Characterization of End-User Needs to Optimize the Development of the Rapid Earthquake Damage Estimation (RED-E) System in Canada

by

Megumi Patchett
B.Sc., University of Victoria, 2020

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ABSTRACT

In the event of a significant earthquake in Canada, responders would face a dearth of information crucial for situational awareness in the initial hours to days. To address this issue, the Geological Survey of Canada is developing the Rapid Earthquake Damage Estimation (RED-E) system to generate maps of modelled structural, social, and economic loss within tens of minutes after a significant earthquake. The studies presented in this thesis were initiated to optimize the development of RED-E to ensure that the intended end-users (including first responders, emergency managers, and critical infrastructure operators) will make full use of the products. First, informational interviews were carried out to elucidate end-users' immediate needs, priorities, and challenges following seismic events, thus guiding the development direction of the RED-E system. Then, feedback was solicited from end-users on the potential products of RED-E in three wireframes: text, static (PDF format), and dynamic (GIS format). Overall, all three wireframes were well received, and this study confirms that all of the intended RED-E data outputs will be highly helpful for the end-users.

This thesis validates the current progress of the RED-E project and includes suggestions for improvements. The study findings underscore that most end-users struggle to attain critical situational awareness immediately post-event, suggesting that it will likely take about three days to weeks to gain complete and credible situational awareness after a major earthquake. The main findings indicate the need to make RED-E outputs transmittable in multiple formats. For example, a simple text output can be communicated even in the case of telecommunication interruption, using amateur radio or satellite phones. A summary PDF format with maps is highly valuable to enable understanding of the extent of impacts at a glance, and an interactive GIS format is also highly valued since it can contain a large amount of data for users to choose from. Modelled outputs on road disruption, impacts on other critical infrastructure, and secondary hazards were identified as valuable to end-users.

This thesis provides a comprehensive outline of the essential requirements of the RED-E system and documents end-user feedback on an initial prototype, paving the way for its future implementation. Through informational interviews with end-users, this study has shed light on their immediate needs, priorities, and challenges following seismic events, thereby guiding the design requirements of the RED-E system.

The introduction of RED-E products promises to significantly enhance the ability of end-users to prioritize response efforts until ground-truth data are available and to expedite search and rescue as well as resource allocation processes. The positive reception further underscores the potential efficacy of RED-E products and signals the need for deployment of such products across Canada. In conclusion, the RED-E system, with its ability to generate seismic damage and loss estimate maps swiftly, is poised to significantly improve the way responders and end-users in Canada handle the first 24-48 hours following large earthquakes.

Contents

List of Tables

List of Figures

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DEDICATION

This Master's thesis is dedicated to the victims and their families of all great past earthquakes.

Chapter 1

Introduction

1.1 Introduction

The most critical period for rescuing individuals trapped under debris occurs within the first 24 to 48 hours following a major earthquake (de Bruycker et al., 1983; Noji et al., 1990; Coburn et al., 1992)(Figure 1.1). Trapped victims' survivability is a function of rescue capacity and time (Coburn et al., 1992). The most common cause of earthquake-related mortalities is structural collapse (Coburn et al., 1992), making early search and rescue a priority. The quicker rescuers can arrive, the higher a victim's survivability; a lack of situational awareness, however, presents a massive obstacle.

An example is the case of the M_w 6.9 Great Hanshin-Awaji earthquake (also known as the Kobe earthquake) in 1995, where the absence of situational awareness significantly hampered the response (Tierney and Goltz, 1997). This event resulted in an extensive economic loss (estimated at US$114 billion, three times the recorded cost of any previous natural disaster in history)(Horwich, 2000), 6,279 fatalities, over 136,000 housing units destroyed, and more than 300,000 persons left homeless. The event illuminated the harsh reality and struggles of the post-seismic phase and the criticality of acquiring situational awareness in the first hours (Tierney and Goltz, 1997). In that event, ambiguity regarding the extent and severity of the disaster at multiple government levels was the leading cause of delays in immediate response and providing emergency aid (Tierney and Goltz, 1997).

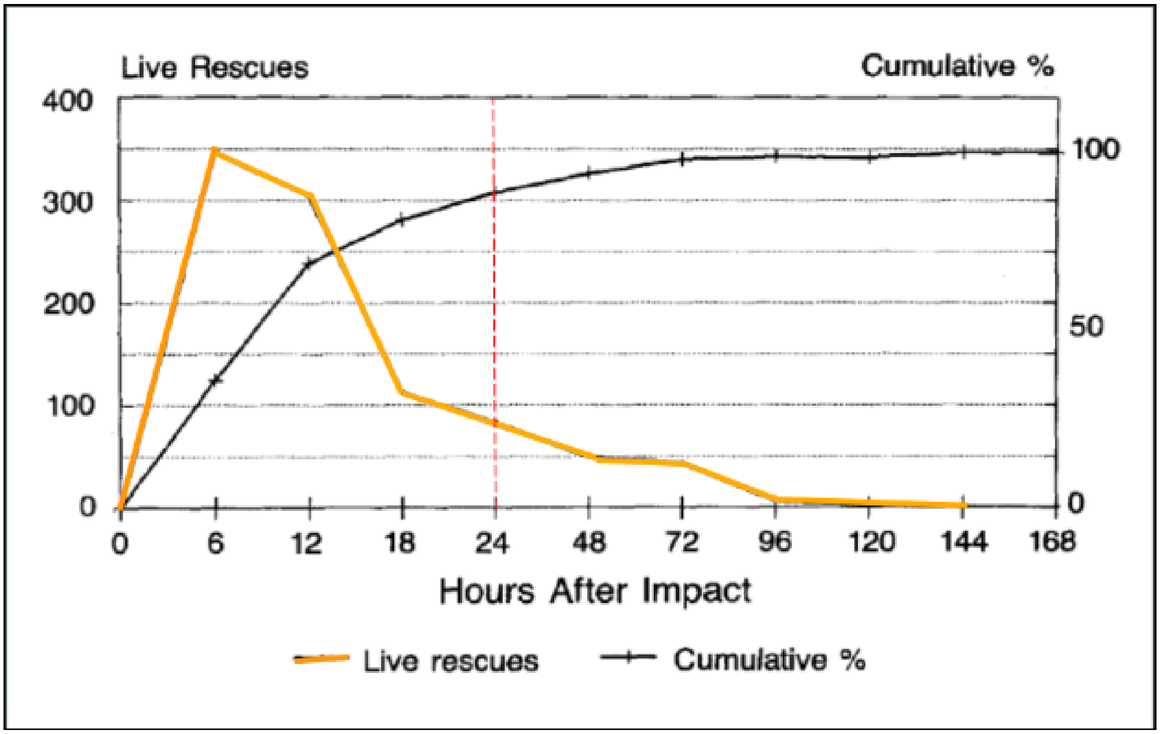

Figure 1.1: Urgency in post-earthquake rescue efforts. Modified from Noji et al. (1990). The chart highlights the criticality of an immediate response. It displays the rapid decrease of survivability in trapped people inside collapsed buildings. The solid orange line indicates the number of live rescues, and the cumulative percentage displays the percentage of live extrication following a large earthquake in Soviet Armenia in 1988.

Learning from damaging global seismic events, and using a thorough understanding of seismic hazard and building stock in Canada, the Geological Survey of Canada (GSC) has recently developed a seismic risk modelling approach for the entire country (Hobbs et al., 2023a,b). They also developed a prototype application of this risk model to rapidly estimate the extent of loss and damage following a large earthquake, for assisting early earthquake response in Canada (Hobbs et al., 2020). Rapid estimation of damage after major earthquakes can be and has been a valuable tool to assist in timely response to ensure public safety (Wald, 2013), and as such, the GSC plans to implement this proof of concept in the coming years by analyzing and addressing the specific needs of end-users.

This chapter outlines the usage of satellite and drone imagery in emergency response, followed by a description of notable global examples of rapid disaster modelling systems, which can estimate and identify the areas of severe impacts, the number of fatalities, and economic losses. It then describes Canadian seismic hazards and risks and provides an overview of the proposed Rapid Earthquake Damage Estimation (RED-E; pronounced "ready") system. Finally, the main objectives and structure of this thesis are outlined.

1.2 Usage of Satellite and Drone Imagery

Satellites and drones have the potential to capture critical ground-truthing data on the extent of damage following large earthquakes. However, there are limitations to their use for emergency response, as outlined below.

1.2.1 Limitation of Satellite Usage for Emergency Response

Several globally available optical satellite agencies can provide images during post-disaster times. Organizations such as Copernicus Emergency Management Services (https://emergency.copernicus.eu/mapping/copernicus-emergency-management-service), the United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme (UNOSAT)(http://www.unitar.org/unosat/), and the International Charter of Space and Major Disasters (http://www.disasterscharter.org/) work to promptly release hazard and damage maps online, primarily utilizing optical satellite imagery. These organizations automatically access and download data upon activation by government authorities and manually assess damage to structures.

However, there is often a delay before these images can be made available. For example, after the 2023 Turkey–Syria earthquakes (M_W 7.8) on February 6th, Copernicus Emergency Management Services took over two days to deliver the first products. Even though the case was activated about three hours after the seismic event, the image acquisition did not occur until the morning of February 7th, and processing time took another 24 hours (https://emergency.copernicus.eu/mapping/copernicus-emergency-management-service). Similarly, for the same event, UNITAR did not acquire the image until February 9th, and the first product only became available nine days later (http://www.unitar.org/unosat/). Another example is the Noto Hanto earthquake (M_w 7.5) that occurred on January 1st, 2024. The International Charter of Space and Major Disasters was activated about 24 hours later and took more time to process images (The International Charter of Space and Major Disasters, 2023). Utilizing remotely obtained imagery to assess damage poses fewer risks to emergency responders compared to ground-level inspections, and it is indeed a powerful tool. However, the acquisition of images, which relies on the revisit times of satellites and analyzing these images, remains time-consuming due to reliance on manual methods.

Another limitation of optical satellites is their inability to image through smog, ash, or clouds because they operate as passive systems using shorter wavelengths and rely on sunlight for illumination (Diederichs, 2020), indicating that such optic satellites will not be able to obtain data if the seismic event occurs at night, on a cloudy day, or if the target location is filled with dust from damaged structures which is common during and immediately after a significant seismic event. Additionally, their nadir-looking orientation may overlook structural damage on building sides, and collapsed buildings with intact roofs can be challenging to identify due to the absence of height information, potentially leading to misclassification of damage (Diederichs, 2020).

An active SAR (Synthetic Aperture Radar) satellite is a type of Earth observation satellite equipped with radar sensors that actively emit microwave signals toward the Earth's surface and receive the reflected signals to generate high-resolution images (NASA: Opendata for Open Science, nd). Coherence change damage maps, which use phase coherence to map building damage, identify and quantify the change between pre-seismic and co-seismic coherence maps, emphasizing the regions of decorrelation caused by the earthquake (Diederichs, 2020). However, timely data acquisition, which can be limited by the satellite revisit times, can be the largest obstacle to making radar satellite imagery suitable for life-safety purposes (Diederichs, 2020). Revisit time of such satellites varies greatly but is typically around 12-14 days for individual satellites and 4-8 days for a constellation (Diederichs, 2020). The latest Canadian satellite system launched in 2019, known as RADARSAT Constellation Mission (RCM), with a three-spacecraft fleet of Earth observation satellites, is operated by the Canadian Space Agency to monitor natural disasters, and can achieve a 4-day revisit time with 2-4 hour processing time for the post-disaster coherence change damage maps (https://www.eoportal.org/satellite-missions/rcmeop-quick-facts-section) (Government of Canada, 2019). They are Sun-Synchronous Orbit (SSO) Satellites, however, which rely on solar as their power source, suggesting that it would take at least until sunrise to capture an image if the event occurs at night, and the satellites can only take images upon request, not continuously, unlike the optical sensor satellites, since it is energy consuming to actively provide the energy source for imaging (Government of Canada, 2023). Even with the accelerated image acquisition and more speedy data processing time, it could still take 4 days for images to be available following an event, and cannot provide sufficiently detailed information. It is also important that maps use change detection as a proxy for damage rather than measuring damage directly.

1.2.2 Limitation of Drone Usage for Emergency Response

Unmanned aerial vehicles (UAVs), often known as drones, are compact aircraft that operate autonomously. The utilization of drones has been rapidly advancing in various fields (Daud et al., 2022). However, there are a few limitations to the use of UAVs during the post-disaster phases. The first and foremost issue is access to airspace. UAV operations are highly restricted and not allowed to fly within the security perimeter of a police or first responder emergency operation during the post-disaster phase (Transport Canada, 2019, 2021). A drone flying near these areas may interfere with emergency personnel aircraft and the work of emergency personnel. UAV operations are subject to airspace restrictions or require special permissions from authorities, which can prolong the deployment (Transport Canada, 2021; Daud et al., 2022).

Other constraints include the inability of drones to capture clear images in harsh weather, dust, or smoke; UAVs' limited battery life and, therefore, limited flight times, making it challenging to cover disaster zones extensively; processing and analyzing large volumes of UAV-captured data can be time-consuming; availability of highly skilled personnel who can effectively deploy UAVs for damage assessment is highly limited (Daud et al., 2022); and lastly, Transport Canada (2019), requires UAVs' line-of-sight communication with the operators. Obstacles such as buildings or terrain features will, therefore, limit the coverage area of drones during the post-disaster damage assessment.

Satellite and UAV technology is advancing and becoming more accessible, enhancing their capabilities for rapid response during the post-disaster phase. A rapid loss modelling tool can serve as a practical and effective solution, particularly at the local and regional levels of emergency management. However, satellite and UAV usage can complement these rapid damage modelling tools. For instance, rapid damage modelling can pinpoint areas of severe damage, enabling the prioritization of satellite and UAV applications in these identified areas to generate coherent change maps. While neither satellites nor UAVs can identify specific buildings with people inside or estimate the number of displaced individuals within minutes to aid immediate emergency response, they can be utilized as complementary. After rapid modelling has approximated severely impacted areas, satellites and UAVs can confirm obvious structural damage and provide valuable supplementary information.

1.3 Global Examples of Rapid Damage Modelling Systems

Many rapid damage modelling systems exist (Figure 1.2). They can mainly be split into two categories by the regions they cover: global versus local systems (Erdik et al., 2011). Examples of global rapid earthquake damage assessment tools include Prompt Assessment of Global Earthquakes for Response (PAGER; Wald et al.,2008), EarthQuake Loss Assessment for Response and Mitigation (QLARM; Wyss, 2014), SEISAID (Taillefer et al., 2023; Negulescu et al., 2024) and Rapid Earthquake Consequences Assessment System (RECAS; Leone et al.,2024). Local-scale rapid damage modelling systems include ShakeCast, the Taiwanese Earthquake Rapid Reporting System (TELES; Yeh et al., 2006), the REal-time Assessment of Earthquake Disaster in Yokohama (READY System; Huang et al.,2013), and the SUPer-dense REal-time Monitoring Earthquake system for city gas supply (SUPREME; Guérin-Marthe et al., 2021). "Local" systems are country, city or facility-specific systems tailored to their local or facility needs (Erdik et al., 2011). Both global and local rapid damage modelling systems have their advantages and disadvantages. The former tend to be technologically robust and can be validated frequently through actual events. The latter can, however, include more detailed local specificities that will influence the estimation of losses and the specific needs of stakeholders (Figure 1.2) (Guérin-Marthe et al., 2021).

This section will highlight the two most notable global rapid damage models: PAGER and QLARM. As will be discussed below, both systems are well-known and applicable globally but differ in their methodologies. The PAGER system generally estimates the damage and loss from ShakeMaps (estimated shaking intensity maps) and a set of fragility and vulnerability functions, while QLARM generates its damage estimations from scenarios based on empirical relations derived from up to 1,000 past earthquakes for which the losses were known. A summary of these systems and their differences is provided in Table 1.1.

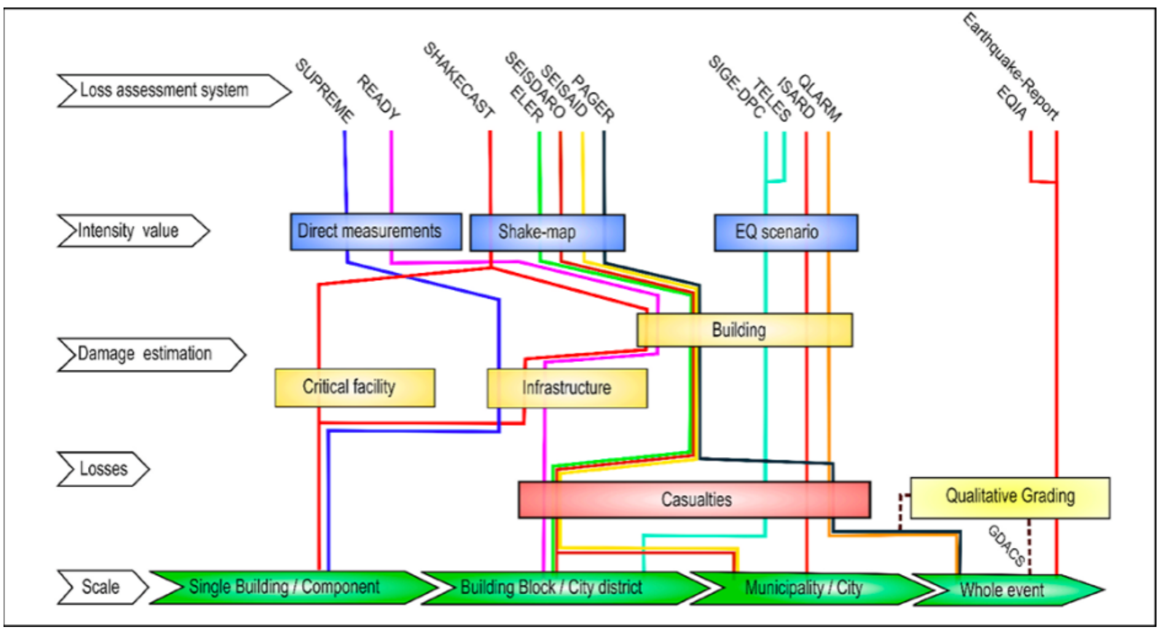

Figure 1.2: Main characteristics of global damage and loss assessment systems (Guérin-Marthe et al., 2021).

Table 1.1: Comparison of Global Rapid Earthquake Damage Estimation Systems

	PAGER	TwoPAGER	QLARM
Thresholds to initiate the system	> M_w3.5 for domestic earthquakes and >M_w 5.5 for global events	Only available for domestic earthquakes that triggered orange or red alert in PAGER (typically > M_w 6)	Global earthquakes > M_w 5.9
Input	ShakeMaps + empirical, analytical or hybrid vulnerability	Uses ShakeMaps + HAZUS risk model	Earthquake parameters + GMPEs
Speed	Within 30 min.	A few to several hours after an earthquake	Within 30 min.
Update	updated as additional data becomes available		
Output	Estimated fatalities and economic losses with uncertainties	First page is consistent with PAGER, but the second page includes HAZUS loss results: estimated economic loss, fatalities, injuries, debris, and shelter needs	Fatalities and average damage to buildings
Scale	Global or US domestic use: population exposed at each shaking intensity level	Global: exposure of each population settlement	Global
Operationality	Operational	Under implementation	Operational

1.3.1 PAGER

PAGER has been operated by the United States Geological Survey (USGS) since 2007 (Wald et al., 2010b). The system automatically provides the likelihood of fatalities and financial losses, with comments describing the dominant types of vulnerable buildings in the region, exposure and any fatality report from historical nearby earthquakes in a one-page summarized format with a map and tables, generally within 30 minutes (Figure 1.3)(Wald et al., 2010b). The report is generated for global earthquakes exceeding M_w 5.5 and earthquakes exceeding M_w 3.5 within the United States (Erdik et al., 2011; Wald et al., 2008, 2020). The one-page report is distributed to first responders, government agencies, and media via e-mail, and made publicly available on the USGS Earthquake Hazards Program Web pages, and it is updated as additional sensor data and reported intensities information becomes available (Wald et al., 2008; Erdik et al., 2011; Wald et al., 2010b).

PAGER: Methodology

The PAGER system, like other risk assessments, requires three inputs: hazard, vulnerability, and exposure. Hazard denotes the probability or level of earthquake shaking, encompassing phenomena like ground motion, and sometimes liquefaction and landslides. Exposure refers to the geographic placement, characteristics, and significance of assets, buildings and occupants within communities. Vulnerability represents the likelihood or probability that these assets will be damaged or ruined when subjected to earthquake impacts (Global Earthquake Model Foundation, 2020). For the hazard input, PAGER uses ShakeMap, which is a colour-coded contour map used to communicate the geographical extent of ground motion intensity caused by an earthquake. ShakeMap is automatically triggered for global seismic events with M_w >5.5, and for M_w >3.5 domestic events in the US, at a resolution of approximately one square kilometre (Jaiswal and Wald, 2011). ShakeMaps are generated using data from seismic sensors, which measure ground motion during an earthquake, and other sources, such as geologic information for site amplification effects and the geometry and dimensions of the causative fault (Wald et al., 2005). If the ground motion recordings are insufficient, which could occur due to poor coverage of seismograph stations in certain regions, inaccuracies in recording data, or the inability to capture the full extent of ground motion in highly complex seismic events, ShakeMaps will be created using empirical Ground Motion Prediction Equations (GMPEs) based on magnitude, site amplification, and distance to the epicentre of causative fault (Wald et al., 2005). The system chooses the most appropriate GMPE from a suite of GMPEs based on the seismic and tectonic settings of the location. Although applying the GMPEs can introduce uncertainty (Guérin-Marthe et al., 2021), the ground motion estimation is improved by observations made by people in the impacted region through the USGS "Did you feel it?" system, which allows people to report their experiences; these

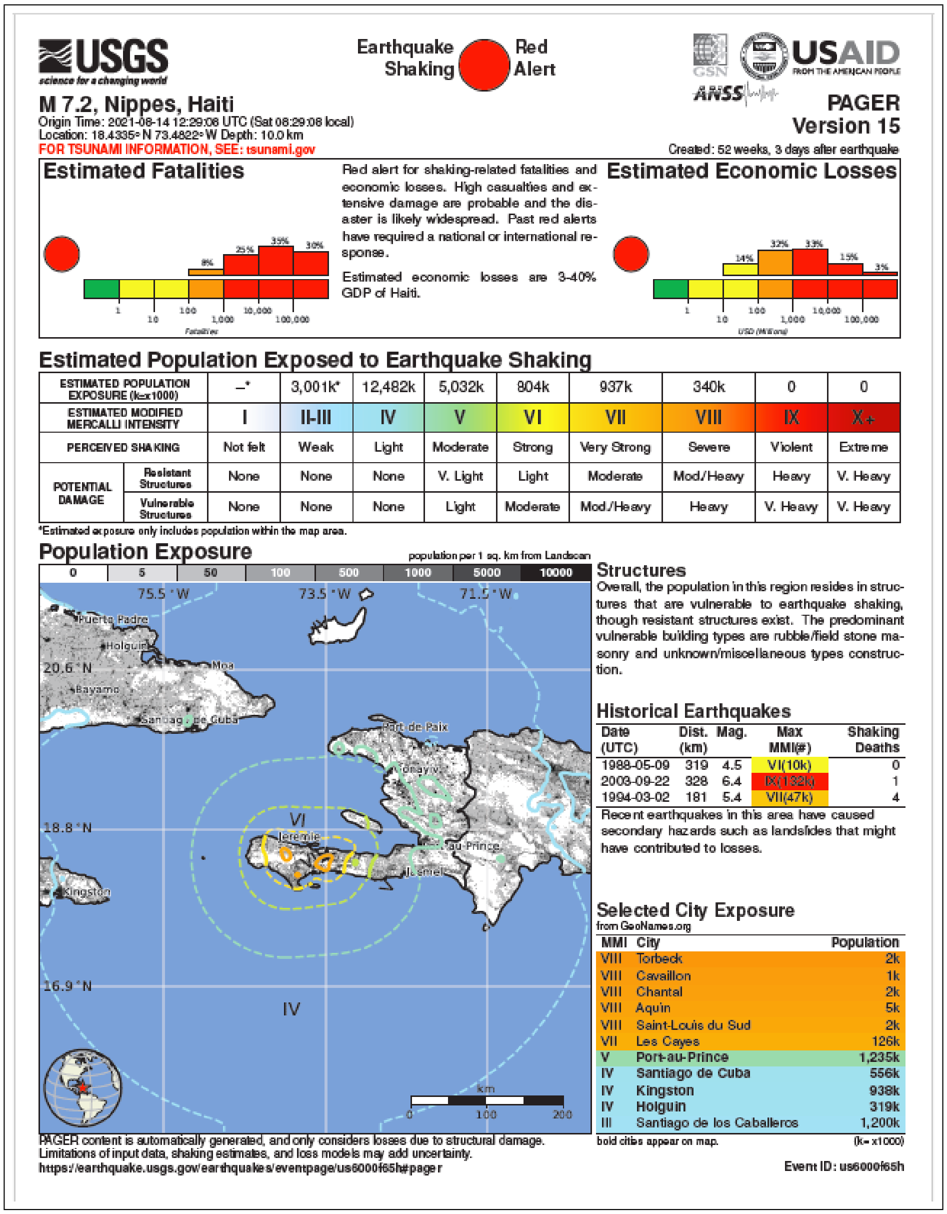

Figure 1.3: Example of PAGER report from the 2021 M_w 7.2 Haiti earthquake. It displays the estimated fatalities and economic loss with probabilities (top-left to right, respectively), and the estimated exposed population based on shaking intensities in Modified Mercalli Intensity. A map indicates the locations of the exposed population with various shaking intensity levels that are colour-coded (orange indicates people feeling very strong shaking while blue suggests people feeling weak shaking). The summary also provides a list of large historical earthquakes in the area for comparison (USGS, 2021)

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reports are used to estimate local shaking intensities, which are in turn used to constrain ground motion distributions (Wald et al., 2010a). These site-corrected shaking intensities serve as the basis for vulnerability and loss estimation for the PAGER system (Jaiswal and Wald, 2011).

