existing educational programs is also provided, where information on current best practices is being shared through educational programs.

Table 20: Summary table of reviewed resources organized by climate hazard.

Resource Title	**Description**	**Reference**
Wildfire		
National Guide for Wildland-Urban Interface Fires	Provides guidance on hazard and exposure assessment, property protection, community resilience and emergency planning to minimize the impact of WUI fires.	[17]
Natural Resources Canada	The Canadian Wildland Fire Information System (CWFIS) creates daily fire weather and fire behavior maps year-round and hot spot maps throughout the forest fire season, generally between May and September.	[18]
Environment and Climate Change Canada	Interactive maps showing the dispersion of wildfire smoke, the total levels of fine particulate matter ($PM_{2.5}$), ground level ozone (O3) and nitrogen dioxide (NO2) over the next 72 hours.	[20]

FireSmoke Canada	Interactive forecasts of hourly, daily average and daily maximum concentrations of $PM_{2.5}$ smoke particles at ground level from wildfires.	[23]
Government of British Columbia	Provides access to WUI risk class maps for communities across British Columbia.	[26]
Crown-Indigenous Relations and Northern Affairs Canada	Hosts the First Nation Adapt (FNA) program, which provides support to First Nation communities and organizations located south of the 60th parallel to assess and respond to the impacts of climate change, in order to increase their climate resilience.	[27]
Intact Centre on climate Adaptation – Climate-Ready infographics	Three steps to a cost-effective FireSmart Home & Three features of a wildfire-ready community: A series of infographics that outline adaptation options from low-cost/Do-it-yourself to more complex upgrades.	[65]
Institute for Catastrophic Loss Reduction: protecting your home from wildfire	Outline of steps that can be taken to decrease the vulnerability of a home to wildfires, from inspection to action.	[69]
Wildfire-Resilience Best-Practice Checklist for Home Construction, Renovation and Landscaping	Information to encourage the uptake and implantation of adaption measures to decrease risk of damage resulting from wildfires.	[71]
Flooding		
Crown-Indigenous Relations and Northern Affairs Canada	Hosts the First Nation Adapt (FNA) program, which provides support to First Nation communities and organizations located south of the 60th parallel to assess and respond to the impacts of climate change, in order to increase their climate resilience.	[27]
National Research Council of Canada	Guide for design of flood-resistant buildings – an approach that can be used during the design of new buildings to decrease their vulnerability to flood damage.	[31]
FloodSmart Canada, Know your Risks	A list of Canadian flood maps organized by provinces, territories and municipalities.	[34]
Natural Resources Canada	Natural Resources Canada has launched the Flood Hazard Identification and Mapping Program, in order to update existing flood hazard maps of higher-risk areas across Canada, through partnership with provincial and territorial governments.	[35]
Public Safety Canada	Provides information on how to prepare for a flood, including what to do before, during and after.	[36]
Environment and Climate Change Canada	Provides information regarding the causes and costs of flooding, measures to reduce flood damage, and summary of some of the major flood events in Canadian history.	[37]
Environment and Climate Change Canada	Implemented a coastal flooding prediction and alerting program, in order to issue coastal flooding alerts and forecasts across the country, using both the probability and expected impact of an event.	[38]
Indigenous Services Canada	Provides information needed to ensure that emergency preparedness and response plans are in place, as well as providing information on the funding available for eligible flood mitigation preparedness and response measures.	[39]
Flood Resilient Design Framework	A resource that provides examples of flood resilient design approaches for different home archetypes, along with a design checklist.	[74]
National Research Council of Canada	Guidelines for improving flood-resistance for existing buildings – outlines adaptation options specifically developed for existing buildings.	[85]
Habitations + Inondations Mesures D'adaptation Résidentielle	Provides a table of fortification techniques and design strategies for residential homes to increase their resilience to flooding. The table classifies the strategies as key measures, adaptation measures and avoidance measures.	[86]
Institute for Catastrophic Loss Reduction: protecting your home from basement flooding	Outline of steps that can be taken to decrease the vulnerability of a home to flooding, from inspection to action.	[87]