Exposure inputs are derived from the LandScan gridded population database, the Global Rural-Urban Mapping Project (GRUMP) database, demographic data compiled by the United Nations, data published by population censuses of different countries, a CIA fact book on workforce data by sector of employment, and the PAGER building inventory database (Jaiswal et al., 2011; Jaiswal and Wald, 2011).

PAGER applies the most suitable vulnerability model out of three options (empirical, semi-empirical, and analytical) for fatality estimations based on the availability of past events with fatalities, building inventories, and the level of building code implementation. The first method is the empirical approach, designed for regions with a high number of past events resulting in mortality (Jaiswal et al., 2009; Erdik et al., 2011; Guérin-Marthe et al., 2021). A global empirical model was developed by Jaiswal and Wald (2012), providing a country or region-specific earthquake fatality ratio that is derived from historical earthquake casualty data as a function of shaking intensity. The method is appropriate for regions that lack data on building inventories and associated vulnerabilities but have enough seismic impact records or comparable records from other similar countries (Erdik et al., 2011; Jaiswal and Wald, 2011). The empirical approach generally applies to developing regions, and changes in population over time are captured in the LandScan population database (Jaiswal and Wald, 2012).

The second method is known as analytical. This approach is used for the US domestic seismic events, and the loss estimation is based on the Federal Emergency Management Agency's (FEMA) HAZUS capacity-spectrum methodology that estimates the response of a structure from spectrum demand and spectral-capacity curves (Jaiswal et al., 2011) (Figure 1.4). This method is more suitable for highly developed countries with robust building code implementation, as it requires detailed building inventories with occupancy rates and structure types (Erdik et al., 2011). Fatalities and injuries are inferred by the damage levels. Casualty rates are recalibrated based on historical data of deaths and injuries.

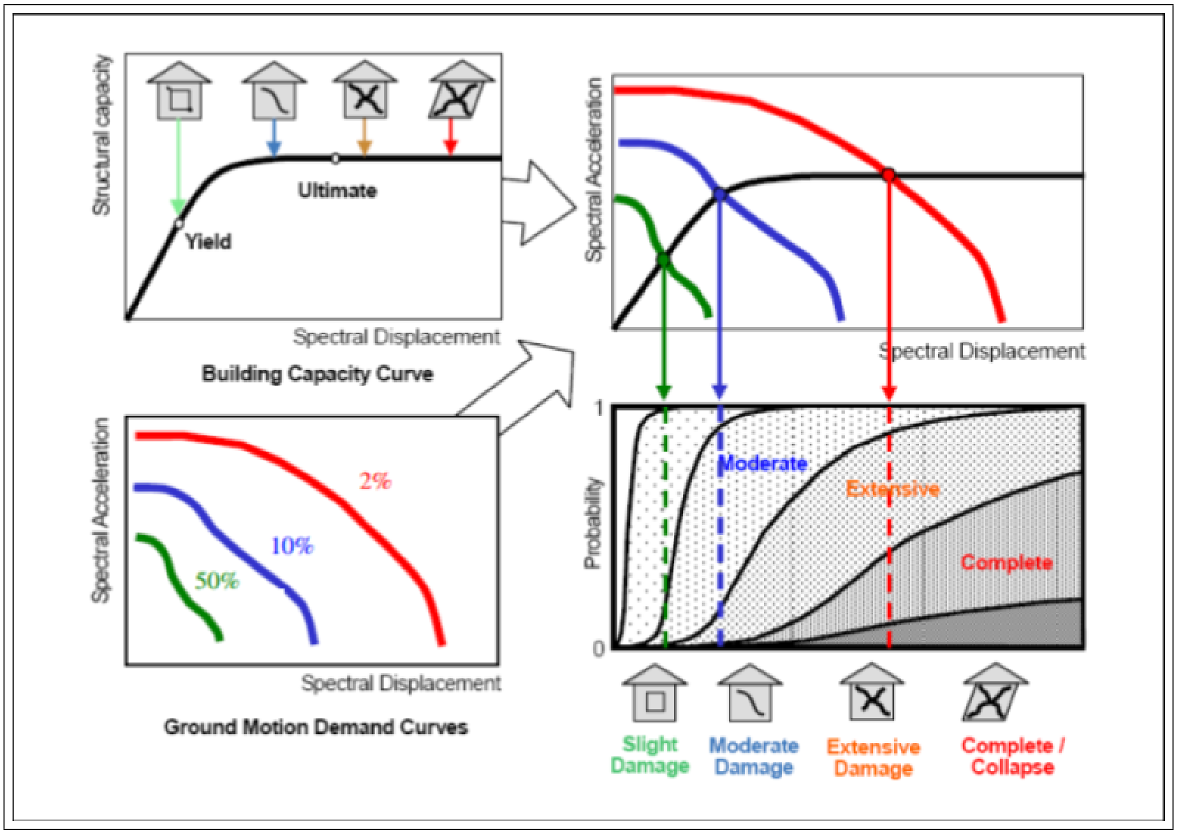


Figure 1.4: HAZUS earthquake loss estimate methodology for buildings (Alam et al., 2017)

A third method is a semi-empirical approach; this approach is considered a hybrid of the empirical and analytical methods. As a forward estimation model, earthquake vulnerability within the semi-empirical model is defined in terms of the probability of collapse of a particular structure type, given the input shaking intensity, but some exposure data are based on expert judgment (Jaiswal and Wald, 2011). PAGER developers collaborated with World Housing Encyclopedia (WHE) experts from twenty-six countries to gather country-specific data for the most common building types (Jaiswal and Wald, 2011). This approach requires basic building inventories and distributions, occupancy data, and vulnerability functions that are assigned by the experts. Many factors affecting casualty rates are determined by comparing intensity measures to historical data on deaths and injuries, using a least-squares fitting method (Erdik et al., 2011).

Both analytical and semi-empirical methodologies use a $1km \times 1km$ grid-base fatality calculation (Jaiswal and Wald, 2011; Jaiswal et al., 2011). The population density levels of each cell are determined, as well as the fraction of the indoor population in residential and non-residential buildings (e.g., workplaces, schools, etc.), with occupancy levels based on the local time of day and a demographic dataset (Jaiswal and Wald, 2011; Jaiswal et al., 2011).

TwoPAGER

USGS PAGER and FEMA HAZUS teams have been working on the new prototype loss model known as TwoPAGER to supplement the current PAGER system for domestic seismic events (Wald et al., 2020). HAZUS is hazard planning and mitigation software developed and operated by FEMA. It utilizes geographic information system (GIS) technology to estimate potential losses (Wald et al., 2020).The system is a combined loss model of PAGER and HAZUS (Figure 1.5). While PAGER can provide rapid (10-30 minutes) loss estimates, the information is general. HAZUS takes longer (2-5 hours) but provides more detailed loss estimation in quantifying structural, social, and economic impacts. The TwoPAGER system was developed to take advantage of both systems. It will provide more detailed damage and impact content in the critical hours after any significant event in the US (Wald et al., 2020). It is intended to provide users with broad, additional aggregated loss estimates based on FEMA's more detailed, more spatially rich HAZUS loss models and building databases while they wait for ground-truth observations, and it is not intended to replace the initial PAGER alerting system.

1.3.2 QLARM

EarthQuake Loss Assessment for Response and Mitigation (QLARM) is another powerful software that can be used globally to estimate building damage, injuries, and fatalities (Figure 1.6)(Erdik et al., 2011). The International Centre for Earth Simulation (ICES) has been operating the QLARM system 24/7 since 2003 (Wyss, 2017), and has estimated the extent of earthquake disasters within less than 1 hour for about 1200 earthquakes worldwide (Rosset et al., 2020). The QLARM report can be communicated to anyone subscribing to the service, on average arriving 30 minutes after an event greater than M_w 5.9 and close to human settlements (Wyss et al., 2018).

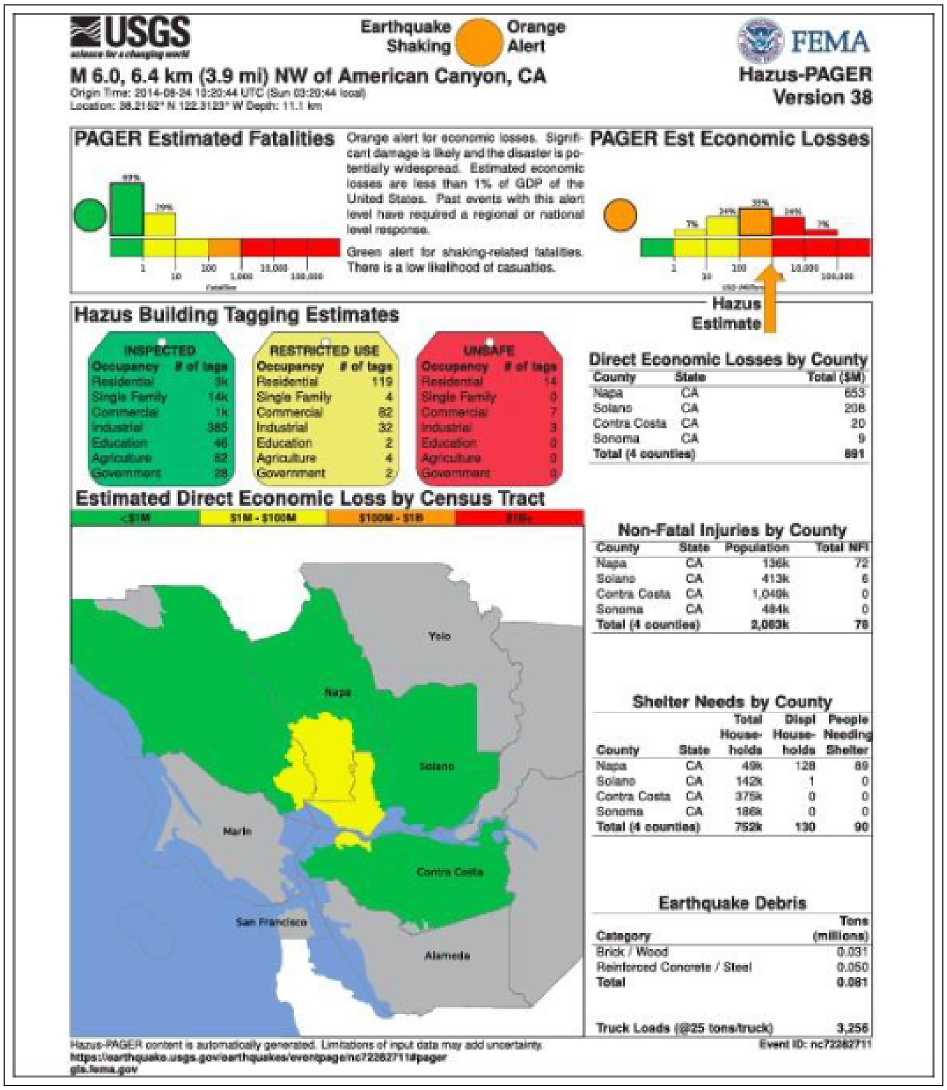


Figure 1.5: Sample TwoPAGER second page output for the M6 Napa Valley, California, earthquake in 2016. The first page of TwoPAGER will be identical to the PAGER report. The second page provides more details. The top-right section depicts economic losses from PAGER/HAZUS estimates. The lower portion has estimated financial loss, building tagging, debris, shelter needs, and the number of injuries from HAZUS (Wald et al., 2020).

Source parameters are derived from GeoForschungsZentrum (German Research Centre for Geoscience) and the USGS (Wyss, 2017). The ground-shaking intensity is estimated based on the event's magnitude, epicentre and depth using global and regional GMPEs. Soil amplification is also considered and calculated using local data to derive an amplification factor for each discrete city model, or using global data on Vs30 values, which refers to the average shear-wave velocity in the upper 30 meters of the Earth's crust (Wald and Allen, 2007), derived from topographic slopes (Wald and Allen, 2007; Erdik et al., 2011).

QLARM Loss Estimation Method

QLARM requires several data sets: (1) up-to-date population numbers; (2) distribution of buildings into EMS-98 (Grünthal, 1998) classes; (3) distribution of the population in buildings of these classes; (4) fragility curves for building resistance to strong ground motions; (5) occupancy rates for different periods of the day (Rosset et al., 2020). QLARM estimates the expected building damage using intensity-based vulnerability models calibrated from over 1,000 past seismic events, which includes records spanning over several centuries incorporating written sources prior to the instrumental period (before 1900), in which actual impact and losses are reported (Wyss et al., 2018; Guérin-Marthe et al., 2021; Grünthal, 1998). Distributions of building stock and population are assigned to city models. Point city models are applied for cases where only summary data for the entire city are available. Discrete city models are used where data regarding city sub-divisions or districts are available (Guérin-Marthe et al., 2021). QLARM has about 2 million settlements in its database, with profiles of the building fragility of each settlement. The population database is derived from national census data and online sources, such as World Gazetteer, Geonames, and National Geographical Intelligence Agency (NGA) (Erdik et al., 2011; Wyss, 2014). Population distribution at the time of the event is also considered in the model.

QLARM uses the European Macroseismic scale (EMS) proposed by Giovinazzi et al. (2006) to calculate the building damages. The system adopts the vulnerability models relevant to EMS 98 vulnerability classes (Grünthal, 1998). The EMS 98 vulnerability model estimates potential damage based on a given intensity (Grünthal, 1998). The EMS 98 damage description is discrete, meaning it has a finite number of

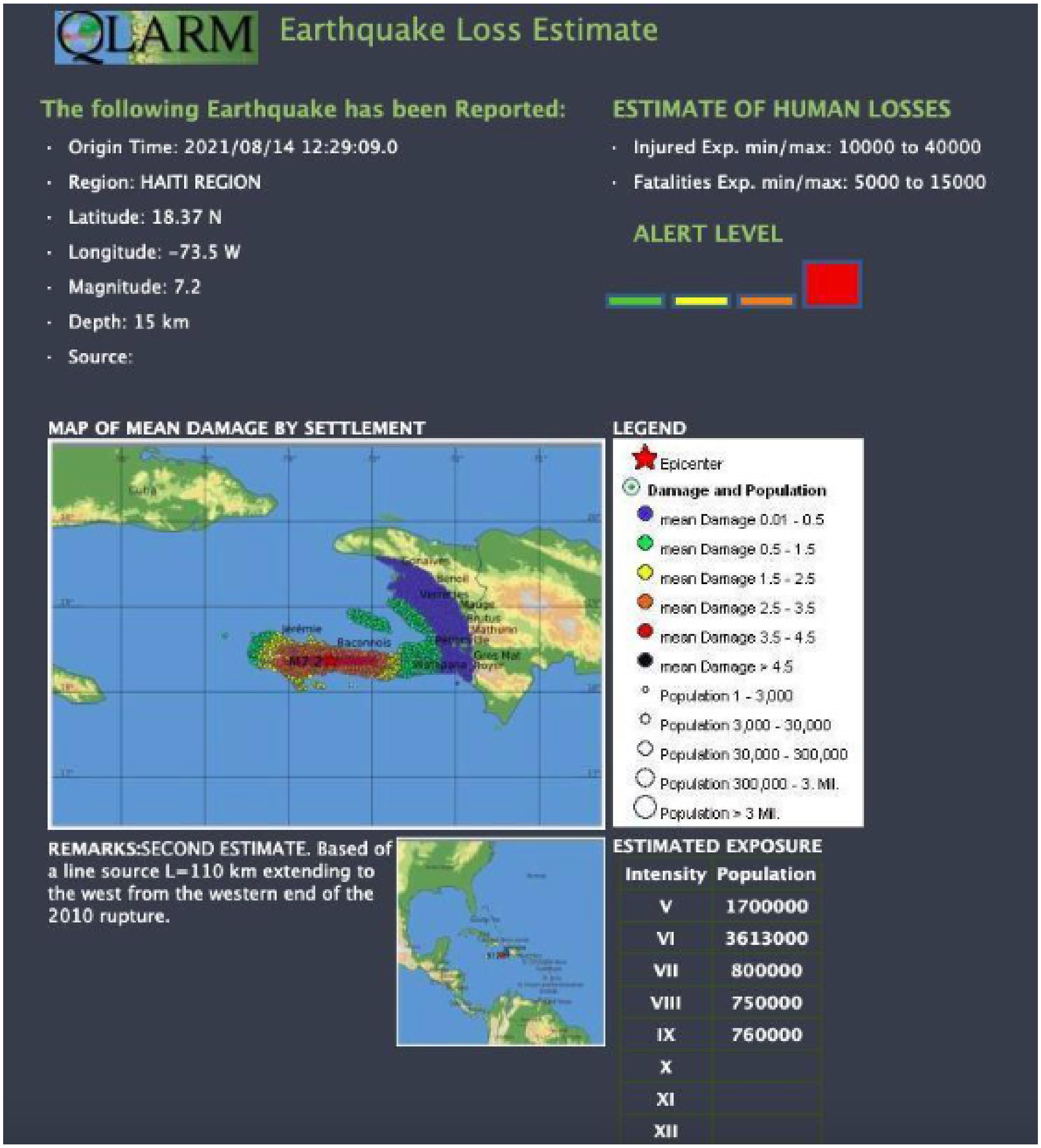


Figure 1.6: QLARM Earthquake Loss Estimate for the August 14th, 2021, M_w 7.2 Haiti event (ICES foundation, nd). Expected damage is computed for each vulnerability class of existing buildings. Mean damage is determined accounting for the proportion of each vulnerability class present in the area ranging from 0 to 5 (Wyss et al., 2018).

possible outcomes and considers six damage grades (no damage, slight damage, moderate damage, heavy damage, very heavy damage, destruction) in six vulnerability classes (Lagomarsino and Giovinazzi, 2006; Wyss et al., 2018).

The human loss estimation model is based on the work of Stojanovski and Dong (1994), whose casualty model applies an event-tree structure to represent different scenarios and their associated probabilities. Each tree branch represents a possible sequence of events leading to casualties, with probabilities assigned to each branch based on historical data or expert judgment (Erdik et al., 2011).

The outcome of QLARM includes the expected percentage of buildings in each of the six damage states in each settlement, the mean damage state in each settlement, and the number of fatalities and injuries, with error estimates, in each settlement (Erdik et al., 2011).

1.4 Earthquake Hazard and Risk in Canada

1.4.1 Seismic Hazard in Canada

Although the numbers of past deaths and injuries from seismic events have been minimal in Canadian history, Canada is a seismically active country (Figure 1.7) (Lamontagne et al., 2007). Seismologists at Natural Resources Canada detect approximately 4,000 earthquakes each year in Canada (Cassidy et al., 2010). At least four significant seismic events have exceeded M_w 8, including the massive 'megathrust' Cascadia event that occurred in 1700, while 17 events between M_w 7 and 8 have occurred since 1600 (Lamontagne et al., 2007). With a relatively short history since European settlement, there have not been many written records of major earthquakes that caused significant societal disruption in Canada compared to other nations. The simplified fifth-generation national seismic hazard map, however, highlights the likelihood of intense shaking (e.g. Figure 1.8). In regions with the highest hazard levels, like coastal British Columbia (BC), parts of Yukon territory, and a small part of Quebec near Charlevoix and Rivière-du-Loup area, there is a 30% probability of experiencing strong enough shaking to cause significant damage over a 50-year period

(Figure 1.8)(Natural Resources Canada, 2021). The probability is less than 1 percent over 50 years for the areas with the lowest hazard levels, and in the regions with moderate hazard levels, there is approximately a 5 to 15 percent chance of shaking intense enough to cause significant damage (Natural Resources Canada, 2021).

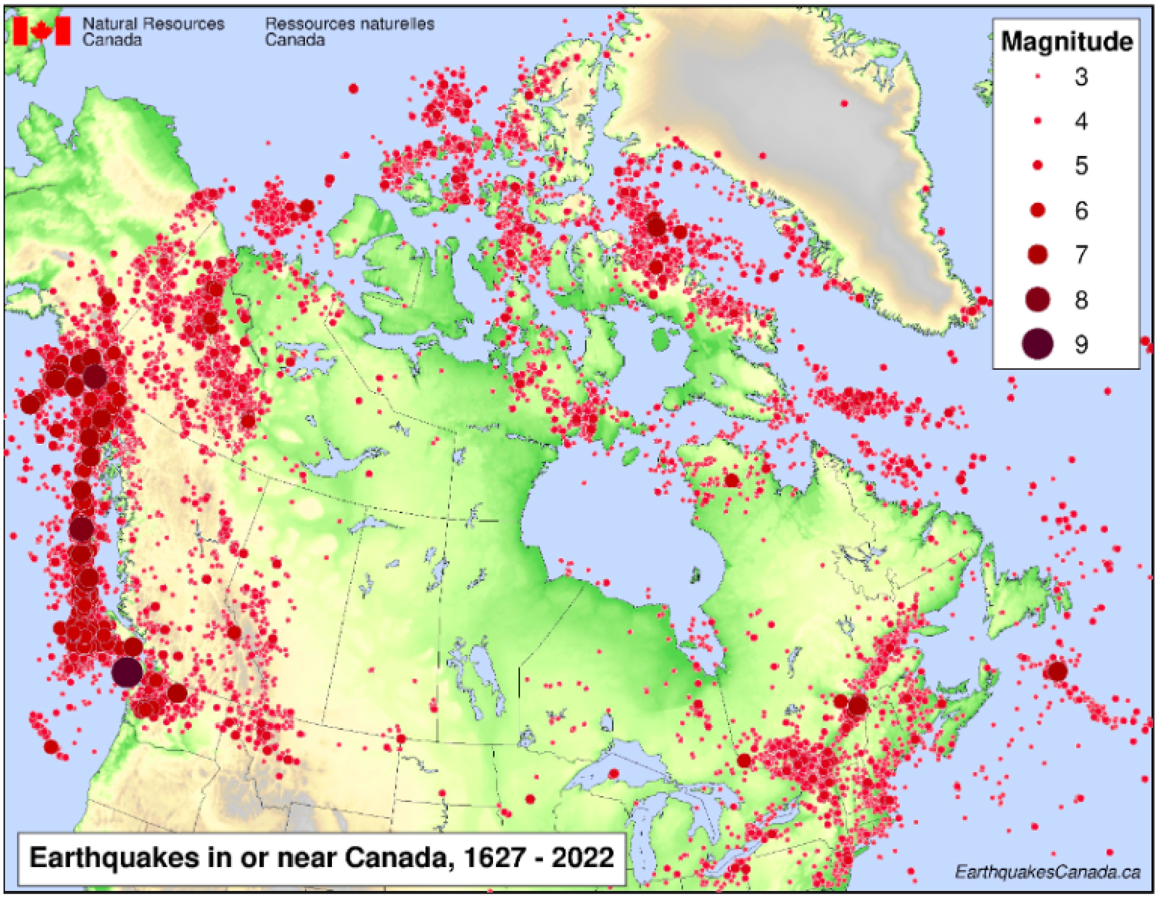


Figure 1.7: Seismicity map indicating the locations and magnitudes of historical earthquakes that occurred in or near Canada from 1627 to 2022. Retrieved from `https://earthquakescanada.nrcan.gc.ca/historic-historique/caneqmap-en.php`. Last accessed date: 2024-02-29.

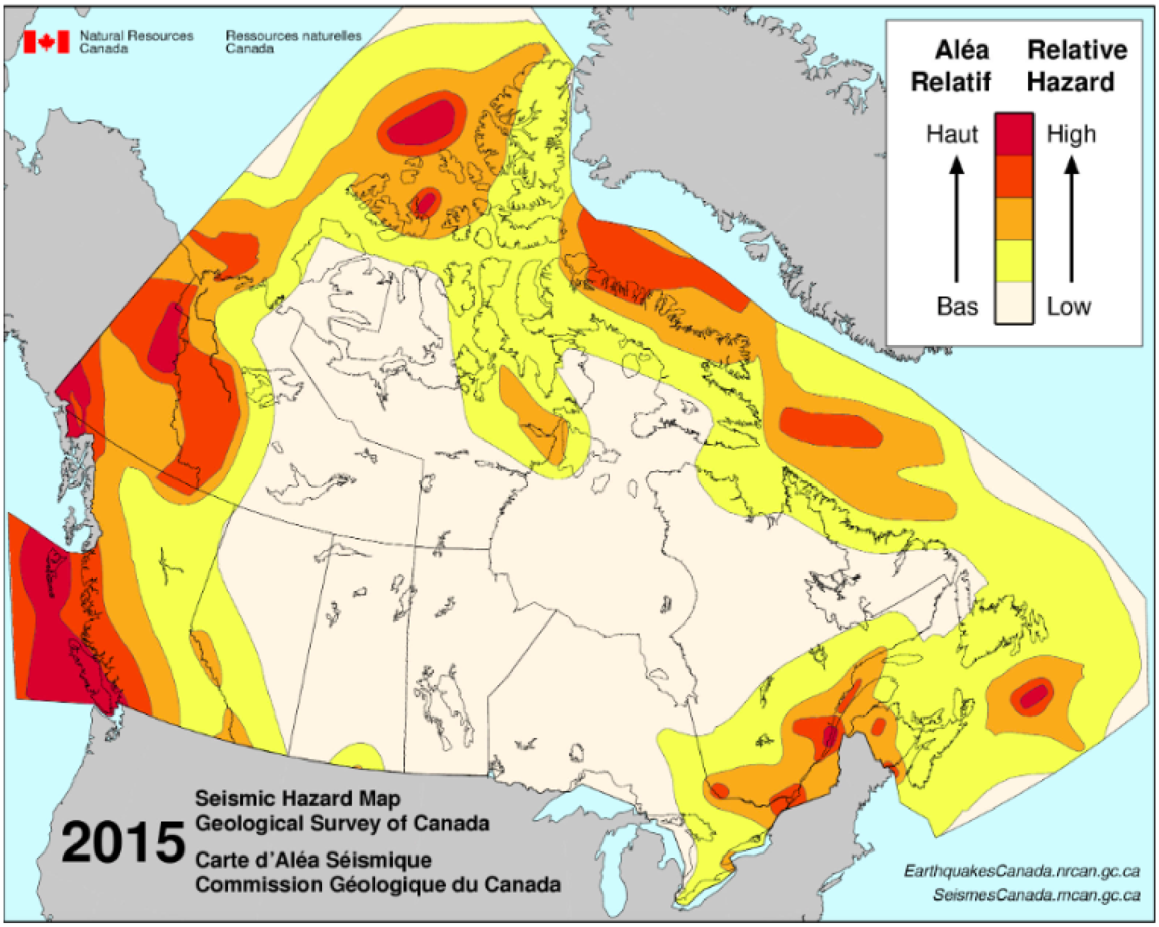


Figure 1.8: Simplified national seismic hazard map for spectral acceleration at a 0.2-second period (Natural Resources Canada, 2021). It shows the relative probability, in a 50-year time period, of ground motions exceeding a level likely to damage one- to two-storey buildings. Although the 2020 national seismic hazard maps have been released, simplified hazard maps have not been made available. Thus, the 2015 simplified national hazard map is utilized here for enhanced hazard communication purposes.

Parts of BC are exposed to the highest hazard level due to their proximity to active plate boundaries, including the Cascadia Subduction Zone (CSZ), where the Juan de Fuca plate subducts northeastward below the North American plate, and the Queen Charlotte Fault along the west coast of Haida Gwaii, a transpressional boundary between the North American and Pacific Plates. Offshore sediment cores from the CSZ margin show evidence of 19 earthquakes that ruptured the full length of the plate boundary megathrust fault from Vancouver Island, BC, to northern California since 10,000 years ago (Goldfinger et al., 2012). The evidence indicates the average recurrence interval for full-margin paleoseismic events (900–1,100 km in rupture length) is ∼500–530 years, with a variance ranging from ∼200 to 1,200 years; smaller events at the CSZ have shorter recurrence intervals of 220–240 years (Goldfinger et al., 2012). The most recent event occurred on January 26th at 9:00 pm Pacific Time in A.D. 1700 Goldfinger et al. (2003), involving a M_w∼9 full-length Cascadia megathrust rupture with an estimated average fault slip of ∼19 m (Satake et al., 2003; Priest et al., 2017). It is possible to estimate the CSZ's time-dependent probability of occurrence based on the timing of the last subduction earthquake (Seemann et al., 2011). Combining all CSZ, crustal and intraslab earthquake sources increases the hazard probability in BC, such that strong shaking can be expected far more often than every 500 years. For instance, for the City of Victoria in the year 2010, the probability of experiencing damaging shaking was estimated at 30% in 50 years and 48% in 100 years (Seemann et al., 2011), and the probability will keep increasing over time until the next CSZ event (Seemann et al., 2011).

Another relatively recent finding that could indicate a greater likelihood of significant damage to the Victoria region is the crustal Leech River Fault. The work of Morell et al. (2018) revealed that the Leech River Fault on southern Vancouver Island has produced three large surface-rupturing earthquakes in the last ∼9,000 years, indicating its capacity to host earthquakes that are larger than M_w 6 in the future. Furthermore, two of the paleoseismic events on the Leech River fault have estimated ages that overlap with those determined for Holocene earthquakes on the Devils Mountain fault, along strike to the east (Personius et al., 2014). This suggests a potential earthquake rupture length up to approximately 100 kilometres, increasing the potential magnitude of future events to M_w 7 (Harrichhausen et al., 2021). This finding was added to the new sixth-generation national hazard model, further increasing the estimated hazard in the area (Adams et al., 2019).

The most recent onshore active fault discovery in southwest BC is the X̲EOLX̲ELEꝀ-Elk Lake fault located 10 km north of downtown Victoria, BC (Figure 1.9). Paleoseismic evidence shows that the fault hosted a M_w 6.1–7.6 event between ∼4,700 and 2,300 years ago (Harrichhausen et al., 2023). This conclusion will potentially increase the assessed hazard level in the area further.

These are some notable examples of recent findings in the region; not all active faults are easy to discover or study, however. This makes it challenging for emergency managers and other stakeholders to prepare for unanticipated seismic events, suggesting the importance of developing a Canadian damage assessment tool, which utilizes real-time strong motion data. Moreover, it's essential to recognize that discovering new faults doesn't alter the current building inventories or structures, which remain the primary cause of injuries and fatalities during earthquakes. While seismic hazard awareness is important, it's equally crucial to understand the fundamental risk posed by the built environment in order to mitigate seismic risk.

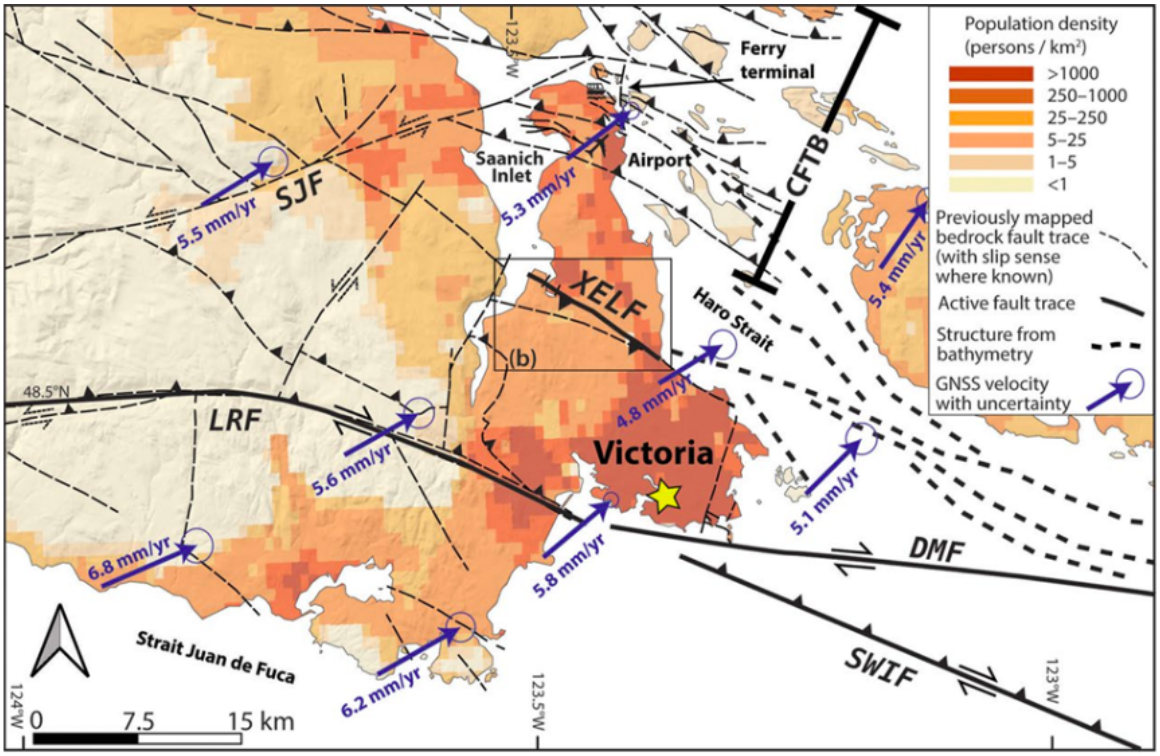


Figure 1.9: Map of southern Vancouver Island showing the location of active faults and potentially active faults including Leech River Fault (LRF), San Juan Fault (SJF), Southern Whidbey Island Fault (SWIF), Devils Mountain Fault (DMF), Cowichan Fold and Thrust Belt (CFTB), and the newly discovered XEOLXELEK Elk Lake fault(XELF) (Harrichhausen et al., 2023).

1.4.2 Seismic Risk in Canada

The seismic risk can be expressed qualitatively as:

Seismic Risk = Seismic Hazard × Exposure x Vulnerability

Risk pertains to the potential losses incurred when a hazard occurs, and it can be quantified in terms of monetary value or the number of fatalities (Figure 1.10) (Wang, 2009). For example, as seen in the national seismic hazard map in Figure 1.8, the areas of Ontario and Quebec have lower hazards than BC; due to its high vulnerability (e.g., older historic buildings, high social vulnerability), however, the City of Montreal has higher seismic risk than the City of Vancouver (Hobbs et al., 2023b). Toronto, often regarded as having relatively low seismic hazard, emerges as one of the top ten riskiest cities in Canada for earthquakes, with the physical factors of risk (hazard, exposure, and vulnerability) being amplified by social vulnerability (limited capacities to withstand and recover from future disasters) (Hobbs et al., 2023b).

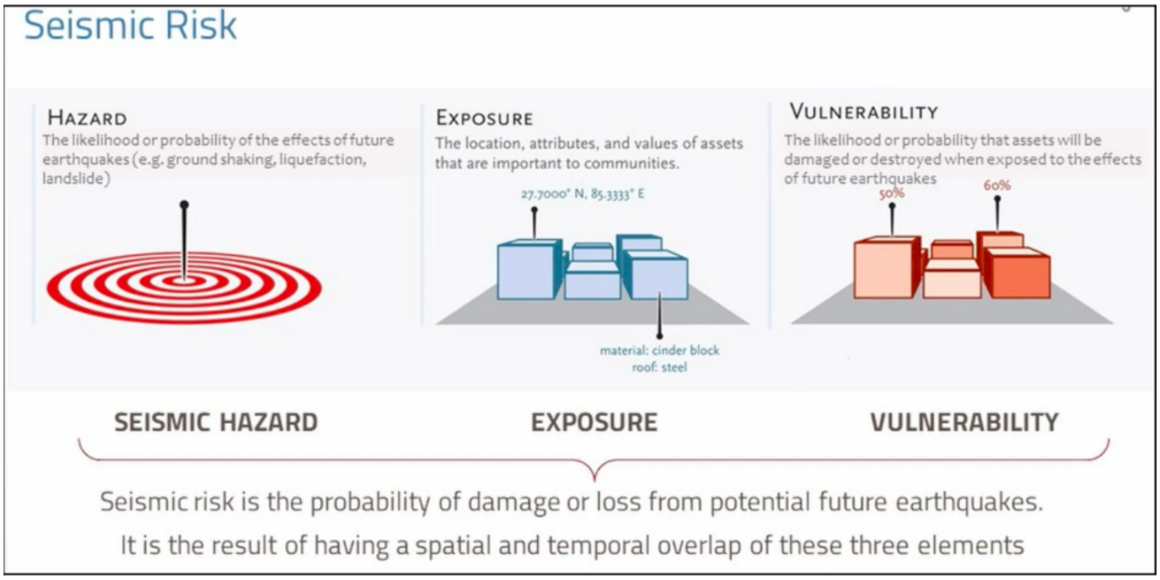


Figure 1.10: Description of seismic risk (Global Earthquake Model Foundation, 2020)

1.4.3 Strong Motions Monitoring Systems in Canada

A dense strong motion seismic monitoring network is a foundation for understanding hazard and being able to respond to large seismic events in the future and developing accurate ShakeMaps. Natural Resources Canada (NRCan) has been operating the Canadian National Seismograph Network (CNSN) since the first deployment of accelerometers in 1963 (Cassidy et al., 2024)(Figure 1.11). In 2019, the largest ever CNSN upgrade was completed, increasing the number of strong motion instruments by ∼40% to a total of nearly 750 (Cassidy et al., 2024). Substantial improvement of strong motion instrumentation was initiated with the National Earthquake Early Warning (EEW) system deployment, slated to be operational in BC by spring 2024 and in Ontario and Quebec in autumn 2024, harnessing the technology of Nanometrics Titan and Güralp Fortimus accelerometers (Cassidy et al., 2024). As of December 2023, a total of 212 strong motion EEW devices have been installed, spaced approximately 20 kilometres apart in most high-risk areas (Cassidy et al., 2024; Bird et al.,

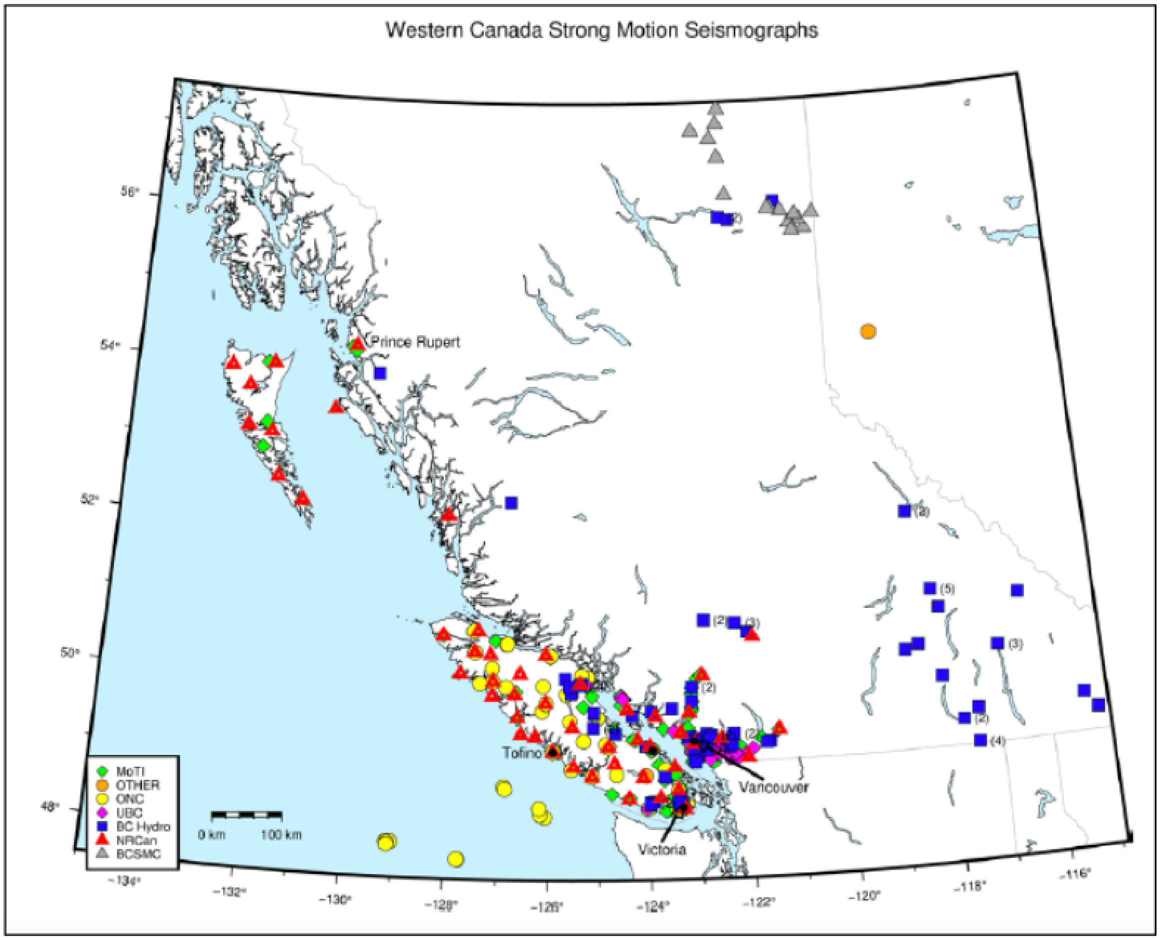


Figure 1.11: Locations of strong motion seismographs in BC (Cassidy et al., 2024). These strong motion seismographs are operated by the Ministry of Transportation (MoTI), Ocean Networks Canada (ONC), University of British Columbia (UBC), Natural Resources Canada (NRCan), and the British Columbia Seismic Monitoring Consortium (BCSMC).

2023)(Figure 1.12). The data from the strong motion networks will be used to understand ground motions better; this is key to enabling the generation of more accurate and reliable ShakeMaps (Cassidy et al., 2019) to serve as a basis for rapid damage modelling, as described.

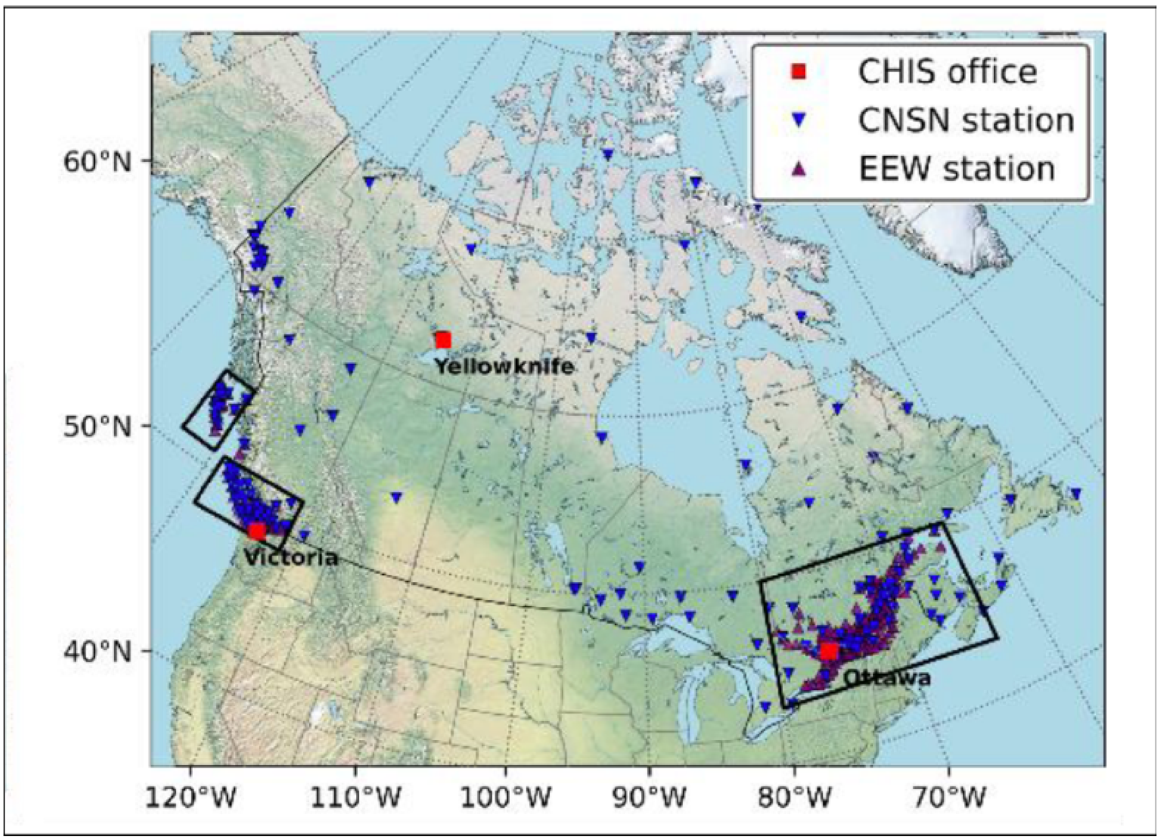


Figure 1.12: The Canadian National Seismograph Network (CNSN) and the Earthquake Early Warning (EEW) networks, which will serve as the source of data for generating ShakeMaps (Crane et al., 2023).

1.5 Canadian Rapid Earthquake Damage Estimation (RED-E) Model

1.5.1 The 2020 Rapid Disaster Modelling Pilot Project in BC

The GSC partnered with the BC Ministry of Transportation and Infrastructure (MOTI), the Canadian Hazards Information Service (CHIS), and Emergency Management BC (EMBC, currently known as Emergency Management and Climate Readiness) to work on a pilot program for rapid post earthquake damage estimation (Hobbs et al., 2020). It was envisaged that such results could be communicated through the Common Operating Picture (COP) Portal, BC's authoritative source for disaster information.

The aim of the pilot system and its successor, known as rapid disaster modelling, was to deliver maps of earthquake shaking intensity and estimated losses to emergency managers within tens of minutes of an event. The triggering thresholds are anticipated to be consistent with EEW notifications. Several steps need to be taken to generate rapid damage modelling. This section outlines the steps from the 2020 proof of concept, which closely resemble the plans for a future Rapid Earthquake Damage Estimator (RED-E) tool. The tool is scheduled to be operational in the next few years, following the implementation of the findings presented in this thesis.

ShakeMap Creation

ShakeMaps (Figure 1.13) are produced using interpolated observations from the local seismic monitoring networks and the most appropriate GMPE for the region (BC Smart Infrastructure Monitoring System, 2022). The RED-E system will utilize the ShakeMap output produced by the EEW strong motion network, which employs a USGS software suite to estimate ground intensities (Crane et al., 2023). Local site effects are considered using the local shear wave velocity (Vs30) values. Calculated

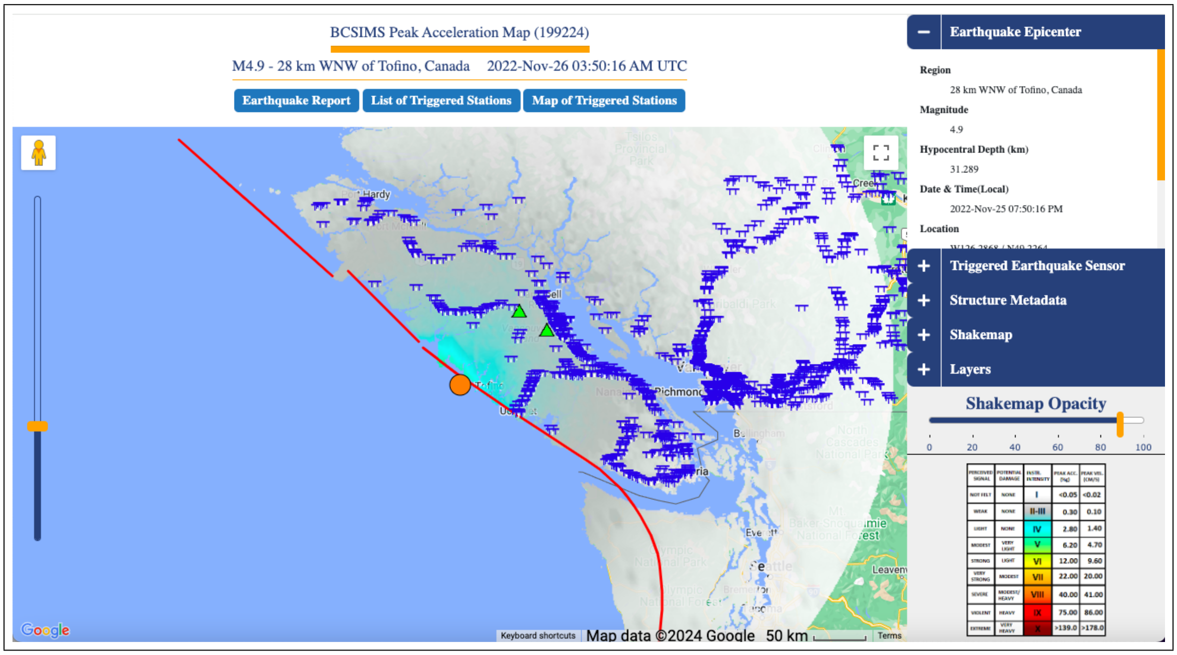


Figure 1.13: An example of a ShakeMap from MOTI/BCSIMS (BC Smart Infrastructure Monitoring System, 2022). This ShakeMap was generated for the M_w 4.9 event that occurred on November 26th, 2022, in the Tofino region. It displays the magnitude, location, date and time, and the resulting shaking intensity in the Modified Mercalli intensity scale, and users can add several layers of critical infrastructure such as schools, hospitals, and bridges, and other information .

outcomes in the form of Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Spectral Acceleration (SA) at different periods are communicated to the BC Smart Infrastructure Monitoring System (BCSIMS) website within about 10-15 minutes (Hobbs et al., 2020), and for RED-E, the similar information will be disseminated by NRCan.

Risk Assessment

In order to estimate loss and damages from the ShakeMap data, the pilot rapid damage modelling system used the OpenQuake (OQ) engine to analyze risk (Hobbs et al., 2020), and the currently developed RED-E system will apply the same software. A routinely used national inventory and a standard set of fragility and vulnerability functions are already available from NRCan to use within OQ (Hobbs et al., 2023a,b). After preparing all the necessary data, the OQ engine estimates the possible damage levels in building structures in the exposure dataset and other impacts, such as economic losses and fatalities. This risk analysis takes about 3-4 minutes, and it generates several text files to be transmitted to GitHub (Hobbs et al., 2020).

Data Architecture

As the GitHub repository receives the text file, automated scripts will transform the raw earthquake model results into information that can be integrated into a Geospatial Information System (GIS) format. The underlying data from the raw model results will be validated through the systems of Python, Structured Query Language, and PostGIS. The systems will generate Sendai indicator (Afrose, 2017) views and index the data into an Application Programming Interface (API) service. The results are pre-formatted with spatial inquiries, which helps users to retrieve spatially relevant data efficiently, using the Representational State Transfer (REST). After this process, users can access the data via API or GitHub (Hobbs et al., 2020). On GitHub, files are available as GeoJSON, which is a format for encoding a variety of geographic data structures, and as GeoPackage representations - an open, standards-based, platform-independent, portable, self-describing, compact format for transferring geospatial information. API services adopted for the rapid damage modelling are aligned to industry standards and apply caching (the process of storing copies of files in a cache or temporary storage location so that they can be accessed more quickly) for low latency (Hobbs et al., 2020). Figure 1.14 shows a sample loss estimation generated using the process mentioned above.