Intact Centre on climate Adaptation	Canadian Provincial and Municipal Flood Protection Subsidy/Grant Programs: List of grant and subsidy programs across the country intended to increase the uptake of adaptation actions.	[88]
Intact Centre on climate Adaptation	Three steps to cost-effective home flood protection: An infographic that outline adaptation options from low-cost/Do-it-yourself to more complex upgrades.	[89]
Floodsmart Canada – Helping Canadians Prepare for Floods	Provides a list of resources organized by province and territory, for Flood/Emergency preparedness, Guides, toolkits and maps, Emergency notifications and alerts as well as any available incentives and or grants.	[90]
Extreme Wind		
Institute for Catastrophic Loss Reduction: Increasing High Wind Safety for Canadian Homes: A Foundational Document for Low-Rise Residential and Small Buildings	Provides a list of wind risk reduction measures that can be implanted for both new and existing buildings to improve the continuous load path between roof and foundation.	[40]
Environment and Natural Resources	Provides weather warnings, forecasts, up-to-date tropical conditions and hurricane track maps.	[43]
Public Safety Canada	Provides information on how to prepare for a hurricane, including what to do before, during and after.	[47]
Western University - Northern Tornados Project (NTP)	Improving tornado alerting effectiveness for Canadians as well as increase the general understanding of weather events and predictions under future climate change scenarios.	[48] [49]
Institute for Catastrophic Loss Reduction: protecting your home from severe wind	Outline of steps that can be taken to decrease the vulnerability of a home to severe wind, from inspection to action.	[91]
Improving windstorm and tornado resilience	An overview of building envelope and load path improvements that can be used to increase the resilience of wood-framed, one- and two- family residential structures.	[92]
Extreme Heat		
Mapping Spatial Patterns in Vulnerability to Climate Change-Related Health Hazards: 2020 Report	A set of interactive maps and accompanying report for communities across British Columbia that highlighting their level of risk to extreme heat events.	[25]
Provincial Health Services Authority – Preparing for summer weather	An online resource that outlines signs and symptoms of heat illness and information on demographics that might be at greater risk to the effects of extreme heat.	[52]
National Research Council of Canada – Climate Resilient Buildings: Guideline for management of overheating risk in residential buildings	A list of passive and active adaptation solutions along with results from computer simulation quantifying their potential to reduce occupant's risk of overheating for multiple building archetypes.	[58]
Mapping the vulnerability and exposure to extreme heat waves of populations living in housing in Canadian communities	An interactive map and accompanying report that highlights the level of risk of 156 urban regions across Canada to extreme heat events.	[59]
Climate Atlas of Canada	An interactive map which shows the number of extreme heat days across Canada under multiple climate change scenarios and time periods.	[61]

Intact Centre on Climate Adaptation	Irreversible Extreme Heat: Protecting Canadians and communities from a lethal future. A list of adaptation options and their key benefits or potential limitations.	[95]
Health Canada - Staying Healthy in the Heat	An infographic to help convey the risks associated with extreme heat on humans, and outline key adaptation measures one can do to reduce body temperatures and stay safe during periods of extreme heat. The infographic also provides a summary of the health concerns, signs and symptoms of heat related illness, a summary of those are most at risk of heat related health effects.	[98]
Intact Centre on Climate Adaptation	Three steps to cost-effective home heat protection & apartment and condo heat protection: A series of infographics that outline adaptation options from low-cost/Do-it-yourself to more complex upgrades.	[99] [100]

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9 Definitions

Adaptation needs: The circumstances requiring action to ensure the safety of populations and the security of assets in response to climate impacts. [140]

Adaptation options: The array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorised as structural, institutional, ecological or behavioural. [140]

Agent: a physical process or chemical or biological substance, including contaminants in the building materials themselves, that, alone or in combination, acts on a building or building elements to cause degradation. [141]

Agents of Deterioration: moisture (atmospheric and rainfall) is a particularly important issue in assessing the long-term performance of wall assemblies. [141]

Assembly: an arrangement of one or more materials or components to serve a specific overall purpose [141]

Benefit-Cost Ratio: The ratio of the benefit to the cost is called the benefit-cost ratio (BCR), and when the ratio exceeds 1, the benefit can be seen as cost-effective. [70]

Climate Change mitigation: the rapid reduction of GHG emissions to minimise the worsening of future climate loads [19]

Climate Change adaptation: the process of adjusting of our built and natural environments to withstand future risks posed by climate change. [19]

Coastal Flooding: Fooling that occurs in seawater due to storms that causes a rise in the water levels and could lead to tides reaching building. [33]

Construction Class: The minimum requirement of a structure's exterior cladding. [17]

Degradation: deterioration or deformation that leads to adverse changes in a critical property of a building element. [141]

Durability: the ability of a building or building element to perform its function to the required level of performance for its **design service life** in it structure environment under the influence of **environmental actions**. [141]