Currently, two federal seismologists are on call at all times in Canada to respond to earthquakes exceeding M_w 4 across the country. These seismologists could initiate the process of rapid damage modelling using a Jupyter Notebook interface (Hobbs et al., 2020).

Dissemination of Results

The last step is the broadcasting of the results to the intended users who could apply this information. In 2020, the outputs were hypothetically transmitted to GeoBC's

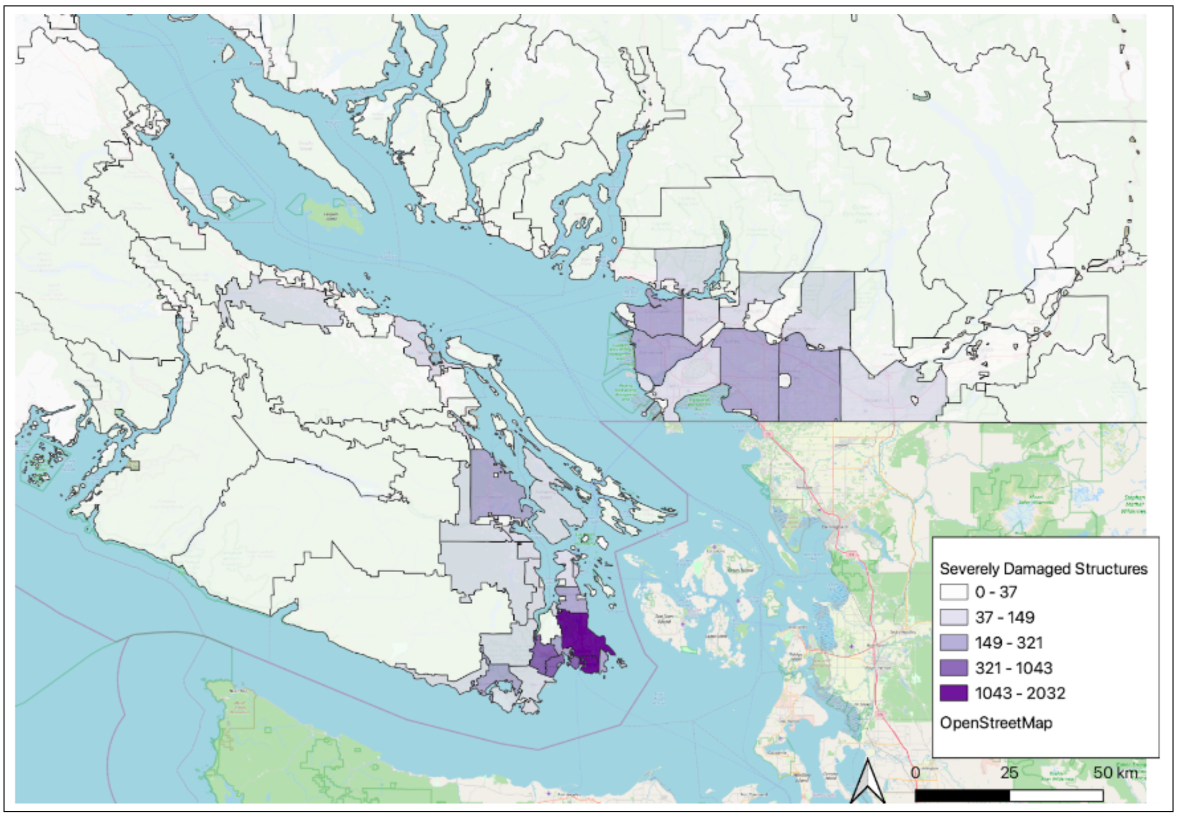


Figure 1.14: A sample output of losses, calculated using the OQ engine and displayed in GIS format. The map showcases the estimated number and locations of severely damaged structures in the southwestern BC region using an M_w 7.3 complete rupture of the Leech River fault scenario.

online situational awareness platform (COP). The COP is an authoritative source of information during a disaster in BC and is used strictly by the province's emergency operations workforce. GeoBC can choose to extract the entire suite of indicators or a subset of the most relevant indicators for the event in question, such as areas with a high likelihood of entrapment requiring extrication, the estimated number of casualties requiring hospitalization, number of displaced people, and direct economic impacts from the event. The data can be displayed as a simplified dashboard with information and maps, where users can choose to overlay critical infrastructure or jurisdictional information (Hobbs et al., 2020).

Next Steps

NRCan is now advancing the proof of concept to a more widely applicable product by utilizing the near real-time seismic data from the strong motion networks used by EEW, ensuring that end-user needs are considered regarding what information will be provided, and in what format(s). Giovinazzi et al. (2006) point out that as valuable as a rapid damage modelling system might be, if the system is not immediately usable or comprehensive to end-users, its value will be quickly forgotten or dismissed. Thus, it is critical to involve insights from the end-users early in the development of the tool to ensure the system becomes "applicable applied research."

1.6 Motivation for a Canadian rapid risk modelling system

Canada is a seismically active region, and the consequences of future significant seismic events are estimated to be economically and socially devastating (Hobbs et al., 2023b). The first generation of the Canadian Seismic Risk Model identifies that the national 500-year economic losses have the potential to exceed the capacities of the insurance sector to absorb expected financial consequences (Hobbs et al., 2023b). Many small to large communities are identified as at high risk, based on compounding factors of physical and social dimensions of vulnerabilities (Hobbs et al., 2023b).

Granted, it is critical to proactively prepare and mitigate risk for forthcoming seismic events in Canada; it is important to assess the need for a Canada-specific loss-modelling system, when other global systems already exist, as described earlier in this chapter.

The QLARM and PAGER systems are among the longest-standing systems operating globally that can communicate the scale of global seismic events in tens of minutes. Their cumulative experience as a global rapid loss estimation system allows for validation and calibration of the model outputs with ground-truth data more frequently, strengthening their capacity. Additionally, USGS has the capacity to estimate the potential extent and exposure of the population to secondary hazards such as liquefaction and landslides. Although it is not a part of the PAGER product, it is one of the rapidly produced USGS products. However, it should be noted that it does not include any fatalities/economic loss calculations derived from secondary hazards.

The limited availability of Canadian seismic events/datasets can pose some challenges to estimating and validating the model outputs of a new Canadian system, and one might consider that using the PAGER product would be more beneficial. It is certainly valuable for Canada to use the output of PAGER to grasp the scale at a glance. As explained in the "PAGER: Methodology" section, the PAGER system will likely rely on the analytical approach for future events in Canada since Canada lacks empirical data and has robust building code implementation and inventory data for the estimation of losses based on exposure data and fragility/vulnerability functions.

However, the PAGER system is not a stand-alone/open-source product that is adaptable or modifiable to customize to Canadian needs. A Canadian system (as described in the next section) can integrate more detailed data to increase accuracy. For example, such a system could consider social vulnerability layers, scale down to local perspectives, update population census and building inventory data, and add soil amplification factors from micro-zonation work. The PAGER system serves its purpose as a product that can rapidly communicate the impact scale; however, PAGER cannot provide a local Canadian perspective to end-users with other important details such as smaller geographical scales, numbers of displaced people, and various levels of injuries, which could be significantly and more directly valuable for emergency response purposes.

Furthermore, while Canada utilizes USGS's ShakeMap and EEW softwares to produce comparable products, adopting USGS's PAGER system for Canada would not be more practical. Canada has already made substantial devotion and investments in developing its own comprehensive and in-depth risk model using the OpenQuake Engine, which has been publicly accessible on RiskProfiler.ca since 2023. By incorporating near real-time seismic parameters, modelling outputs can be easily generated to help end-users. Failing to leverage this valuable, sophisticated, and regionally appropriate product would be a lost opportunity.

Unlike the application of the PAGER system, the Canadian system described in the next section (RED-E) allows the inclusion and update of data specific to Canada, using more updated and detailed building exposure information that is not employed by the other global systems (Journeay et al., 2022). The system will apply Canadian-specific fragility and vulnerability curves to estimate building damage, reflecting Canadian building codes and inferred construction trends advised by experts (Hobbs et al., 2023a). Generally, other global damage modelling systems only present maps for hazard threats (maps of the population exposed to different levels of shaking). However, as described later the RED-E system is capable of calculating and generating detailed, small-scale (as small as neighbourhood level) maps of anticipated shaking, structural damage, injuries, potential fatalities, displaced populations, and financial loss, which can add more value to the end users.

1.6.1 Foreseeable Limitations of the Rapid Disaster Modelling

Advancement in the realm of rapid damage modelling has been impressive. There are, however, some noteworthy points to emphasize. Because many rapid damage modelling systems use ShakeMaps as a foundation, it is critical to determine the distribution of shaking intensity as accurately as possible; it is currently difficult, however, to estimate the faulting mechanism or fault dimensions right after rupture or during an extended earthquake rupture. Especially for large earthquakes with extended faulting mechanisms and fewer empirical data, accurate estimation is challenging, which can increase associated errors in the modelled loss and damages

(Guérin-Marthe et al., 2021). Another source of uncertainty can derive from the characterization of amplification factors. Most ShakeMaps systems are built on Wald and Allen's (2007) site characterization model based on topographic slope. To generate more accurate ShakeMaps, it is therefore necessary to apply regionally specific microzonation site maps, and locally suitable site conditions should be used wherever possible (Guérin-Marthe et al., 2021). The estimation of human impacts is often based on empirical data and is simple; due to its criticality, however, further research, such as the work done by Jaiswal and Wald (2012), should be conducted to reduce uncertainty (Guérin-Marthe et al., 2021).

1.7 Thesis Objectives and Outline

This thesis aims to characterize end-user needs in the immediate post-disaster phase following a large earthquake to improve the proof of concept further and contribute to the development of a serviceable RED-E system at a national scale. This study was conducted based on the User Centered Design (UCD) principle to optimize product usability and increase its effectiveness by accommodating user needs (Twomlow et al., 2022) (Figure 1.15). Chapter 1 has provided descriptions of post-disaster products to observe the scale of seismic impact, such as satellite imagery and usage of UAVs, and a literature review of globally available rapid damage modelling systems. It also introduced a past risk modelling pilot project in BC. Chapter 2 discusses the motivations for the Canadian Rapid Earthquake Damage Estimation (RED-E) system and the design and outcomes of the informational interviews conducted with potential users. Chapter 3 showcases wireframes that were developed based on the informational meeting results and summarizes feedback on the wireframes. Lastly, Chapter 4 offers a conclusion.

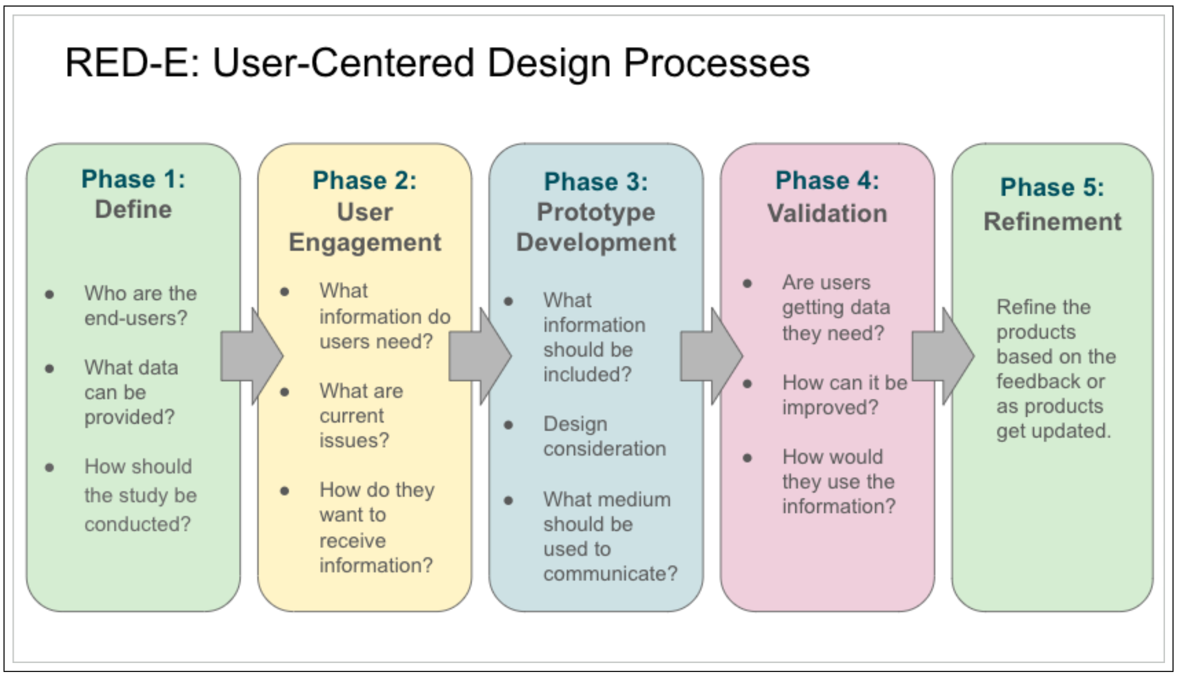


Figure 1.15: User-Centered Design (UCD) Framework (modified from Loos et al., 2024 and Marísa et al., 2023.)

Chapter 2

Characterizing the Needs and Decision Points of End-Users

2.1 Introduction

As discussed in Chapter 1, the first 24 to 48 hours after a major earthquake is the most critical period to save lives (de Bruycker et al., 1983; Noji et al., 1990; Coburn et al., 1992). Yet, available situational awareness information within the first 24 hours is minimal (Wald et al., 2008). Preliminary information on earthquake impacts can be collected by windshield/walking surveys, in which the surveyors conduct observations while driving or walking through the affected area, flyovers, dispatch calls and, to some extent, social media (Applied Technology Council, 2019), but such information is unlikely to be timely, complete and reliable. Having information immediately after the earthquake would allow decision-makers to prioritize the rescue effort and initiate planning for mass care for the displaced population more effectively.

The Geological Survey of Canada's proposed damage modelling system, the Rapid Earthquake Damage Estimation (RED-E, pronounced like "ready") tool, quantitatively estimates the probability of damage and impacts to buildings, people, and economic assets within tens of minutes following major earthquakes. The goal is to estimate the likely extent of damage in the region based on real seismological information immediately after a major earthquake, using pre-established risk assessment protocols. The assessment is not expected to be as accurate as a boots-on-the-ground inspection; the tool could, however, fill a critical gap in situational awareness in the first 48 hours post-event, before any aerial, vehicular, or on-foot reconnaissance can be performed. The RED-E system can model the damage extensively, covering large and remote areas that local support may not be able to access promptly. It can be used to model earthquake impacts and identify neighbourhoods most likely to have suffered building collapse, roadways blocked from debris, numbers of injured persons, or other major impacts almost instantly.

In order to make such a tool useful, there needs to be an understanding of users' needs, challenges, and priorities. Therefore, this study aims to use information gathered in interviews to characterize the needs of emergency managers and first responders after a major earthquake. This effort is part of a larger goal to involve stakeholders early and throughout the development of the RED-E product based on the UCD principle (Figure 1.15).

This chapter describes the envisioned RED-E tool as it was presented to stakeholders, as well as the questions asked of them. Anonymized stakeholders' responses are included, followed by a summary to characterize the most essential features of any future RED-E system as identified by the stakeholders.

Systems like RED-E could help with many of the goals of emergency managers and other decision-makers during the post-event response phase. For example, clear priorities during the rescue phase include ensuring the health and safety of responders, saving lives, reducing suffering, protecting public health, protecting infrastructure, and protecting property (Emergency Management BC (EMBC), 2022). Other priorities are to optimize the allocation of resources in order to maximize the benefit for the most significant number of people, and to stabilize situations. The RED-E tool is intended to allow end-users to operate more decisively and swiftly during the early stage of the response period.

2.2 Methodology

Specifically, Canada's RED-E tool will target response decision-makers: first responders, emergency managers, and CI operators. To gain insight into the needs of end-users in the first 24-48 hours following a major earthquake, this study conducted informational interviews with participants from different governmental and non-govenrmental organizations. The participants received an email requesting oral confirmation of consent, providing a brief description of the RED-E system, and requiring verbal consent to participate at the start of each session. Participants from each organisation answered 18 prepared questions during the 1-2 hour virtual meetings. The results of the informational meetings were anonymized and compiled into this report, which will be used to help optimize the future RED-E tool.

In some cases, the researchers followed up with participants afterward to clarify any salient points or to ask permission to reference the agency they work with by name. The study was designed to include participants from many regions across Canada by connecting through the virtual environment, and attention was paid to ensure there were respondents from fields of emergency preparedness, response, and CI. All questions allowed open-ended answers, and discussion between participants was permitted. The full list of questions and detailed answers are provided in the appendix.

Generally, the UCD approach involves five distinct phases (Interaction Design Foundation- IxDF, 2016) (Figure 1.15). The first phase involves defining the study and gaining an understanding of the context in which end-users may use a product, and then the second phase requires the developers/designers to uncover the users' requirements. The third phase involves the development of solutions, and the fourth phase requires the evaluation of proposed solutions, followed by the last phase, where final refinement of the product will occur based on the feedback from phase four (Interaction Design Foundation- IxDF, 2016). Under UCD practices, developers accommodate the characteristics and needs of a product's end-users (those who will eventually use a product) throughout the design process, rather than solely concentrating on the data/information being conveyed, considering their cognitive, affective, and behavioural points of view, as well as users' social, organizational, and cultural context (Twomlow et al., 2022). By following a UCD approach, thereby it increases the likelihood that products will be deemed useful, comprehensible, and user-friendly by the end-users and hence be adopted by them (Twomlow et al., 2022). Other UCD product development examples validate that UCD leads to more effective and successful products (Twomlow et al., 2022).

These interviews represent the second phase of the User-centered Design (UCD) process, necessary for developers to generate a complete picture of the end-users' real-world situation, to understand their needs, obligations, and the problem the product aims to address (Twomlow et al., 2022). This is the most time-consuming but important step in the process that informs the design process, enabling the development of the most effective products based on the users' perspective (Twomlow et al., 2022).

2.2.1 Respondents' Backgrounds

The study included 27 participants representing 12 organizations from the federal to municipal levels of government, 3 First Nations, 1 non-political organization, and 1 academic institution; more details are listed below.

- 13 participants represent local municipalities: 2 first responders and 11 emergency managers
- 6 participants represent First Nations and a non-political organization advocating for 31 First Nation communities
- 7 participants represent federal and provincial governments of the health, transportation, and housing sectors
- 1 participant represents an academic institution
- 4 participants represent government bodies from Eastern Canada
- 23 participants represent various levels of government and non-political organizations in Western Canada

2.2.2 Criteria for Respondents

A contact list was generated based on previous engagement work at the GSC, which included emergency managers at various levels of government in identified high seismic-risk regions. An approved letter by the University of British Columbia (UBC) ethics committee was sent out to 38 individuals by email to recruit participants for the study. Special attention was paid to small communities with high seismic risk identified by the Seismic Risk Model Index studies (Hobbs et al., 2023b). Not all smaller communities responded to their invitations, however. The study successfully involved some participants from the eastern region of Canada, where Hobbs et al. (2023b) and Goda et al. (2020) identified a higher than publicly appreciated seismic risk. Another area the study attempted to include is the Yukon territory; no emergency managers could be available, however, due to ongoing wildfire emergencies in the summer of 2023.

2.3 Interview Results

For clarity and brevity, responses are qualitatively grouped and summarized. 18 open-ended response questions were posed and allowed multiple answers, intended to probe for information and informed opinions useful for improving RED-E products. Only 13 questions directly relevant to developing the RED-E products are highlighted in this section to increase readability and to keep this thesis succinct; the full questions and responses are, however, available in Appendix A.

2.3.1 Q1: "How quickly do you expect to be able to deploy first responders after a major earthquake?"

Many respondents could not answer this question definitively since the response time depends on the time of day, size of events, epicentral locations, and individual circumstances (Figure 2.1). If emergency managers and first responders are not physically and mentally ready and their families or homes require aid, the public should not

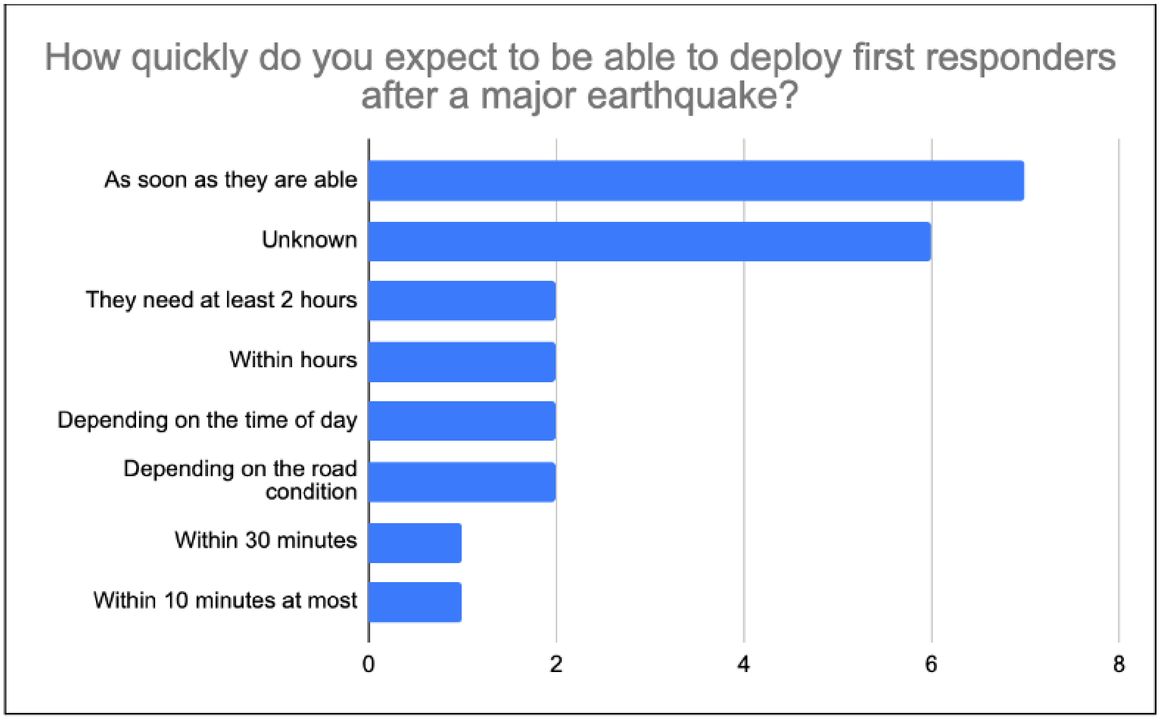


Figure 2.1: A summary of participants' answers to question "How quickly can you deploy after a major earthquake?".

expect help immediately. A few participants answered that if they were physically and mentally ready and their families were fine, they could be deployed in as little as 10 minutes.

2.3.2 Q2: "How do you gain situational awareness after a major earthquake?"

Most responses suggest that situational awareness will be developed based on surveys conducted on foot or by vehicles, 911 calls, and reports from fire halls (Figure 2.2). Respondents commented, however, that windshield/walking surveys and provincial rapid damage assessment tools, such as RDA, also known as Post-Disaster Building Assessment (PDBA) in BC or PDAT in Ontario, become challenging if roads are not drivable, and 911 calls can only work if telecommunication is still available and if lines are not overwhelmed. On-foot or vehicular patrols would take longer to collect data from broader regions, and once gathered, information needs to be relayed to headquarters via radio or other accessible telecommunications. In many smaller communities, officials still go door to door to check on residents. One municipality has electric bikes to carry out surveys, which could be effective when roads are inaccessible by larger vehicles. Few municipalities have local radio-equipped teams to develop situational awareness if other telecommunications are down. Many cities and hospitals gain information through people coming to the Emergency Operation Centres (EOCs) after they are set up, indicating a time lag in gaining situational awareness and an issue with spatial coverage. Security and traffic cameras could be helpful if connections are still viable, but respondents remarked that cameras might be unreliable since not all buildings have them and they rely on electrical connections.

Social media was mentioned several times, but many respondents expressed the following concerns. Social media could pose problems rather than solutions since it is challenging to validate the data, and people often ask for help but do not post subsequent updates to indicate whether or not they remain in need. One respondent referred to a case where the rescuers arrived at the location, but the person who asked for help was already ok. Drones were also mentioned, but their capacity is highly limited by the availability of technicians, equipment, restriction of aerial space near an emergency zone, and a potentially slow approval process.

By far, most emergency managers in all locations depend on first response teams to patrol, volunteer teams to conduct a Rapid Damage Assessment (RDA) (Bowles et al., 2019) for BC or Provincial Disaster Assessment Teams (PDAT) in Ontario, or calls/visits from the public to gain situational awareness; these processes can be time-consuming and incomplete even weeks after the event. All the above-mentioned methods would likely take longer than 24-48 hours to gain full situational awareness.

2.3.3 Q3: After an earthquake, what is the first thing you would do once you have reported for duty?

The primary responsibilities of emergency managers after a significant earthquake are setting up EOCs, contacting colleagues to gauge their capacities, and developing plans for rescue, evacuation, and shelter needs. First responders' responsibilities are to check in and report their status, report on fire hall conditions, deploy teams to

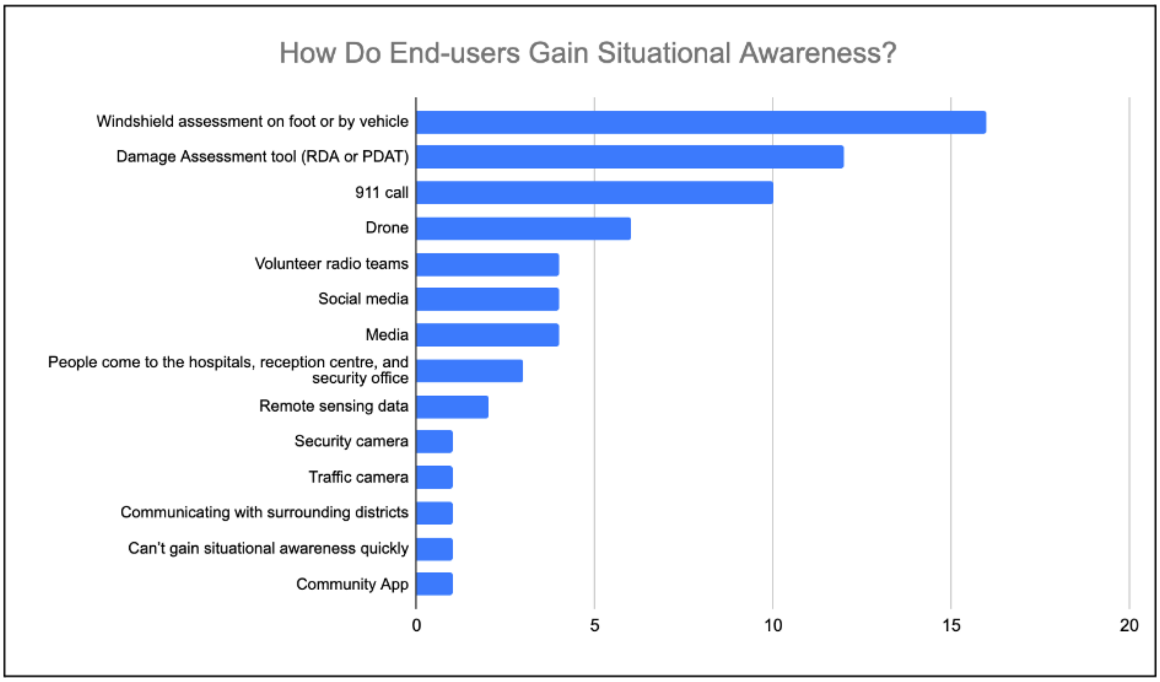


Figure 2.2: A summary of participants' answers to the question: "How do you gain situational awareness after a major earthquake?". RDA stands for Rapid Damage Assessment (RDA) in BC and PDAT stands for the Provincial Disaster Assessment Team (PDAT) in Ontario.

survey and dispatch the response teams based on 911 calls. They need to secure safe evacuation routes, and they must identify and prioritize where to survey first. As they deploy their teams, they need to protect the lives of rescuers first and then the public.

2.3.4 Q4: "Ideally, what information would you want in the first 24 hours after an earthquake?"

Universally, every respondent appreciated the information that the Canadian Hazards Information Services (CHIS, a part of NRCan) and RED-E can provide, such as the estimated earthquake size, rupture depth, epicentral location, shaking intensities in various locations, the time of the event, estimates of structural damage extent, and number of injuries or potential fatalities in the community. The discussions were held with the understanding that the above-mentioned information could be provided and respondents were asked what additional information could be useful for them.

Every interviewee wanted to know the expected road conditions and the areas of power and telecommunication outages (Figure 2.3). First responders are especially keen to know the locations with the greatest likely concentrations of victims, i.e., not the areas of most damaged, empty buildings, but those of damaged occupied buildings. The number of injuries and their locations are valuable for hospitals. The number of displaced people is critical for supporting shelter needs. The majority of participants stated the importance of telecommunication, transportation, and road conditions for developing situational awareness, resource transportation and allocation, and evacuation efforts. Bridges serve as bottlenecks, and their significance deepens for more remote communities where a bridge is the only connection to neighbouring communities. One First Nation community indicated that they have their canoes to cross the river if needed, signifying their resiliency. In many cases, however, first responders and emergency managers live outside the community they serve, and bridges and, similarly, highways in many communities serve as arteries; the condition of transportation corridors is something participants want to know immediately.

Knowledge of the habitability and functionality of structures, especially for critical infrastructure such as hospitals, is essential to plan shelter and facilitate operations.

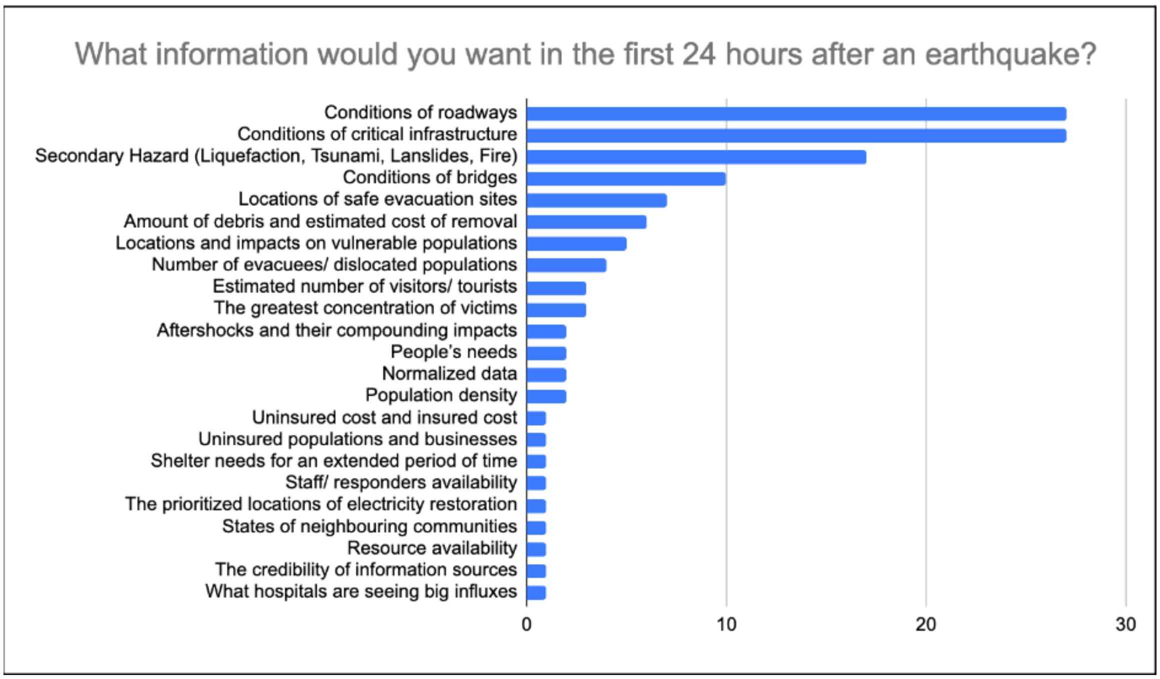


Figure 2.3: A summary of participants' answers to the question: "Ideally, what information would you want in the first 24 hours after an earthquake?" The information that RED-E is capable of providing at the time of the discussion is omitted, such as the estimated earthquake size, rupture depth, hypocentral location, shaking intensities in various locations, estimates of damage extent, and number of injuries or potential fatalities in the community.

The condition of natural gas lines, sewage lines, health clinics, fire halls, airports and ports is something end-users want to know immediately.

The location and extent of liquefaction and landslides, debris, and the cost of debris removal are also valuable information for them. The topic of tsunamis was brought up many times; some feel strongly about including the impacts of tsunami waves triggered by an earthquake. One person indicated it would "negate the tool's value if it does not include the tsunami impact". A few respondents hoped to gain information on aftershocks as they occur and wondered if the compounding impacts from aftershocks would be considered in the revised RED-E output; this can be extremely helpful information for them.

Additionally, many interviewees highlighted the importance of gaining information on the impact on vulnerable populations. A few respondents also wanted to know the estimated number of tourists since they can be considered vulnerable populations. Tourists/visitors are difficult to account for and not easy to reach with relevant information (e.g., warnings)(Bird et al., 2010) and they tend to be unfamiliar with the area with little connections to local communities (Becken and Hughey, 2013). For example, according to the most recent annual report of the Downtown Victoria Business Association 2023, for the city of Victoria, cruise ship passengers alone bring 700,000-970,000 visitors annually (Mauneau, 2023), and they will need to be sheltered temporarily until it is safe for them to leave again. There are many popular destinations in BC that host a large volume of tourists and these cities and townships need to consider the impact of the influx. Some information that is especially valuable for the Housing Ministry is the modelled number of uninsured, low-income people. The Ministry financially supports the uninsured population during sudden, unexpected, extraordinary (in a historical measure), widespread and expensive natural disasters. Having rapid access to the likely number of uninsured people impacted by a major earthquake can allow for an expedited approval process.

2.3.5 Q5: "How long does it take to gain complete and credible situational awareness?"

As mentioned earlier, the current way to identify the number and locations of injured people and the most impacted areas from a major seismic event is mainly from first responders travelling on foot or by vehicle, conducting a windshield/walking survey, and from dispatch calls (Figure 2.4). Some cities have conducted risk analyses, identifying the areas of high concentration of fragile structures with high population density to prioritize the area in advance, but the majority have not conducted such studies. With the current systems, it is difficult to determine the locations and approximate the number of injuries within 24-48 hours. Many respondents struggled to estimate how long it might take to develop complete and credible situational awareness because it depends on many factors, such as the time of the day, the size of the event, and location. Several respondents mentioned that if it happened during the day on a weekday while they were on duty, participants could respond immediately, but this will not be the case at night, while they are off-duty, and/or on weekends. If the event happens at night, there is an extra delay due to the need to wait for daylight to know what truly happened. Most respondents expressed that gaining credible and complete situational awareness will take at least three days to several weeks.

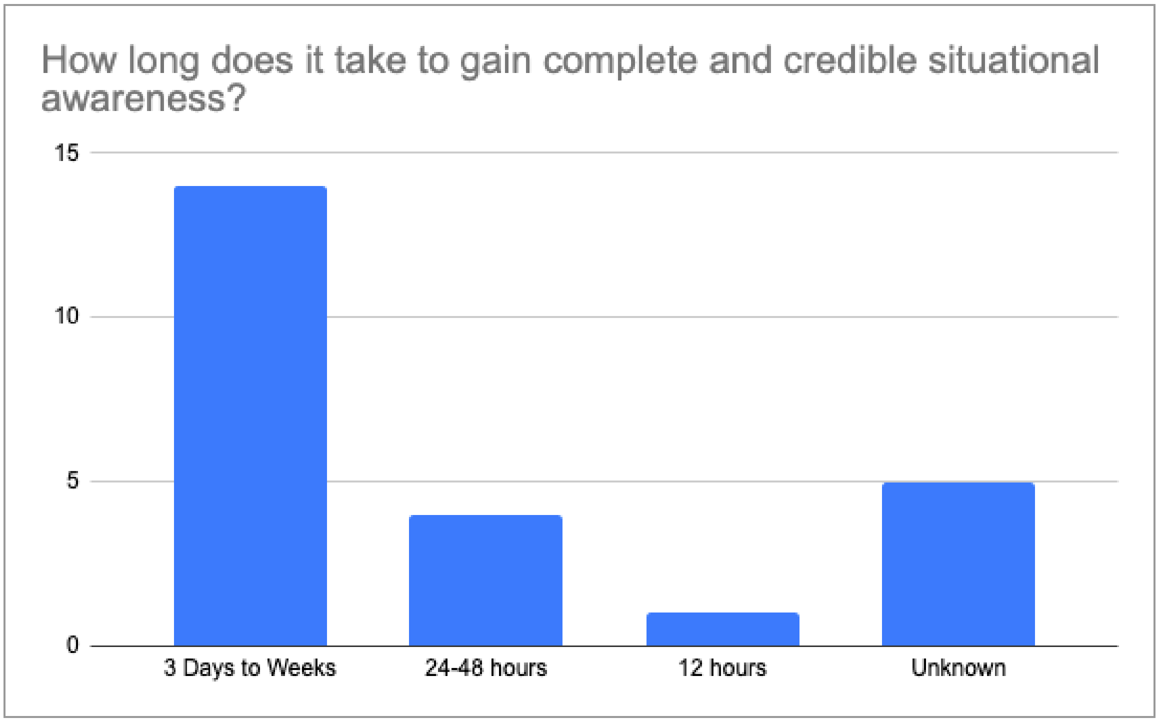


Figure 2.4: A summary of participants' answers to the question: "How long does it take to gain complete and credible situational awareness?".

2.3.6 Q6: "What are the current obstacles to gaining situational awareness quickly?"

Undrivable roads, highways, and bridges are identified as the top barriers to gaining situational awareness. The majority of respondents expressed that if roads are not drivable, it will be one of the biggest obstacles to gaining situational awareness. Especially for rural communities, where only a few roads are established, losing transportation means that situational awareness cannot be gained until the roads are drivable or external supports become available, which may take days to weeks. Some emergency managers, first responders, and other staff do not work within their community and need to drive into the community, adding to the complexity of the post-disaster situation. Some expressed that roads are outside of their jurisdiction, making it more challenging to monitor and repair.

Following transportation, the loss of telecommunication was identified as another significant barrier to developing situational awareness. It will cause a time lag in contacting the necessary staff and officials. For some communities, if they lose telecommunication, there is not much they can do other than drive to the communities to check on people. Only a few local governments have reliable teams of volunteers equipped with amateur radios. Not many communities are well prepared for telecommunication blackouts.

Some users mentioned the limited capacity issues of first responders even on regular days, expressing that too many 911 calls are on hold, waiting for longer than they should on normal duties, implying more difficulties of staff capacity immediately after a significant seismic event. Many communities lack the capacity to handle a large disaster, and there might be only one person reporting with the help of many volunteers, making it difficult to gain situational awareness quickly. Many described the lack of availability of trained staff, engineers and personnel to make crucial decisions.

Other identified barriers include damage to other critical infrastructure in addition to transportation, causing a lack of electricity, drinking water, and sewage services. A few people mentioned the rumour mill: validating/countering social media information/disinformation would be complex and time-consuming.

2.3.7 Q7: "Are the response teams deployed to the most disrupted areas or based on other prioritization systems?"

BC emergency managers and first responders prioritize rescue efforts based on British Columbia Emergency Management Systems (BCEMS) guidelines (Emergency Management BC (EMBC), 2022). In order, priorities are

1. to ensure the health and safety of responders
2. to save lives
3. to reduce suffering
4. to protect public health
5. to protect infrastructure, and

6. to protect property

Indeed, many emergency managers and first responders emphasized the importance of responders' safety; they are critical assets in times of emergency. Many mentioned that they might not always send responders to the most disrupted area, especially if the buildings are not full of people, but they prioritize if the area has the highest concentration of vulnerable populations to benefit the greater good. However, they need to ensure the safety of the responders. Vulnerability levels are a key factor in the planning of rescues. "People with rich resources and large backyards without tall buildings next to them will not be the first on the priority list." A few first responders mentioned that they try to optimize resources in order to serve the greatest possible number of people. To achieve this, they need to gain situational awareness to know where to distribute the limited resources. Additionally, stabilization of situations is also critical to protect the public. Many small communities do not have their own first responder capacity. According to one respondent, in reality, who will get external support may depend on how close the relationship is between who is deploying the responders and who is receiving the support, which diverges from the BCEMS guideline.

2.3.8 Q8: "How do you share collected data, and with whom do you share it?"

In response to the question above, participants indicated that information summarized from the windshield/walking survey or damage assessment would be shared with neighbouring municipalities and provinces through provincial calls or provincial GIS portal such as the COP. Calls led by the provincial governments will include important stakeholders, including impacted local governments and First Nations, as well as the electricity, transportation, and medical sectors.

2.3.9 Q9: "What information is needed to determine mass care needs and allocate supplies within the first 12 hours?"

Types of information that enable end-users to make decisions on resource allocation and mass care needs within the first 12 hours are: the extent of damage to CI, including road networks, bridges, power, water, gas, and sewage; the state of road accessibility to ensure evacuation routes or routes for first responders to reach impacted areas; the number of injuries and their locations; the number of displaced population and their locations; the number of impacted vulnerable populations; the number of tourists at the time (Figure 2.5). End-users also want to know how many people rely on medical equipment that needs power, their locations, and the number of people with other special needs, including the elderly with functional needs, the deaf and hard of hearing, the blind and sight impaired, and other physical disabilities. The locations of impacted areas with high concentrations of vulnerable populations, care homes, retirement homes, and schools would be valuable data to work with.

Respondents also commented that they need to know the secondary hazards, such as liquefaction, landslides, fire, floods, and tsunamis. For medical service providers, the availability of critical infrastructure to plan and allocate resources to treat injuries and patients' demography and injury levels are valuable. Grasping the accessibility of road networks will be crucial to plan rescue efforts to decide on alternate evacuation routes or whether people need to be airlifted. The capacity for marine ports and airports to function may dictate the level of resource availability. For emergency managers to set up evacuation centres and group lodging swiftly, they need to know what buildings are safe and available (large facilities for group lodging), the conditions of these facilities, and the location and size of standing facilities with operational services—similarly, they need the locations of hospitals, clinics, and other healthcare facilities with an indication of their functionality. The number of transient populations and issues with the supply chain were also mentioned.

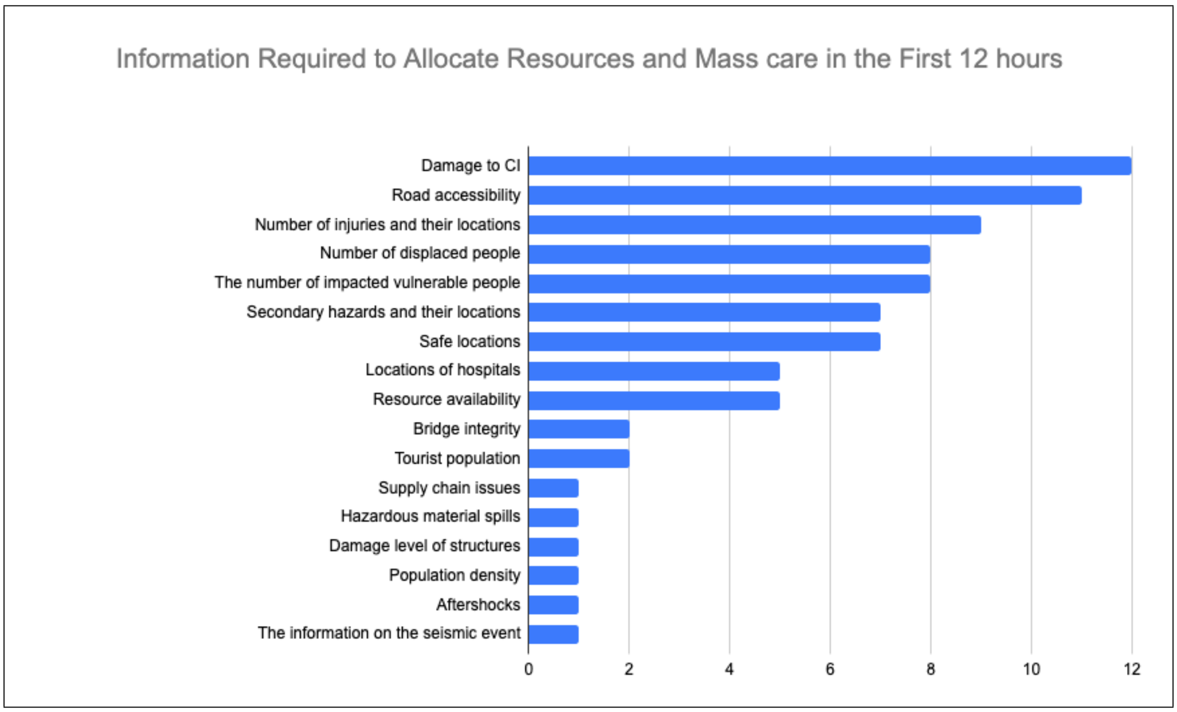


Figure 2.5: A summary of participants' answers to the question: "What information is needed to determine mass care needs and allocate supplies within the first 12 hours?".

2.3.10 Q10: "How do you identify isolated communities that cannot ask for help?"

Likely, telecommunication will be negatively impacted immediately after a significant earthquake. One respondent raised an important point for remote communities with limited telecommunication infrastructure; for such communities, losing one tower would mean their communications are completely severed, except radio communications. For urban areas, however, losing one tower out of many will not impact them as much. This question asks repondents how they identify isolated local communities. With current practices, participants stated that the only way to identify isolated neighbourhoods that cannot ask for help is through the windshield/walking survey if it is at a municipality/township level. In the case of small First Nation communities, they know the locations of vulnerable populations such as the elderly and will visit them door to door. In general, however, large municipalities or townships will wait for notice from the neighbourhoods or conduct windshield/walking surveys. If it is at the provincial/territory level, respondents will not know about the isolated municipalities until they are notified or send out the survey teams to check on them. One respondent remarked that they wanted to avoid a similar situation to what occurred following the 2011 earthquake in Christchurch, New Zealand, where there was a failure to identify the towns needing help. To prevent the worst outcomes, some municipalities educate and train their residents to be self-sufficient for several days. One city has provided containers of supplies throughout the city, with keys to the containers given to residents of the neighbourhoods to support their needs. Respondents want to help not only the wealthy communities with the loudest voices but also communities with limited resources; if the telecommunication and road networks are down, it will be challenging, but respondents agreed that modelling results could substantially help accelerate the response time for isolated communities.

2.3.11 Q11: "How would you like to receive the (RED-E) information?"

Most end-users (70%) desire the RED-E information to be GIS consumable (Figure 2.6). Most emergency managers rely on their provincial GIS emergency operation systems to gain situational awareness, and they wish the RED-E information to be integrated with that system. Many users wish to have the ability to zoom in or out to see their areas of interest. It was also mentioned, however, that many First Nation communities do not use the GIS format, and one non-First Nation local community did not use the provincial system frequently. Many appreciate the PAGER or QLARM styles of one- or two-page summaries with static maps, tables, and other summarised information, which can be easily printed and taken out to the field by staff whose communications are down. Many First Nations responders would find the PDF format helpful as it summarizes information, and they commented that such information can be valuable to visualize the impact as they sit in the regional coordination calls. PDF images could be communicated quickly through local social media apps. Participants stated that this type of summarized information with a map helps them get a quick snapshot of the event's gravity, which is valuable. Additionally, table summaries in simple text are useful for reporting purposes and in times of network disruption.

Many respondents prefer multiple methods to receive the information; this includes GIS consumables, PDF files, and summary texts. Generally, many feel that more methods will be better to increase redundancy. Some prefer a stand-alone system directly from NRCan since this organization represents quality scientific work and credibility. They would like NRCan to disseminate the information directly in multiple formats. Additionally, some First Nation communities are already closely connected to the federal government but have not yet built similar relationships with the province; thus, the information coming through the federal government may be considered more trustworthy.

Conversely, some respondents were critical of the federal website, stating that its capacity must be increased to accommodate significantly larger traffic volumes as more people will be trying to access the data during the post-disaster phase. Some provincial government ministries are not using the federal website to access earthquake information because the site crashed in the past and is considered unreliable during

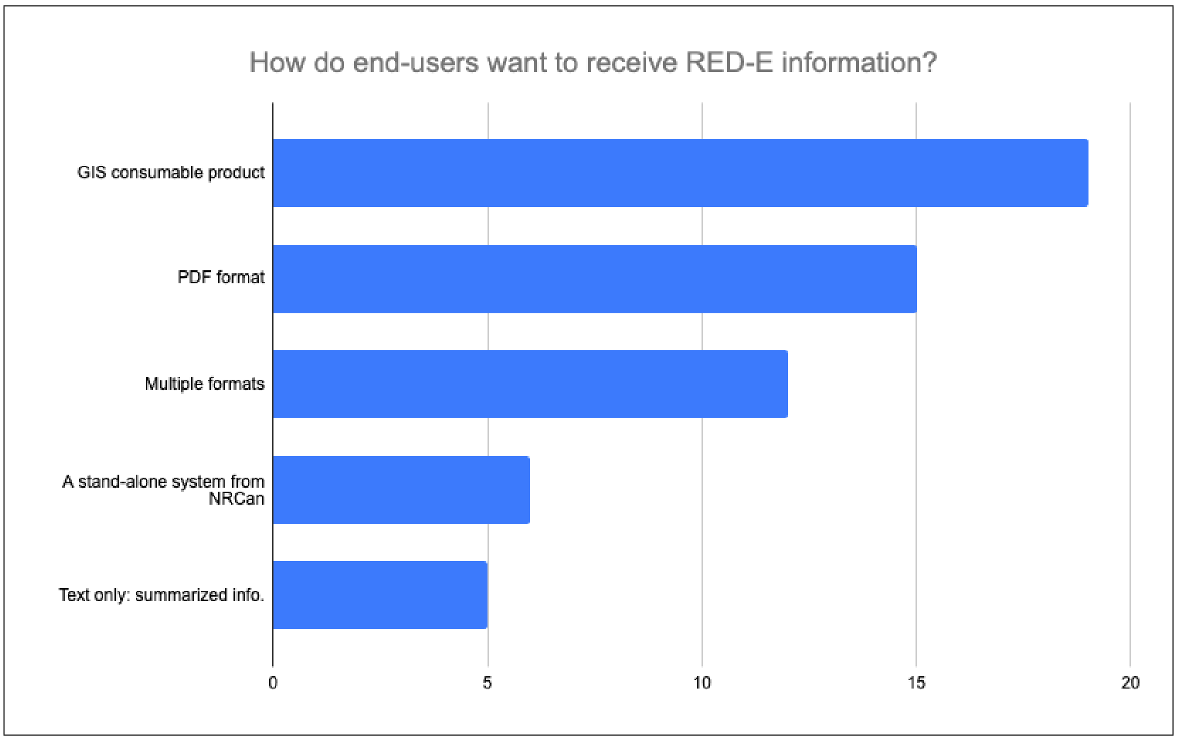


Figure 2.6: A summary of participants' answers to the question: "How would you like to receive the (RED-E) information?". Note that the PDF format report includes maps and tables.

the post-disaster phase when the site will have increased visitors. It was mentioned that the provincial systems can consume stand-alone systems as a custom application. A couple of end-users wish to have access to the developers to ask questions.