Exposure: The presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by climate change. [3]

Exposure Level: The probability of a structure's exposure to flying embers, radiant heat, and/or, direct flame during its lifecycle. [17]

Extreme Weather: The occurrence of a weather variable (such as temperature) that exceeds the upper or lower limit of observed values for that variable. These events are often short-lived and include heat waves, ice storms, heavy downpours, tornadoes, tropical cyclones, and floods. [3]

Failure: the loss of performance resulting from the inability of a building element to perform its required function. [141]

Fire Danger: An indication of how readily vegetation could ignite. [142]

Flooding: A hydrological process that occurs when the waterflow exceeds the water channel's capacity and begins to flow beyond the channel's boundaries. [33]

Flood Plain: A low-grounded area near a river or a water channel. [143]

Flood Stage: The threshold height of a location to which exceeded water levels would cause a flood hazard. [144]

Fluvial (Riverine) Flooding: Flooding that occurs when precipitation runoff causes the waterflow to exceed the water channel's carrying capacity and flows beyond its boundaries. [33]

Hazard: is any source of potential damage, harm or adverse health effects on something or someone. [145]

Limit state: a limit in which the performance of a component is no longer acceptable (the state at which the component should be replaced or refurbished) where an increase in the performance close to but not that of the initial state indicates refurbishment. [141]

Maintenance: actions and measures taken periodically to maintain a desired level of performance. Maintenance includes a planned program of cleaning, repair, or replacement of identified components, such as paint or gaskets. [141]

Maladaptation: Maladaptation is an unintended consequence of an action actions that lead to increased risk of adverse climate-related outcomes, including increased greenhouse gas emissions, increased vulnerability to climate change, more inequitable outcomes, or diminished welfare now and in the future. [140]

Mitigation (of climate change): A human intervention to reduce emissions or enhance the sinks of greenhouse gases. [140]

Mitigation measures: In climate policy, mitigation measures are technologies, processes or practices that contribute to mitigation, for example renewable energy technologies, waste minimisation processes and public transport commuting practices. [140]

Mitigation option: A technology or practice that reduces greenhouse gas (GHG) emissions or enhances sinks. [140]

Natural Hazards: Naturally occurring rapid onset events that could cause a serious disruption to a community or region. Natural hazards include: snowstorms, wildfires/bushfires, cyclones/hurricanes, tornadoes, floods, severe thunderstorms or storm surges, heatwaves, hail ect. [146]

Performance: The behaviour of a building or any of it’s materials, components, assemblies, or systems as related to intended use. [147]

Pluvial Flooding: Flooding that is caused by extreme rainfall events. [33]

Priority Zone: The area that surrounds the structure within the WUI that falls under a distance of 100m from the structure. [17]

Renovation: A program of restoration or modernization of a building element, resulting in a material change, with or without a change in use or occupancy of the building and with or without structural changes. [141]

Repair: an action or measure taken to restore performance to an acceptable level. Repairs, including partial replacement of building elements, can be undertaken as part of the planned maintenance program for a building or initiated to remedy unexpected damage. [141]

Resilience: The ability of a system, community or society exposed to hazards to resist, absorb, adjust to and recover from their effects in a timely and efficient manner, including initiatives to preserve and restore essential structures and functions. [146]

Retrofit: an alteration to increase the performance of a system or component beyond that to which it was originally designed. [63]

Risk: Is the chance or probability that a person (or property) will be harmed or experience an adverse health effect if exposed to a hazard [145]. Or can be defined as the potential for consequences where something of value is at stake and where the outcome is uncertain. Risk is often represented as probability of the occurrence of hazardous events or trends, multiplied by the potential impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard. [3]

Service Life: the actual period of time during which the building or building elements perform to the required level(s). [141]

Storm Surges: A phenomenon that occurs when strong wind pushes sea tides towards the shore. [30]

Design Service Life: the **service life** specified by the designer in accordance with the expectations of the owners of the building and the requirements given within CSA S478:19. [146]

Predicted service life: the service life forecast from demonstrated effectiveness, tests, or modelling or some combination thereof. [146]

Social impact: The effect of disasters on people’s health and wellbeing of individuals and families, and/or the effect on the social fabric of affected communities. [146]

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, negative effects of climate change, including climate variability and extremes. [3]. Is a result of the risk less your capacity to adapt to its adverse effects. [19]

Wildland Urban Interface: An area where human civilization interacts with the natural environment. [17]

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