Most local municipalities want to see data at the neighbourhood level to understand the local-scale modelled impact, but the regional scale is acceptable for the provincial level of government.

2.3.12 Q12: "Are there any concerns about the results of our tool, which are hypothetical, being available to the general public?"

Most respondents expressed concerns about the results being made publicly available (Figure 2.7). They are worried that if the RED-E information becomes available to the public, the data might be misinterpreted as ground-truth data, rather than modelled data. They are troubled that misinformation might circulate on social media, causing unnecessary panic. All the emergency managers and first responders want transparency, but they are concerned that panic could counter rescue efforts. One responder used a tsunami example: "When we had that tsunami warning, people heard there was a tsunami warning, and everyone panicked and drove up to the top of mountains, which was unnecessary and just caused major other impacts…it's good for them to have information as long as they have the education and know what to do with it".

Some end-users are concerned that data availability might heighten the public's rescue expectations that might not be met. Another worry is the potential to generate disaster tourists physically and virtually, which can cause physical and virtual (website) traffic, respectively. Another concern was that if the modelling data were somehow incorrect, it may cause a loss of trust from the public.

Most respondents recommend separating public-facing sites and documents from those designed for specialized users, with different scales and details. According to end-users, it is not abnormal to have internal documents for emergency management sectors and separate documents for the public. They also suggested considering a security clearance to use the tool and some detailed information to be password protected, especially if it includes the estimated number and locations of fatalities or critical injuries, which can be emotionally triggering for the public. They recommended consulting with experts who are trained to know what information should be available to the public. If the tool is to be available to the public, it needs to be accurate and reliable, and ensure that it comes from a trusted source and does not conflict with other data.

Respondents suggested clearly indicating that the RED-E outputs are modelled data, educating the public before launching publicly, and letting the public have different scales and details of data to protect privacy and to avoid disaster tourists. Thus, separating public-facing and internal sites for end-users would make sense. Many feel that the PAGER or QLARM types of summarized information would be most suitable for public use.

Education is a critical component if RED-E eventually has a public-facing site; modelling uncertainties and limitations must be clearly communicated. Other concerns are privacy issues and house insurance concerns. Many Indigenous communities prefer keeping their own information within their governments and do not always feel comfortable sharing their data with non-Indigenous governments; thus, respecting their privacy is essential. Some expressed their concerns that their house insurance premium might be impacted by the result of this modelling system. Also, having experts' input before making the data available to the public will be important, including ensuring it does not conflict with other data. This could be achieved by consulting social scientists who study societal reactions to rapidly produced seismic communication tools such as EEW information, PAGER, and QLARM and conducting literature reviews on how other rapidly generated seismic or other natural hazard information has been perceived by the public.

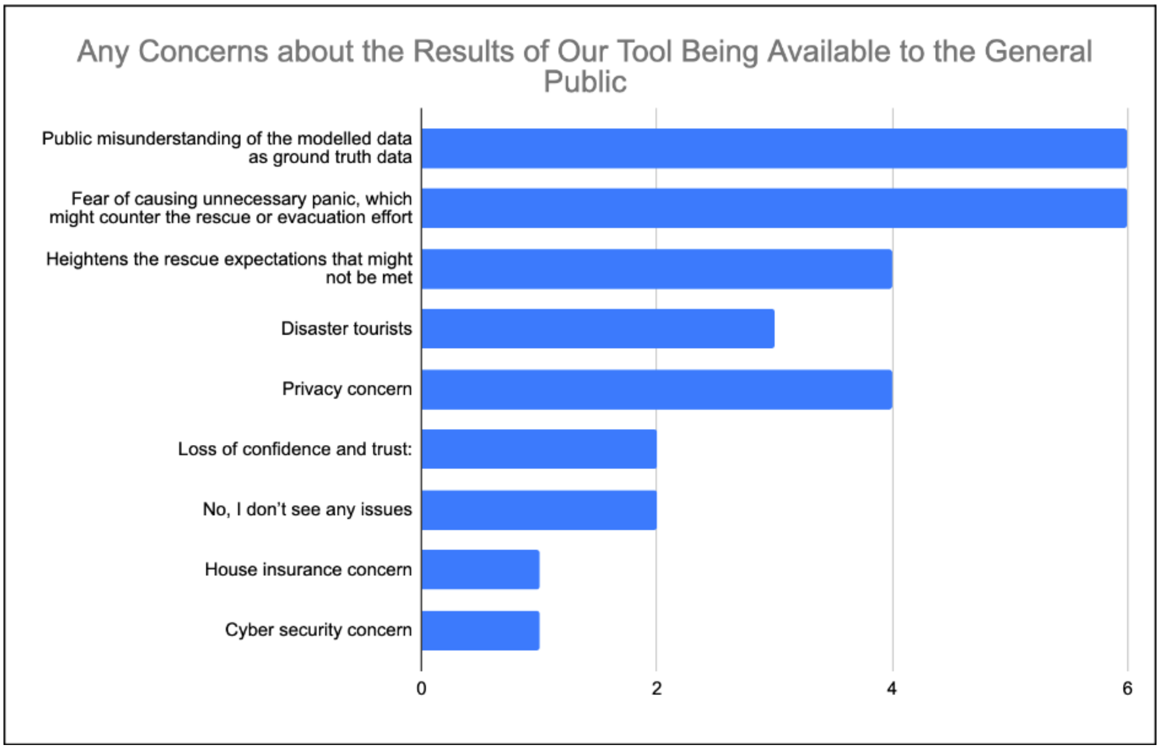


Figure 2.7: A summary of participants' answers to the question: "Are there any concerns about the results of our tool, which are hypothetical, being available to the general public?"

2.3.13 Q 13: "Do you foresee challenges integrating a tool like our Rapid Earthquake Disaster Estimator in your agency? If so, what might it be?"

Some end-users foresee issues as they integrate the RED-E into their organizations, such as staffing capacity and technical capacity, especially if system use requires a new skill set and cost. The system is free, but respondents are concerned that there might be an indirect cost to train, update the system and subscribe. Resources and capacity were mentioned as an issue for almost all small-capacity municipalities' representatives. They suggested having a training component with simulated earthquakes on a regular basis. Some expressed that training would be useful if the RED-E system has the ability to add ground-truth data as events evolve, but if the system only has a modelling component, there is no need for training.

There may be additional requirements for provincial-level governments, such as using only Canadian servers, and the approval process might take a while before they are authorized to use the system. Concerns about security clearance were also brought up.

2.3.14 Additional Recommendations from the end-users

Respondents want to see a user-friendly interface, for the system to be intuitive, and for it to require a similar skillset to that needed to operate their existing GIS systems. Many end-users strongly wish the RED-E system to be consumable with their provincial GIS system because having all the information in the same system would be highly efficient, allowing them to focus on one system. Many end-users suggested having options to provide real-time feedback, such as to indicate if the modelled impacts are accurate or the ability to see/add photos. One respondent asked for normalized data to gain a better understanding of the impact scales. Some respondents questioned if equality in data collection is considered and how physical, cultural, and financial vulnerabilities are included in the system. They suggested that the RED-E system needs clear contact points for users to suggest refinements or amendments.

Other questions concern how often data will be updated to minimize uncertainty and keep the system outputs current and relevant and who will be updating it. A few respondents recommended that the impact of aftershocks be cumulatively considered and if the data could be refreshed as they occur. They also wanted to know the uncertainty regarding the modelling results.

2.4 Limitations and Future Work

The study sought to include participants from Canada's seismically active regions, where the official language is English, due to the investigators' language limitations. By utilizing a virtual meeting environment, the study included end-users from Ontario and largely from BC, specifically, where high seismic hazards and risks are anticipated. Not all smaller communities responded to the invitations; thus, they were not included in the study. The study attempted to include the Yukon Territory; no emergency managers could be available, however, due to ongoing wildfire emergencies in the summer of 2023. Conducting the same study in Quebec and the Yukon Territory could also be a potential avenue for future studies. The user-need informational meetings are the first steps in the process of refining the RED-E system. The next step for this project is to build the prototype RED-E system and ask interested participants to test it to see if it aligns with their needs.

2.5 Summary and Conclusions

The future RED-E system, which will leverage Canada's Seismic Risk Model and ShakeMaps, which will be produced as an output of the EEW system, to model impacts from significant earthquakes in the first tens of minutes following a major event, will be developed based on consultation with emergency managers and first responders. This chapter covered the process and results of the interviews conducted to gain insights from the end-users to ensure the tool can provide what they need to make timely decisions during critical hours. The most important outcomes from the informational meetings are summarized below:

- Based on the findings, the RED-E system should be communicated through multiple sources. Respondents desire to receive the RED-E information through (1) dynamic maps / GIS consumable products that can be used in provincial or local GIS systems as well as through the NRCan Earthquakes Canada website independently after ensuring that the national site would be able to accommodate the anticipated, large traffic volume, (2) PDF formats with a map and tables of essential information, and (3) simple text format. End-users welcome multiple methods to increase redundancy. End-users appreciate having the option to zoom in and out as is possible in GIS, and many local governments wanted details as fine-scale as the neighbourhood level.

- Most interviewees responded that it currently would take three days to weeks to gain complete and credible situational awareness after a major earthquake, indicating the RED-E system can assist in filling the information gap as a prioritization tool to dispatch response teams during critical hours to save lives.

- The top three concerns for a public-facing RED-E product are: potential public misunderstanding of the modelled data as ground-truth data, fear of causing panic, which might counter the rescue or evacuation effort, and heightening rescue expectations that might not be met. Many suggested having separate formats/data types for the public versus official end-users.

- The three most identified, significant obstacles to gaining situational awareness were road blockage, loss of telecommunication, and staff shortages. The completeness and quality of situational awareness and the time it takes to gain it are deemed highly dependent on road conditions and the availability of telecommunication networks.

- Information that is highly desired within the first 24-48 hours:
  - Damage to Critical Infrastructure (CI) including road and other transportation facilities, telecommunication, power, water, hospitals, etc.
  - Number of displaced people
  - Number of injuries and their locations
  - Number of impacted vulnerable populations
  - Secondary hazards and their locations (tsunami, liquefaction, landslides, fire)

  - Safe locations to evacuate
  - Aftershocks
  - Number of tourists/ visitors
  - Supply chain issues
  - Hazardous material spills

- During post-disaster times, emergency managers and first responders depend on foot or vehicular reconnaissance, 911 calls, and rapid damage assessment volunteer teams such as RDA to gain situational awareness. However, rapid disaster building assessment will likely take weeks to complete, emergency calls are an incomplete picture of the disaster, 911 lines are likely to be jammed, and windshield assessments are time-consuming and challenging to cover the entire disaster region evenly.

- Many respondents commented that a tool like RED-E could be a valuable asset to support the planning processes, to prioritize the rescue effort and ensure people's safety.

- There are no constructive ways to identify impacts quickly in isolated communities when communications are down, and the only ways to conduct reconnaissance are to directly drive, walk, bike, boat, or fly into the community to assess the situation. The RED-E system could be used by the province/territory or federal government to proactively identify towns or regions which are likely to have been hard hit and to initiate contact.

- The top three issues end-users may face as they integrate the RED-E system are staffing capacity, technical issues, and the cost to train staff and upgrade the system. Others mentioned that it may take a while for RED-E to be approved as their organization's official product, and many organizations require data to be hosted entirely on Canadian servers. End-users suggested having training components beforehand and user-friendly interfaces.

- Results should be provided in absolute and normalized terms. For example, casualties should be reported as the number of casualties as well as the number of casualties divided by residents in the neighbourhood/municipality/region.

- participants also expressed a desire to have the ability to add ground-truth data as it becomes available.

Overall, many users anticipate that the system will be extremely valuable; they expressed great excitement. For the provincial governments, this tool can allow them to act more proactively to foresee local governments' needs before they receive requests from them. For the local government, it can be a prioritization tool to initiate the rescue effort, initiate support requests, and identify potentially safe locations to house displaced populations.

In the first 24-48 hours after a major seismic event, emergency managers and first responders can anticipate a lack of information as conducting ground-level surveys to gain situational awareness is unlikely to be initiated immediately and will be time-consuming. Based on the informational meetings, the end-users would highly appreciate having the RED-E tool as it can be a helpful guide to fill the gap until ground-truth data become available. The statement is especially true if the tool implements users' recommendations, as expressed herein.

Chapter 3

Designing RED-E Wireframes and Analysis of Evaluation Results

3.1 Introduction

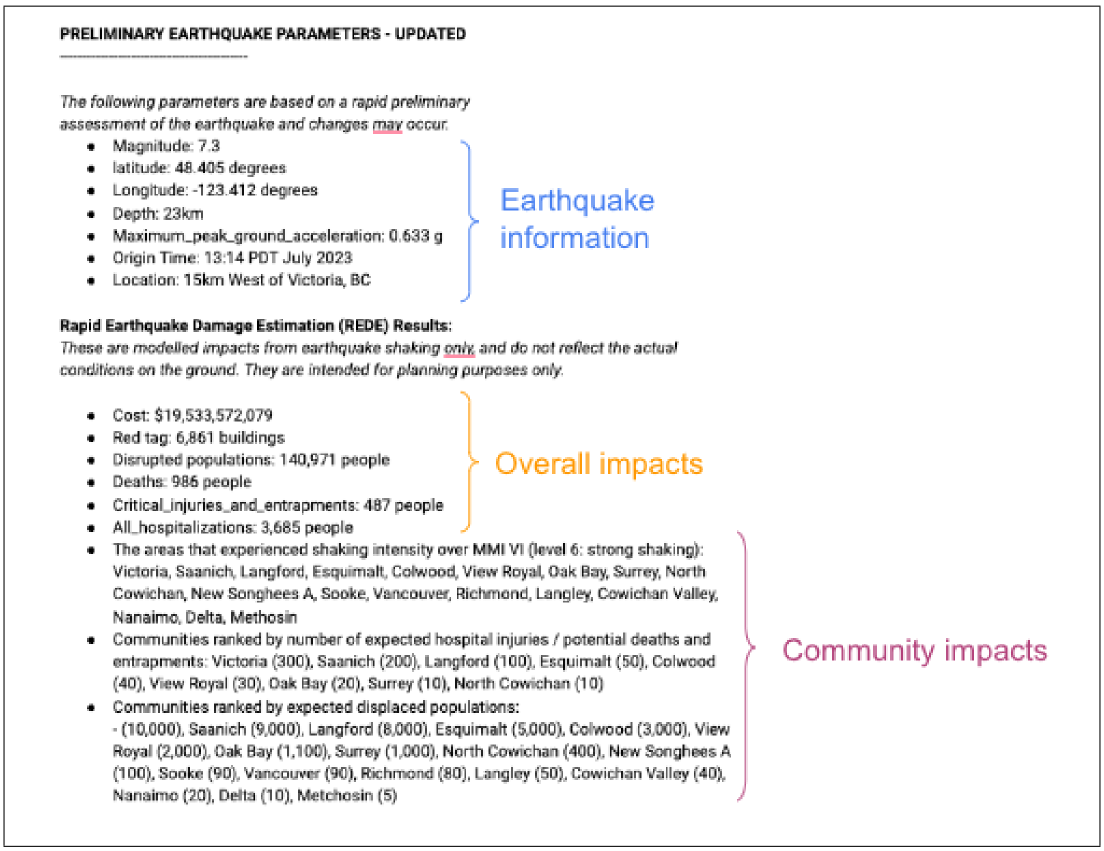
This chapter describes the third and fourth parts of the UCD development phases (Figure 1.15) to improve the conceptual model of the RED-E system by engaging with end-users. The RED-E design process has involved conducting informational interviews with targeted users (UCD phase 2, Figure 1.15), including 27 individuals from 17 organizations in Canada, including emergency managers, first responders at municipal, provincial, and national levels, and Critical Infrastructure (CI) operators, to gain an understanding of their needs immediately after a significant earthquake (3. The results of those informational interviews can then be used to develop wireframes (conceptual images that describe the functionality of a tool without attention to styling) of the RED-E tools (UCD phase 3). The current chapter will describe the prototype development and testing (UCD phases 3 and 4, Figure 1.15). Feedback on the wireframe versions was then solicited from two emergency management teams at both municipal and provincial levels who were previously involved in the first phase of the informational interviews.

3.2 RED-E Product Wireframe Versions

The three RED-E product wireframes include text, static, and dynamic formats. These three formats will make it possible to share information whenever data-based communications are down, compromised, or fully functioning, respectively. As a sample scenario case, all wireframe versions generally used the risk model results of full rupture of the Leech River fault (M_w 7.3 earthquake with an epicentre 15 km west of downtown Victoria) using the OpenQuake engine, but it should be noted that some values (e.g., uncertainty ranges) are fictitious, added only for illustrative purposes, and are not based on the modelling results.

3.2.1 Text Version

The text format is the most straightforward and readily accessible product, even during low-bandwidth times (Figure 3.1). It mimics the messages sent by the United States Tsunami Warning Centers (https://www.tsunami.gov/). Potential users of RED-E (Chapter 2) and study participants of PAGER in the US (Loos et al., 2024) have supported using this approach when the communication network is compromised. The text version includes the general seismic event data provided by CHIS/NRCan, encompassing estimated values of magnitude, location (in longitude and latitude and described as a general location, e.g., 15 km west of downtown Victoria), depth, maximum shaking intensity in Peak Ground Acceleration (PGA; in g), and origin time. It has RED-E modelling results, which encompass estimated total values of financial cost, number of red tag buildings (unsafe for occupancy), disrupted populations, fatalities, critical injuries and entrapments, and the number of hospitalizations, followed by community impact which lists the following information: areas that experienced shaking intensity over MMI VI (level 6: strong shaking), municipalities ranked by number of expected hospital injuries/potential deaths and entrapments, and municipalities ranked by expected displaced populations.



PRELIMINARY EARTHQUAKE PARAMETERS - UPDATED

The following parameters are based on a rapid preliminary assessment of the earthquake and changes may occur.

- Magnitude: 7.3
- latitude: 48.405 degrees
- Longitude: -123.412 degrees
- Depth: 23km
- Maximum_peak_ground_acceleration: 0.633 g
- Origin Time: 13:14 PDT July 2023
- Location: 15km West of Victoria, BC

Rapid Earthquake Damage Estimation (REDE) Results:
These are modelled impacts from earthquake shaking only, and do not reflect the actual conditions on the ground. They are intended for planning purposes only.

- Cost: $19,533,572,079
- Red tag: 6,861 buildings
- Disrupted populations: 140,971 people
- Deaths: 986 people
- Critical_injuries_and_entrapments: 487 people
- All_hospitalizations: 3,685 people
- The areas that experienced shaking intensity over MMI VI (level 6: strong shaking): Victoria, Saanich, Langford, Esquimalt, Colwood, View Royal, Oak Bay, Surrey, North Cowichan, New Songhees A, Sooke, Vancouver, Richmond, Langley, Cowichan Valley, Nanaimo, Delta, Methosin
- Communities ranked by number of expected hospital injuries / potential deaths and entrapments: Victoria (300), Saanich (200), Langford (100), Esquimalt (50), Colwood (40), View Royal (30), Oak Bay (20), Surrey (10), North Cowichan (10)
- Communities ranked by expected displaced populations:
  - (10,000), Saanich (9,000), Langford (8,000), Esquimalt (5,000), Colwood (3,000), View Royal (2,000), Oak Bay (1,100), Surrey (1,000), North Cowichan (400), New Songhees A (100), Sooke (90), Vancouver (90), Richmond (80), Langley (50), Cowichan Valley (40), Nanaimo (20), Delta (10), Metchosin (5)

Figure 3.1: Wireframe RED-E product in text format.

3.2.2 Static Version

The static product is in a Portable Document Format (PDF) with comprehensive visuals such as maps, tables, descriptions of the event, and the estimated losses. The potential RED-E users highly favoured a PDF format since it is easily shareable and understandable, with maps and charts to understand the spatial extent of impacts (Chapter 2). The usefulness of the PDF format was also validated by Loos et al. (2024). The study participants confirmed that maps are an effective way to reveal information about affected areas visually, enhancing people's understanding. Such information can help decision-makers to see who is affected and assist in determining whether further information is required (Loos et al., 2024). The study also demonstrated that the current PAGER format in PDF is easily shareable, and they stressed its value (Loos et al., 2024).

The overall page of the static version includes large-scale maps encompassing all impacted areas and a summarized table of estimated values for fatalities, dislocated populations, severe injuries, damaged buildings of different levels, and economic impacts of the region (Figure 3.2), while the subsequent pages convey the municipality-specific estimated results. Three different example versions of the community-specific page of the static RED-E were created (Figures 3.3, 3.4, 3.4) to solicit feedback on what should be included. The three versions are differentiated by the presence of an impact summary map (Figure 3.3), a damaged buildings map (Figure 3.4), or a social vulnerability map (Figure 3.5). All maps are created using QGIS software, 3.28.1-Firenze version, with results from modelling the M_w 7.3 Leech River fault earthquake day-time scenario. The maps on the first page used the census subdivision boundaries, whereas the maps on the second page used the settled area boundaries (Journeay et al., 2022). Census subdivision boundaries indicate the area that is a municipality or an area that is deemed to be equivalent to a municipality for statistical reporting purposes, and settled area boundaries delineate the area where urban development and human habitation are concentrated and are used as the smallest geometry for calculating seismic risk. The settled area boundary is not required to be continuous like a Census Dissemination Area. The settled area outlines where a cluster of buildings exists, and the size of a settled area boundary in urban settings can be equivalent to a Census Dissemination Area, which is often 1 km^2. Large swaths of Canada where no building cluster exists, are not represented by settled area boundaries, however

(Journeay et al., 2022).

The building damage levels indicated in RED-E output include extensive, complete, and collapsed. Extensive damage refers to buildings that are conditionally habitable, such as these that sustained large diagonal cracks across shear wall panels or at plywood joints; permanent lateral movement of floors and roof; the toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations. Complete damage refers to uninhabitable structures that may have large permanent lateral displacement or be in imminent danger of collapse due to failure of the cripple wall or the lateral load resisting system; structures that may have slipped off their foundations; structures with large foundation cracks. The collapsed damage level is a subset of complete structural damage. On average, within the area of buildings with a state of complete damage, 3 percent are expected to collapse (Federal Emergency Management Agency,2012;Hobbs et al., 2021; Figure 3.6)

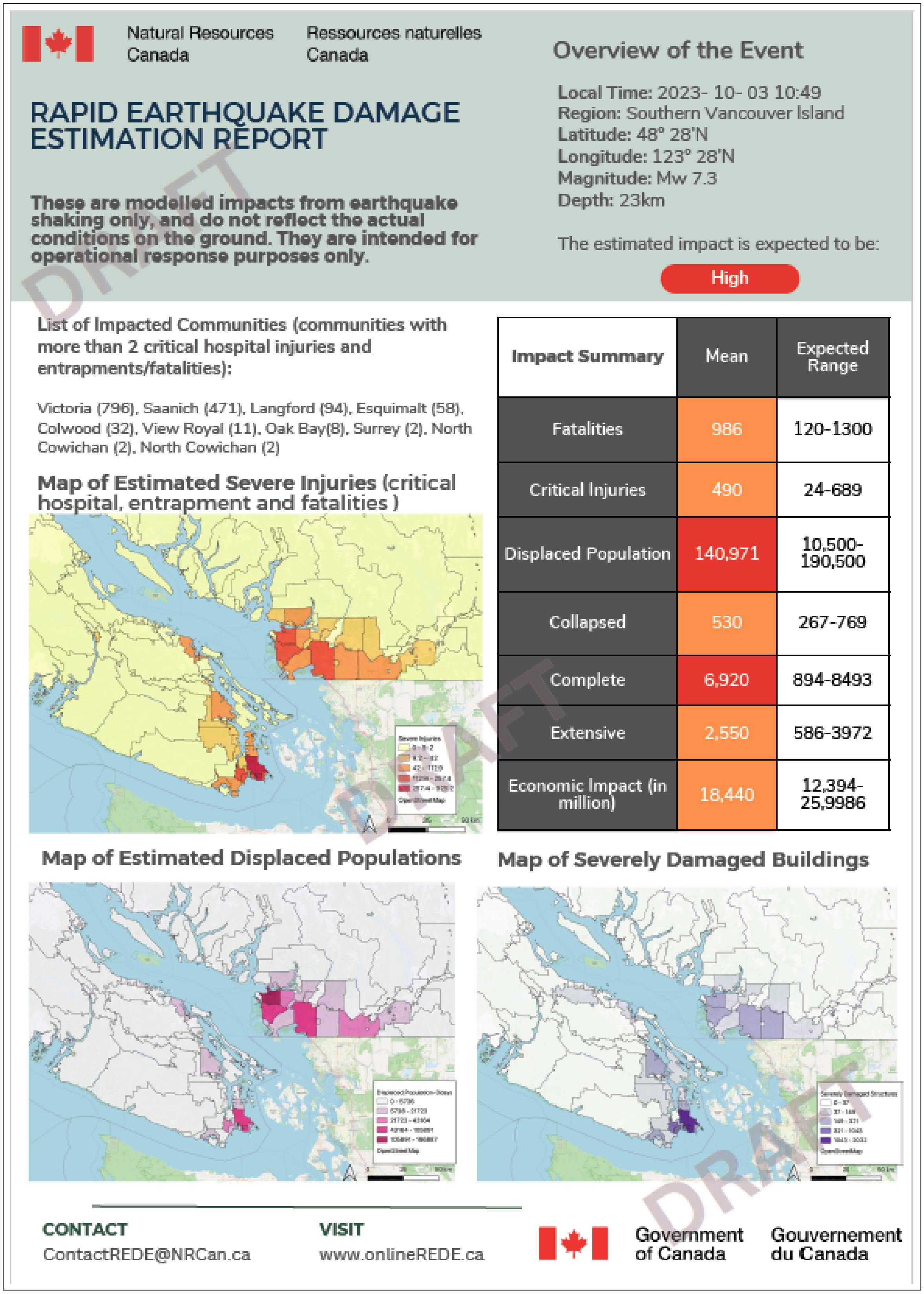
The modelling output reflects the time of the event. Daytime is considered to be 9 am-5 pm, nighttime is 7 pm-7 am, and transit is intervening hours of 7-9 am and 5-7 pm (Federal Emergency Management Agency, 2012; Hobbs et al., 2021).

Description of damage adopted includes:

- Colour-coded impact level (red, orange, yellow, and green)
- Disclaimer that information shown is based on modelling, not ground-truth data
- Overview information, which is the same information included in the text version (estimated magnitude, location, origin time, and depth)
- List of impacted communities (communities with more than 2 critical hospital injuries, and/or entrapment/fatalities)
- Colour-coded impact summary table; a table which includes estimated fatalities, injuries, displaced populations, numbers of buildings in different damage levels (collapsed, complete, and extensive), and economic impact. Each value is displayed with uncertainties
- Three maps of estimated severe injuries (which combines critical hospital, entrapment, and fatalities), estimated displaced population, severely damaged

buildings (collapse, complete, and extensive combined)

- Link to dynamic RED-E version
- Contact information



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RAPID EARTHQUAKE DAMAGE ESTIMATION REPORT

These are modelled impacts from earthquake shaking only, and do not reflect the actual conditions on the ground. They are intended for operational response purposes only.

Overview of the Event

Local Time: 2023- 10- 03 10:49
Region: Southern Vancouver Island
Latitude: 48° 28'N
Longitude: 123° 28'N
Magnitude: Mw 7.3
Depth: 23km

The estimated impact is expected to be:

High

List of Impacted Communities (communities with more than 2 critical hospital injuries and entrapments/fatalities):

Victoria (796), Saanich (471), Langford (94), Esquimalt (58), Colwood (32), View Royal (11), Oak Bay(8), Surrey (2), North Cowichan (2), North Cowichan (2)

Impact Summary	Mean	Expected Range
Fatalities	986	120-1300
Critical Injuries	490	24-689
Displaced Population	140,971	10,500-190,500
Collapsed	530	267-769
Complete	6,920	894-8493
Extensive	2,550	586-3972
Economic Impact (in million)	18,440	12,394-25,9986

Map of Estimated Severe Injuries (critical hospital, entrapment and fatalities)

Map of Estimated Displaced Populations

Map of Severely Damaged Buildings

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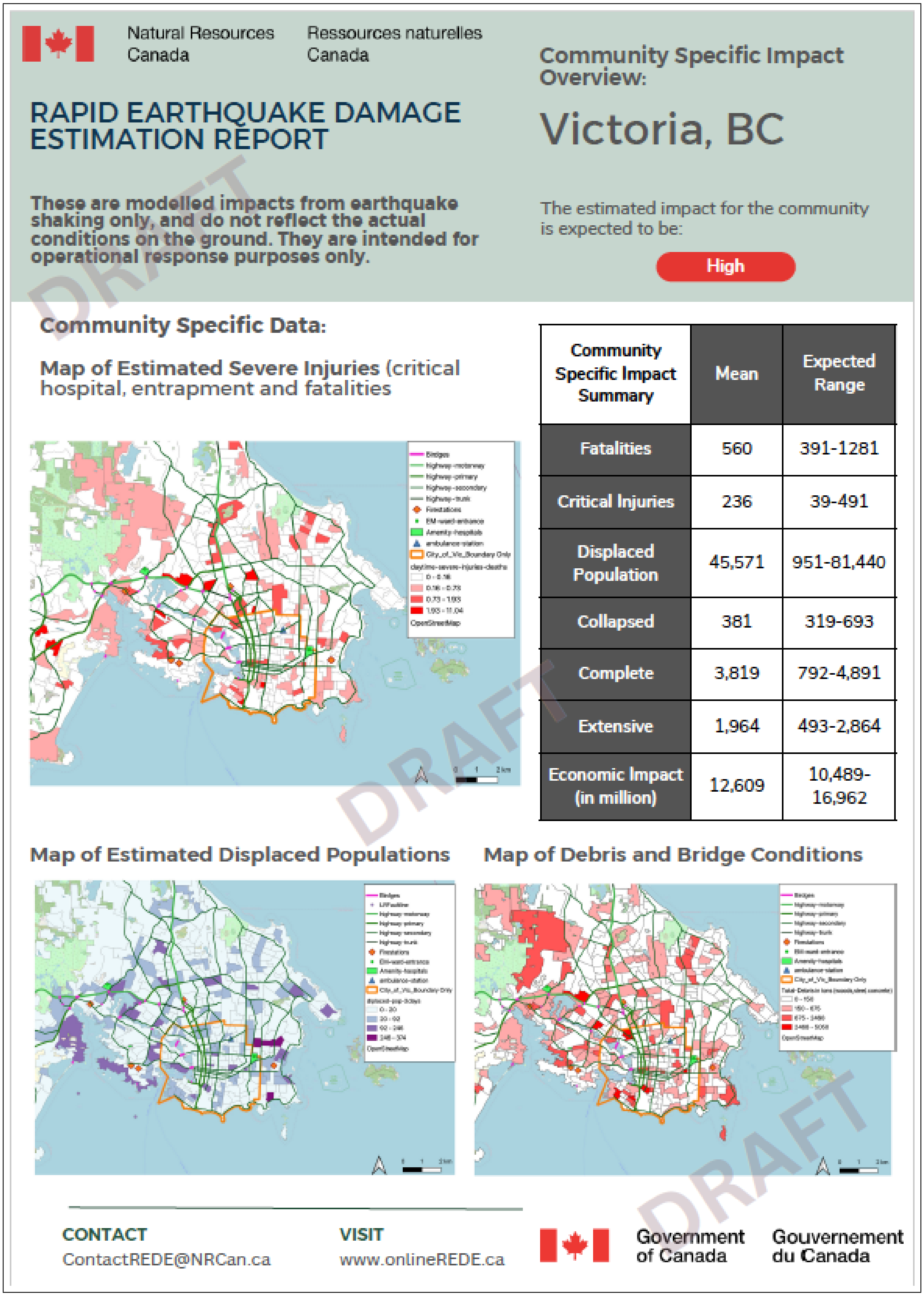
Figure 3.2: The first page of static RED-E, which contains summarized information on the seismic event and estimated impact results for all impacted areas.

The second page of the static version is dedicated to specific municipalities, reflecting feedback from the previous informational sessions (Chapter 2). Three different versions were created to receive further feedback on the wireframes, although all versions include:

- Colour-coded community impact level
- Disclaimer that information shown is based on modelling, not ground-truth data
- Two maps of municipality-specific estimated severe injuries (critical hospital, entrapment, and fatalities combined) and estimated displaced population
- Summarized community-specific data such as total number of critical injuries, fatalities, and displaced population, with range
- Link to dynamic RED-E version
- Contact information

Version 1 (Figure 3.3) has a municipality-specific impact summary table with the same types of information such as fatalities, casual injuries, displaced populations, numbers of buildings in different damage levels (collapsed, complete, and extensive), and economic impact. Each value displays a range of potential losses.Version 2 (Figure 3.4) has a damaged buildings map (including collapse, complete, and extensive damage levels) instead of the summary table. Version 3 (Figure 3.5) has a social vulnerability map replacing the building map.



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RAPID EARTHQUAKE DAMAGE ESTIMATION REPORT

These are modelled impacts from earthquake shaking only, and do not reflect the actual conditions on the ground. They are intended for operational response purposes only.

Community Specific Impact Overview:

Victoria, BC

The estimated impact for the community is expected to be:

High

Community Specific Data:

Map of Estimated Severe Injuries (critical hospital, entrapment and fatalities

Community Specific Impact Summary	Mean	Expected Range
Fatalities	560	391-1281
Critical Injuries	236	39-491
Displaced Population	45,571	951-81,440
Collapsed	381	319-693
Complete	3,819	792-4,891
Extensive	1,964	493-2,864
Economic Impact (in million)	12,609	10,489-16,962

Map of Estimated Displaced Populations

Map of Debris and Bridge Conditions

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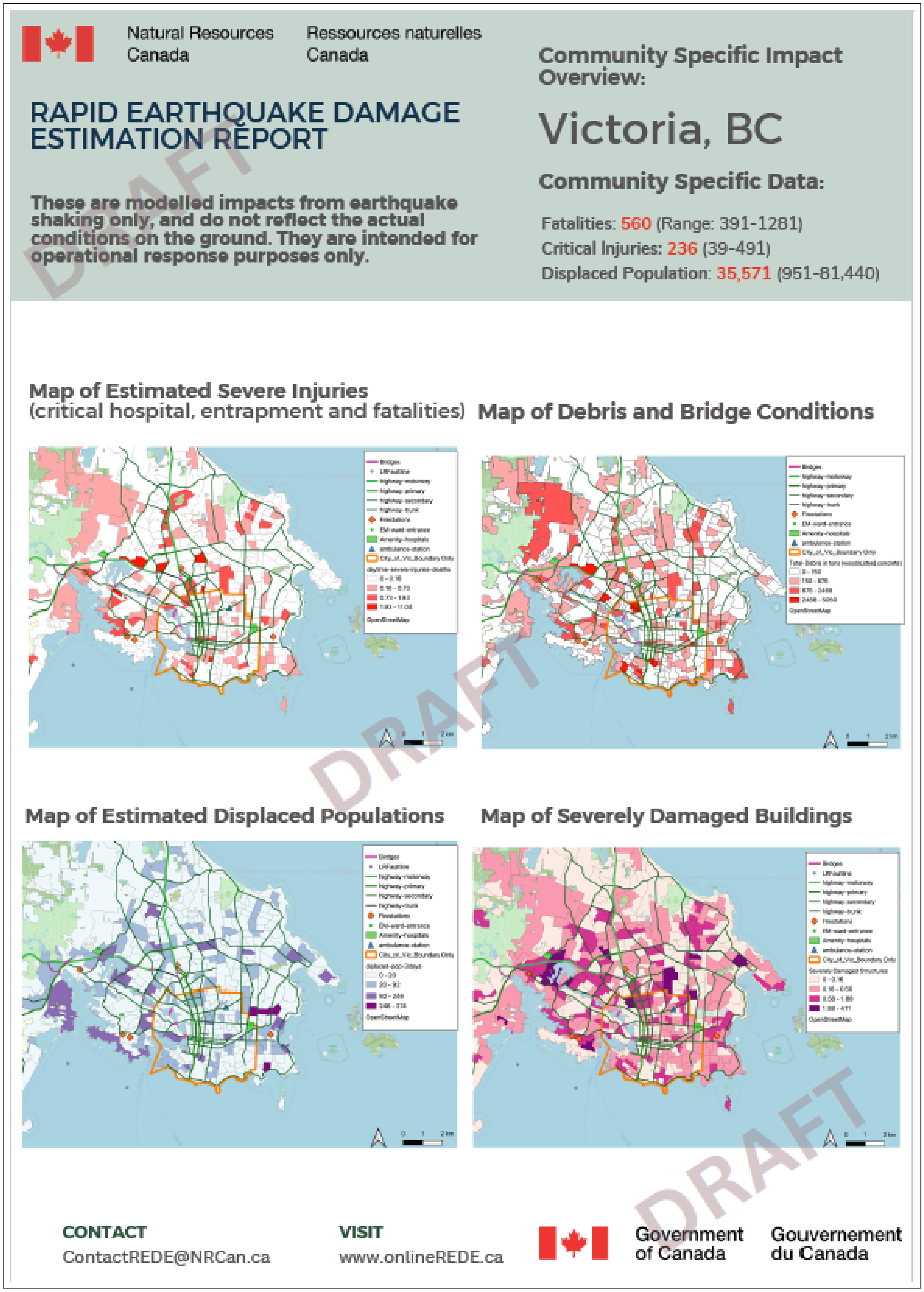
Figure 3.3: The second page of static RED-E: version 1, containing estimated impact results, with municipality-specific information summarized in a table.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RAPID EARTHQUAKE DAMAGE ESTIMATION REPORT

These are modelled impacts from earthquake shaking only, and do not reflect the actual conditions on the ground. They are intended for operational response purposes only.

Community Specific Impact Overview:

Victoria, BC

Community Specific Data:

Fatalities: 560 (Range: 391-1281)
Critical Injuries: 236 (39-491)
Displaced Population: 35,571 (951-81,440)

Map of Estimated Severe Injuries (critical hospital, entrapment and fatalities)

Map of Debris and Bridge Conditions

Map of Estimated Displaced Populations

Map of Severely Damaged Buildings

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Figure 3.4: The second page of static RED-E: version 2, including a severely damaged structure map instead of a summary table or a map of social vulnerability.

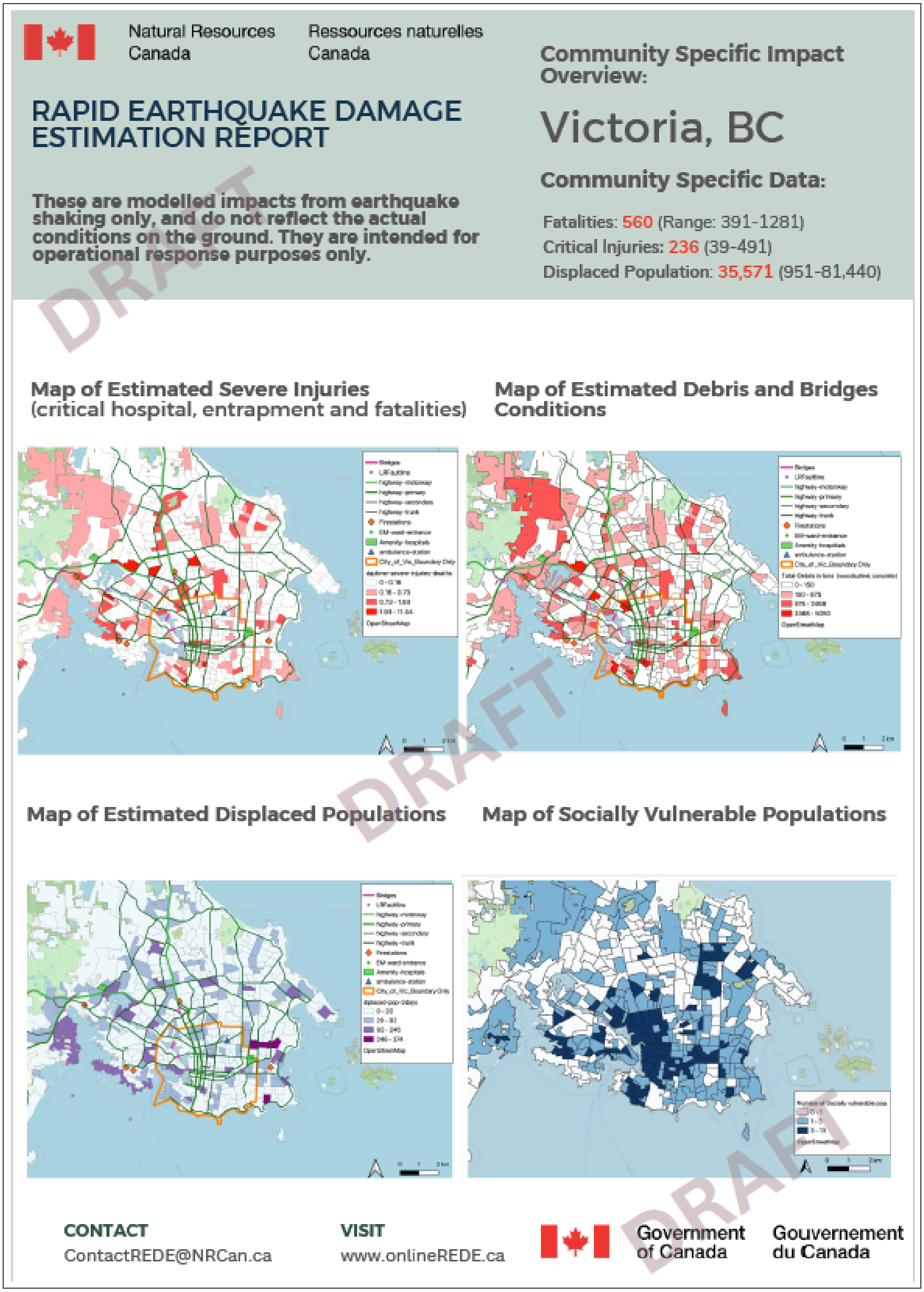


Figure 3.5: The second page of static RED-E: version 3, including a social vulnerability map instead of a summary table or a map of damaged buildings.

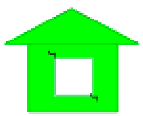
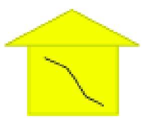
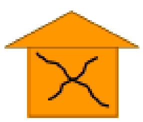
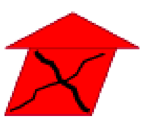
Damage State		Description
	**Slight**	Small plaster cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneers. Small cracks are assumed to be visible with a maximum width of less than 1/8 inch (cracks wider than 1/8 inch are referred to as "large" cracks).
	**Moderate**	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
	**Extensive**	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations.
	**Complete**	Structure may have large permanent lateral displacement or be in imminent danger of collapse due to cripple wall failure or failure of the lateral load resisting system; some structures may slip and fall off the foundation; large foundation cracks. Three percent of the total area of buildings with Complete damage is expected to be collapsed, on average.

Figure 3.6: Description of damage adopted from Federal Emergency Management Agency(2012)

3.2.3 Dynamic Version

Finally, the dynamic version takes the form of Geographic Information System (GIS) data layers that could be shared using an Application Programming Interface (API) request, making it consumable for existing end-user GIS systems. The dynamic GIS version would also be independently hosted through the national Earthquakes Canada website as an interactive map with multiple data layers. Examples of larger scales, which envelop the whole impacted region, are shown in Figures 3.7, 3.8,and 3.9; Figures 3.10 and 3.11 showcase examples of close-ups, scaling down to municipality levels.

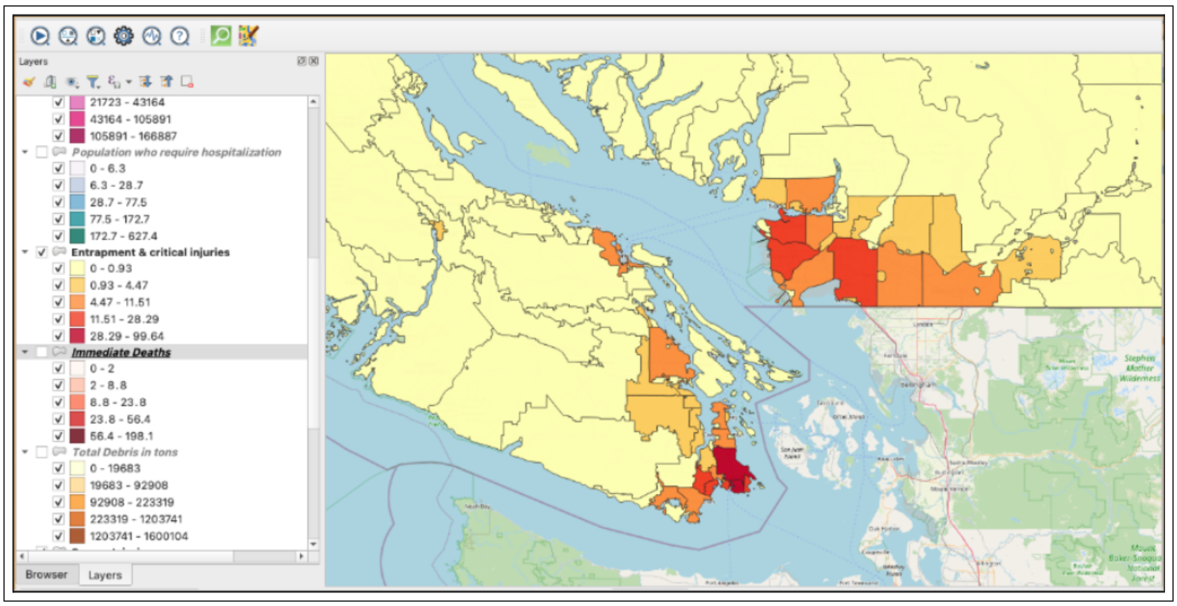


Figure 3.7: The map of critical injuries and entrapment at the census subdivision scale showing the whole impacted region on the dynamic version of RED-E.

Users of the dynamic version will see a disclaimer displayed before using the site and are given the ability to select/deselect the layers and features that are useful/not useful for them. Many emergency management teams use provincial GIS portals, such as the Common Operating Picture (COP) portal in British Columbia and DisasterLand in Ontario (Chapter 2). Some well-resourced communities or groups may also have local mapping systems with their own data layers of Critical Infrastructure (CI), hazardous materials, or identified vulnerabilities. The dynamic version has the following layers:

- ShakeMap
- Severe injuries (hospitalization and entrapment)
- Total debris (brick/wood and concrete/steel combined)
- Complete structural damage
- Extensive structural damage
- Moderate structural damage
- Displaced population
- Total economic loss

The dynamic version also includes features such as city boundaries, bridges, major highways, hospitals, and ambulance and fire stations.

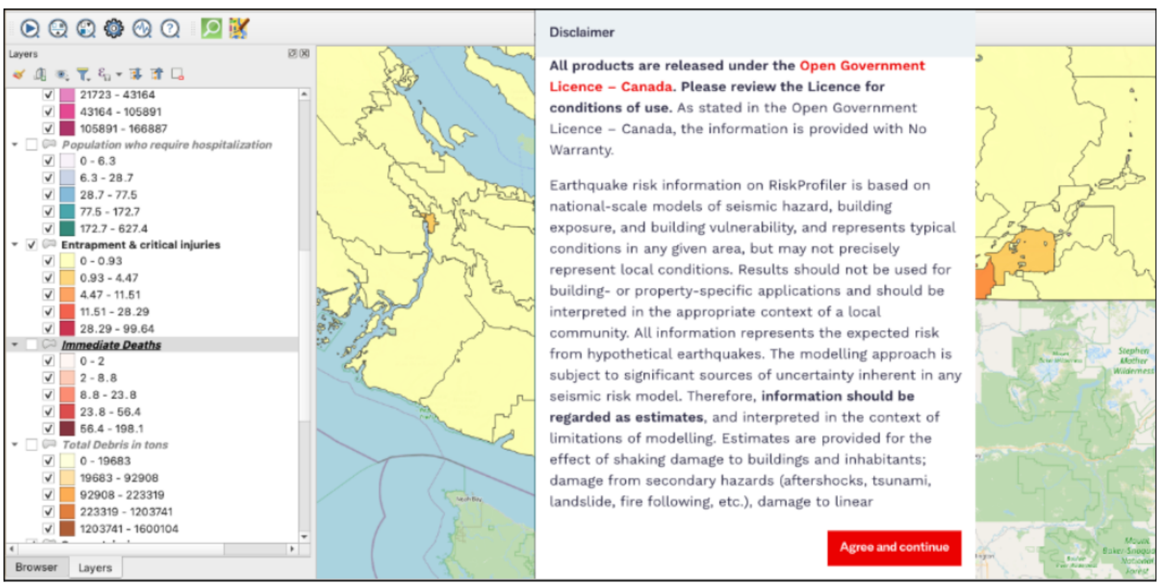


Figure 3.8: Example of disclaimer on the dynamic version. This type of disclaimer will be shown before users can begin to access map layers.

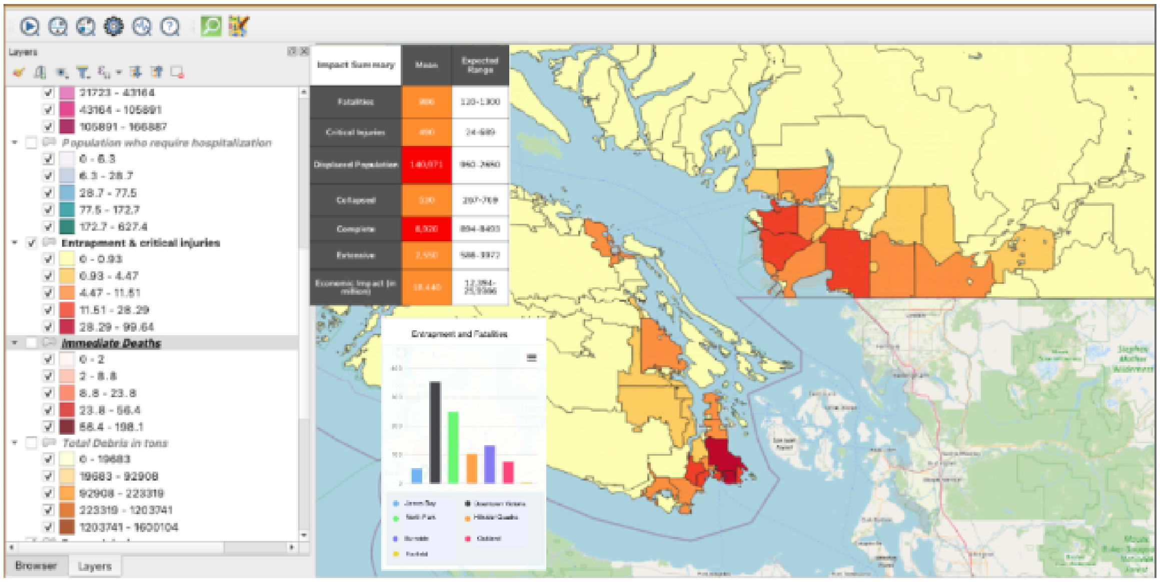


Figure 3.9: Impact summary of whole regions can be seen by clicking the sidebars and census subdivision-specific information can pop up as users click the polygon. A bar graph of regions with high impact can be pulled out as users click sidebars for the whole impacted regions and the same type of information on the census subdivision scale.

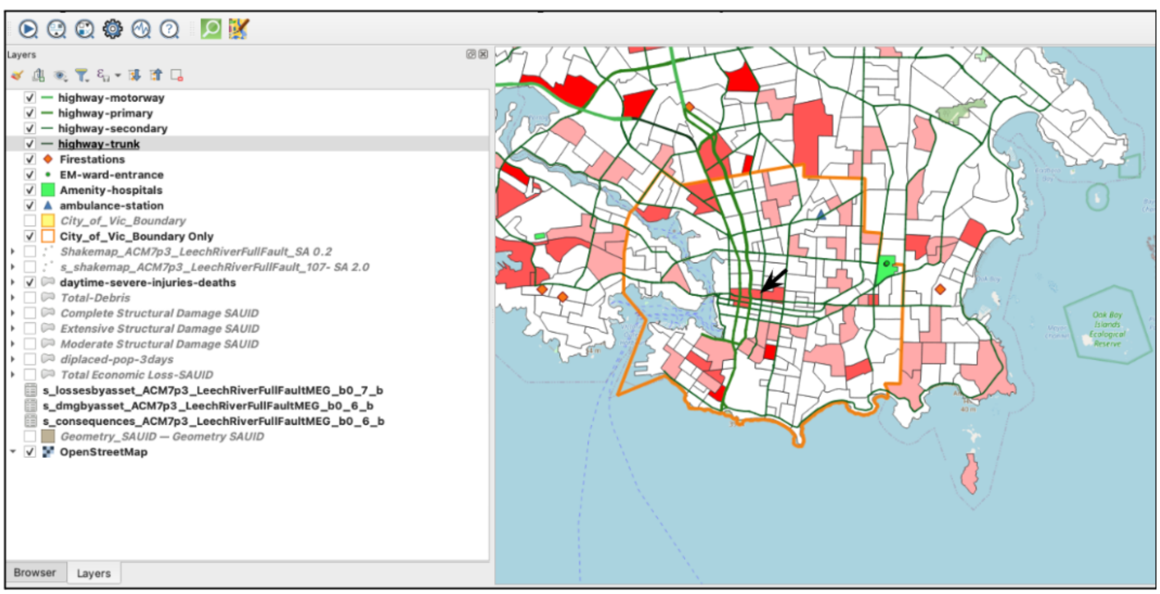


Figure 3.10: How the dynamic version will look if users zoom in. This particular image has features like city boundaries, major highways, hospitals, bridges, and ambulance and fire stations. As users select a neighbourhood's polygon, more information pops up (Figure 3.11).

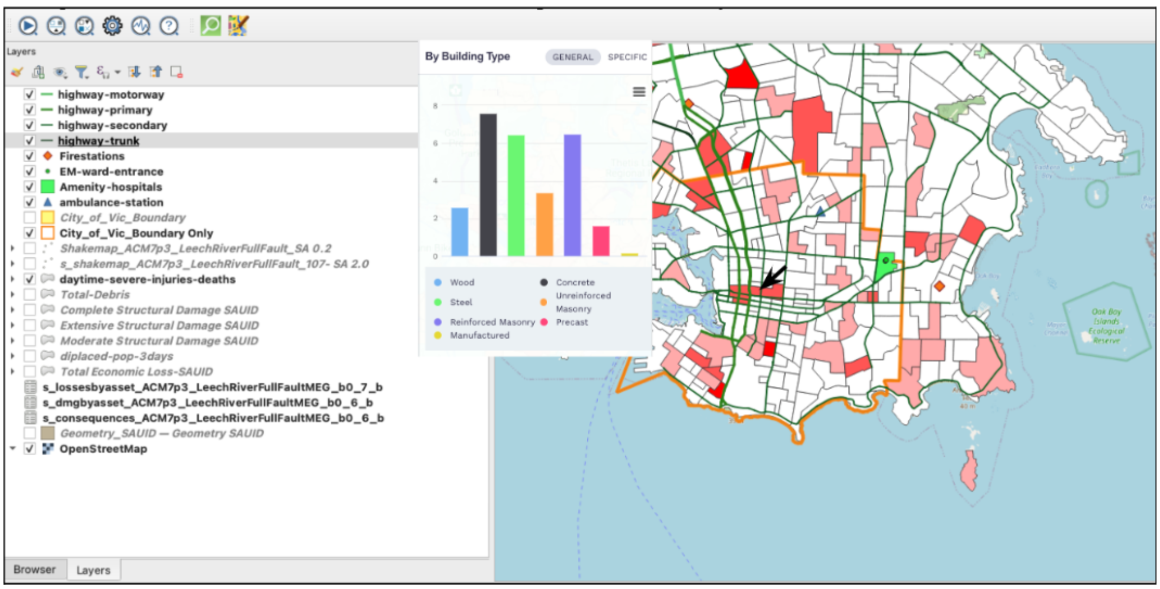


Figure 3.11: The map zoomed in to the Settled Area (SA) level showing the severely damaged buildings. As users click the neighbourhood polygon, more detailed data are displayed in bar graphs, such as what types of buildings are severely damaged, the age of severely damaged buildings, and types of occupancy (residential, commercial, etc.)

3.3 Participants' Responses

Questions and responses from the wireframe review sessions are provided in Table 3.1. The concept discussion using the wireframes involved two teams of emergency managers from the municipality and provincial levels who participated in the first informational session (UCD phase 2). The feedback session that took place over virtual calls. Each session took about two hours. The wireframe versions were provided for the purposes of soliciting feedback (UCD Phase 4) in order to improve the final products.

Table 3.1: Participants' Responses on Developed Wireframes, summarized.

Type of RED-E product	**Questions:**	**Answers:**
Text format	Can you gauge the severity levels from the text version of RED-E?	Users can gauge the severity by using the text format. Some users requested to have even more detailed information as ranked impact at neighbourhood scales (critical injuries, entrapment, fatalities, and shelter-seeking populations) to see which neighbourhood is most impacted. Such users did not mind having a longer version of the text format, but at the same time, they also appreciated the conciseness of the text format. They liked the ranked community information provided in the wireframe since it would allow users to quickly request resources from unimpacted areas or provincial/federal government levels. Some other users wondered how these estimates are made.
Text format	Would you be able to start making decisions based on the information?	Yes, users would be able to start making decisions based on the included information, especially if the products are released by scientifically authoritative institutions like Natural Resources Canada. Knowing the number and general locations of displaced population, fatalities, hospitalizations, and other information is quite useful. It can accelerate the resource request process and secure shelter accommodation.

Table 3.1 – Continued

Type of RED-E product	**Questions:**	**Answers:**
Text format	What might be missing from the text version of RED-E?	• A glossary of terms would be helpful - it strengthens clear communication; the definition of terms could be added on subsequent pages • CI interruption • Information on the impacted demographics • Information on secondary disasters such as tsunami • Visualizations of the impact
Static version (PDF)	The current version of static RED-E has combined the estimates of various levels of injuries (critical injuries, fatalities and entrapment) into a single metric, but would you like to see it separated?	For emergency managers at a municipal level, injury levels should be separated since various levels of injuries, entrapment, or fatalities need to be dealt with by different agencies. However, for the provincial government, such details are not as important.

Table 3.1 – Continued

Type of RED-E product	**Questions:**	**Answers:**
Static version (PDF)	Is the geographic extent shown useful?	The scale works fine for the provincial government, but for the municipal level, it would be even better if the community-specific pages were more zoomed in to only the municipalities.
Static version (PDF)	Would you like to know the amount of debris rather than severely damaged buildings?	Yes, that would be more useful since users would only want to know about building damage as it pertains to displaced/injured population locations, which they already have information on. They would rather use the debris information to initiate the processes to remove debris to clear the transportation networks.

Table 3.1 – Continued

Type of RED-E product	**Questions:**	**Answers:**
Static version (PDF)	What information might be missing from the static version that would be useful for you?	• CI disruptions (transportation networks, airports, ferry ports, underground CI disruption, natural gas, hazardous materials). Knowing the blockage on the transportation arteries is especially valuable. • Ranked list of impacted neighbourhoods • Ranked list of impacted communities • Demographic information • The maps should be colour-blind friendly • Map of population density • Uncertainties in the estimation • Secondary hazard information such as tsunami, liquefaction, landslide, fire • Definitions of the unit in the legends • Normalized values (shown as percentages) • Location of epicentre

Table 3.1 – Continued

Type of RED-E product	**Questions:**	**Answers:**
Static version (PDF)	Any comments on the size of the static version? Are two pages of information too much or too little for each community (and many more for the entire region)?	One team wanted more information but the other feels that two pages are more than sufficient: it should be kept concise.
Static version (PDF)	Would you like to have modelling uncertainties visualized even if it meant additional pages?	Yes, uncertainties can help decision-making. End-users at a municipality level do not mind if the static product becomes longer than two pages to describe uncertainties using maps. For others, if the uncertainty is to be added, it should use histogram types of visualization rather than having more maps to keep it concise.
Static version (PDF)	If you had to choose one map between social vulnerability or severely damaged structures, which one would you keep?	A social vulnerability map is not new information to some users, but the estimated structural damage is. However, not all the municipalities have done hazard social vulnerability assessments, and it is still helpful to be included. Others wonder if social vulnerability maps are useful when the disaster is so destructive, but using a bivariate choropleth map might be a great way to display two pieces of information on one map.

Table 3.1 – Continued

Type of RED-E product	**Questions:**	**Answers:**
Static version (PDF)	How would you use social vulnerability maps if they were included?	It can help in setting up appropriate reception centres in the right locations. Users can prioritize response efforts.
Static version (PDF)	Would you like to see structural damages separated into different levels (green, yellow, and red tags)?	One user said it was not necessary. They can tell it is yellow or green if it is not red. Another user said green can indicate safe locations to shelter people, which can be useful.
Static version (PDF)	Economic damage: Maps are not included, but would that be useful for you?	Not immediately, but perhaps later. Other jurisdictions, such as the Capital Regional District, might find it helpful.
Static version (PDF)	Could you start making decisions based on the information you were given?	Yes, users could, but it would be helpful to see the uncertainties in the estimated results and understand how the estimates are made.

Table 3.1 – Continued

Type of RED-E product	**Questions:**	**Answers:**
Dynamic version (GIS format)	For the dynamic version of RED-E, would you like to see separated layers for debris material (concrete and steel versus wood and brick)?	Yes, that would be useful, and the dynamic version is great, as users can choose what layers and features to add or remove. Dynamic versions should have a lot of information since users can control what they want to see.
Dynamic version (GIS format)	We currently have hospitals, ambulances, fire stations, and major highways - what other features should be added? E.g., schools, airports, etc.	• Care homes • Health clinics • Hazardous materials • Ports for ferries • Airports • Schools
Dynamic version (GIS format)	What information might be missing that you want to know?	• CI disruption • Secondary hazard information (tsunami, liquefaction, landslides, etc.) • Buildings that use natural gas

Table 3.1 – Continued

Type of RED-E product	**Questions:**	**Answers:**
All Products:	Is there a reason that you would prefer that some/all of this information not be made available to the public?	• Users are concerned if the public sees the number and locations of potential entrapments. They are concerned it will be highly emotional and challenging for some and might cause panic and public outcry by heightening the public expectation of rescue. • They understand the liability issues but support open access with a disclaimer such as stating clearly "the information herein is estimated values" or "Stay out! Hazardous area!" to remind the users that the provided information is estimated and keep the public out of danger.

General Feedback on the Wireframes

Participants' responses to questions about all three RED-E wireframes are summarized in Table 3.1; more details are outlined in this section, including detailed suggestions from end-users on how the products could be improved. Below are the general remarks that apply to all three RED-E products.

Overall, the text format (e.g., Figure 3.1) was appreciated by users as it is simple, short, and straightforward. It is meant to be communicable using amateur radio, satellite phones or commercial radio in the case of a telecommunication breakdown. Receiving information on the estimated impacts, such as the numbers of injuries, entrapments, fatalities, damaged structures, amount of debris, shelter-seeking populations, and economic impacts, end-users can gauge the levels of severity, have a sense of what to expect and will be able to request resources from the province or unimpacted regions, especially with ranked community impact information. For the province, having the ranked impacted municipalities' information would give users valuable insight into the areas that need the most support and municipalities that may be able to provide mutual aid. At the municipal level, end-users require different approaches depending on the scale of the impact on people; for example, procedures taken to shelter 100 versus 1,000 people would be different, and the text format can communicate the scale clearly.

Both municipal and provincial users recognize the value of the static format as well, appreciating visuals like maps that illustrate the scale and severity of impacts. They find both the first and second pages valuable as they serve different purposes for different users; the first page describes the larger scale and the second provides municipality-specific information. One team did not mind having a longer version of the static RED-E to include more information, but the other team expressed the value of a concise format and they felt that two pages were already long enough. For the dynamic version, end-users acknowledge the value of being able to add or remove certain features and choose their own layers to visualize, and they welcome as many details as possible, given that they have the capacity to remove them as they wish.

In general, for end-users, having maps of potential entrapments, severe injuries, fatalities, displaced populations, and debris is more valuable than building damages. Maps of collapsed building locations can be helpful; however, they are less valuable than maps that directly pertain to life safety. For example, sometimes collapsed buildings might be empty. Pre-code commercial buildings might collapse, but they will likely be empty if the event occurs at night. For end-users, their priority is to save lives. Thus, they would prefer to have potential entrapment maps, which generally represent the locations of collapsed buildings, especially immediately after the event.

Depending on the scale of the event, the municipality might need to rely on the province or the federal government to support them. The faster they receive the estimated impact report, the faster they can request funding or resources, making RED-E extremely valuable since waiting on the ground-truth data will take hours or days. To request resources, users must communicate the estimated impacts and expected gaps in capacity to respond; thus, the information provided by RED-E is powerful, and it is valuable to have the text format for redundancy in uncertain times.

Users highlighted that providing separate injury levels based on severity is useful since different responses are required by separate agencies for various levels of injuries or fatalities, requiring different resources. For example, fatalities need to be dealt with by coroners, who may be guided by a mass fatality response plan; however, critical injuries require rapid hospitalization, while first-aid level injuries may not require hospitalizations. Entrapments require support from Heavy Urban Search and Rescue, and knowing the estimated entrapment numbers can help get a HUSAR team in the area.

Respondents would like to know the secondary hazard information such as tsunami, liquefaction, landslide, and fire, if possible. Currently, RED-E cannot model tsunami impact using the OpenQuake Engine; however, it may be possible to implement the OpenQuake Engine Liquefaction Calculator in future. Users expressed that even if tsunami modelling is not available, simple potential inundation zones can be layered and that would still be useful.

As reception centres are opened, there may be a plan for two or three different kinds of centres based on the population's demographics. For example, one could be for seniors, and one for families, understanding that they require different types of care. For that reason, having demographic information on the displaced population is valuable.

The RED-E products should be inclusive. During the wireframe concept discussion, it was suggested that RED-E products could utilize maps to display two different pieces of information. For example, illustrating the number and location of displaced people as well as the distribution of the socially vulnerable population (Figure 3.12). The use of such maps can conserve space for static RED-E products and still showcase the estimated impact. The colour palette used in Figure 3.12 was confirmed that people with deuteranopia (red-green colour blindness), the most common type of colour blindness, can distinguish the differences; however, there are other types of colour-blindness to consider.

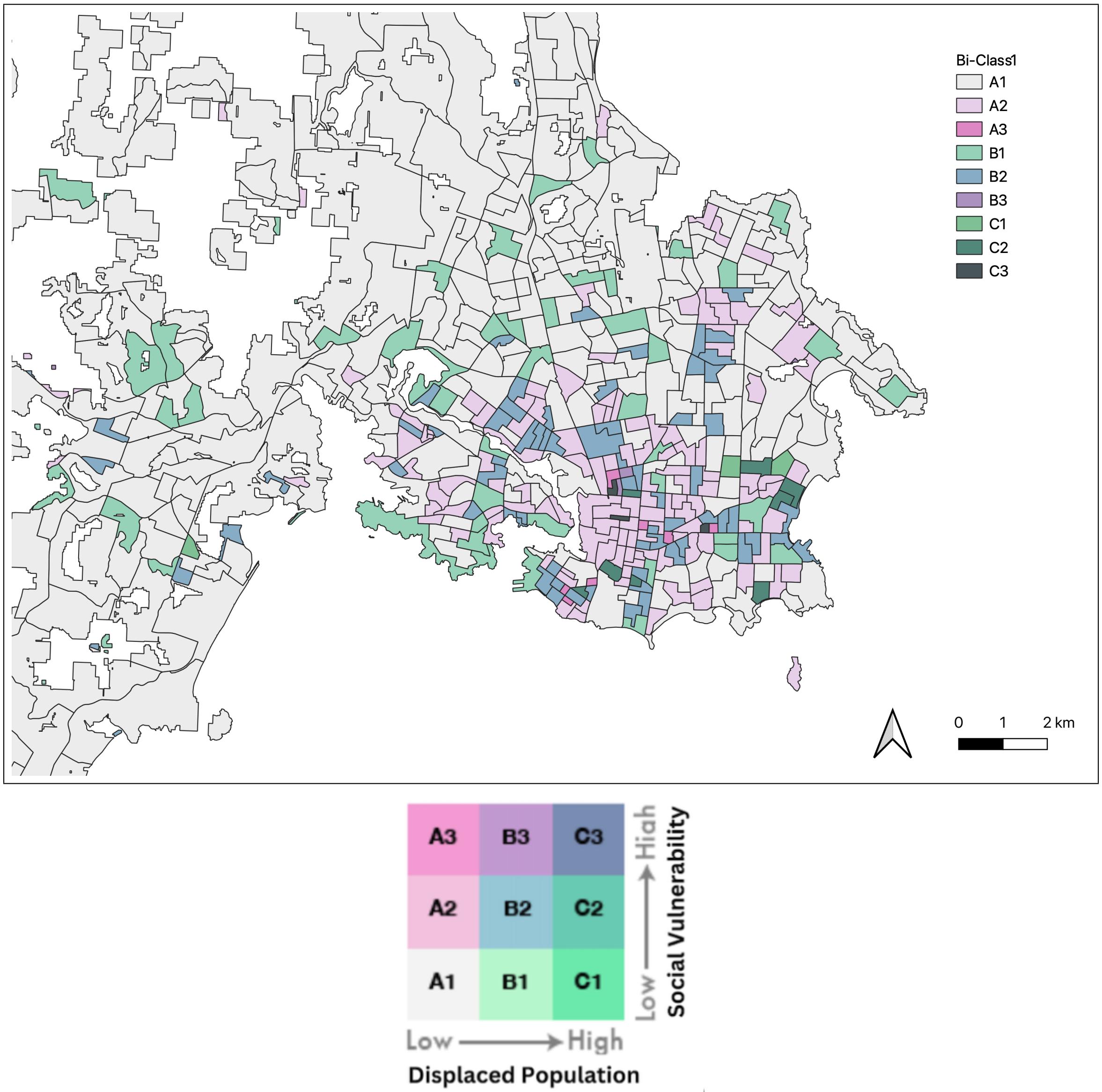


Figure 3.12: An example of a bivariate choropleth map displaying the displaced population and social vulnerability. The legend is modified from Stevens (2015).

3.4 Discussion and Future Work

3.4.1 Inclusion of Critical Infrastructure (CI)

Potential RED-E end-users expressed that they would value being provided with the estimated impacts on the CI, including transportation networks, bridges, airports, ferry ports, and underground structures, and the impacts on manufacturers with hazardous materials. Especially considering the importance of the first 24-48 hours, the ability to get outside support, such as HUSAR teams, to the regions will depend on the conditions of transportation networks; thus, such information will be critical. Aside from the tens of hours it will take to initiate aerial reconnaissance over the disaster area, the three most frequently identified obstacles to quickly gaining credible and complete situational awareness were road blockage, loss of telecommunication, and staff shortages (Chapter 2), as all of these issues limit the ability of staff to conduct reconnaissance or receive reports via phone or the internet. Identification of road blockages could be prioritized in subsequent versions of RED-E. There are prior global examples of such network impact modelling from seismic impact, such as works done by Cho et al. (2001), Costa et al. (2018), and Poudel et al. (2023). There are plans to test out the new linear infrastructure module for the OpenQuake Engine to investigate the effect of earthquakes on roads, specifically in terms of damage to onramps and highway bridges in Canada. This approach could then be leveraged in RED-E to address the comments from end users documented in Chapters 2 and 3.

3.4.2 Inclusion of Secondary Hazards

Many end-users suggested that they would appreciate it if some levels of secondary hazard information, such as liquefaction, landslides, fire, and especially tsunamis, could be included. This type of secondary hazard information can be critical for response teams since, for example, landslides could block the only road for remote communities where using alternate routes is not an option, unlike urban cities, or significantly increase the number of fatalities and injuries. Although the PAGER system from USGS does not include the secondary hazard information in the PAGER itself, a separate site offers information on estimated secondary hazard impacts as a near real-time product, providing the estimated extent of impacted regions of liquefaction and landslides and the potentially exposed population. This is simply the presentation of hazard threats and is different from what RED-E offers, which calculates the loss impacts inferred from structural damage. However, if a similar hazard product could still be useful to end-users, it should and could be considered for inclusion in the future.

3.4.3 Visualization of Uncertainty

Consideration of the inclusion of uncertainty communication in RED-E products is critical. In the versions provided to users for feedback, uncertainties were shown as ranges of estimated numbers (fictitious values used only for illustrative purposes). The interview respondents implied that visualization of uncertainties is helpful for them and can help them navigate their decision-making processes. Studies also reinforce such views, indicating that providing visualized uncertainty for forecast information could narrow users' expectations, providing more precise and valuable information for decision-making with higher confidence levels (Joslyn and Savelli, 2010; Schneider et al., 2022). Figures 3.13 and 3.14 showcase examples from the PAGER system and an associated study. Both figures demonstrate the probability of modelled fatalities and economic losses, but Figure 3.13 includes histograms as currently used by the USGS, and Figure 3.14 portrays uncertainty using scatter plots, as proposed by Karjack et al. (2022). The scatter plot versions were revised based on suggestions made by cognitive scientists and led to significant improvement in understanding of the uncertainties by both technical users and public users (Karjack et al., 2022). Decisions on how the uncertainty should be displayed for RED-E may take further research to explore, but the inclusion of uncertainty communication should be considered the inherent uncertainties in modelling should be thoroughly explained to end-users before the launching of RED-E.

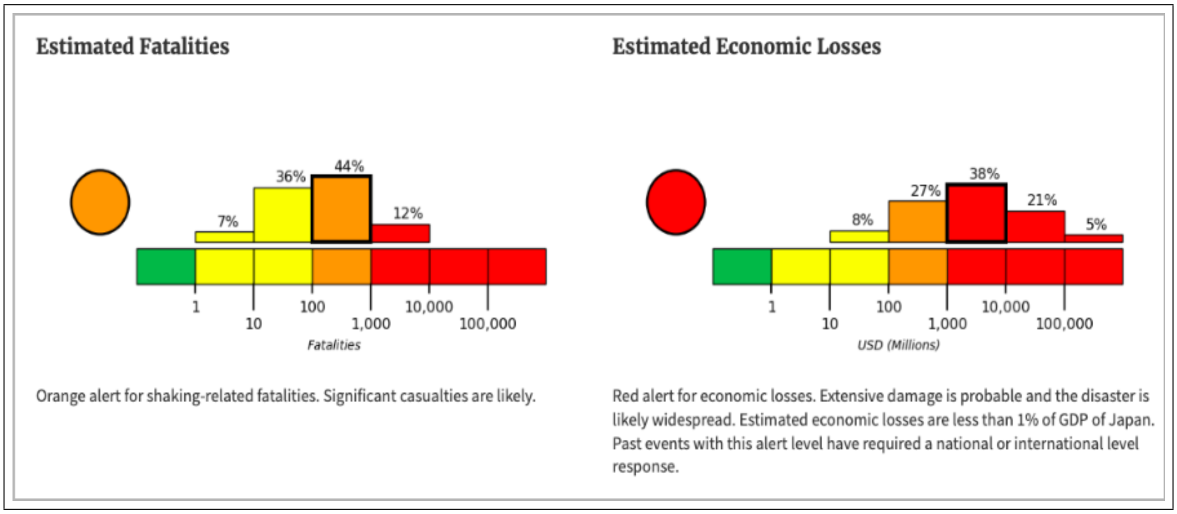


Figure 3.13: Histogram, as currently used by the USGS to express uncertainties /probabilities in PAGER (US Geological Survey, 2024).

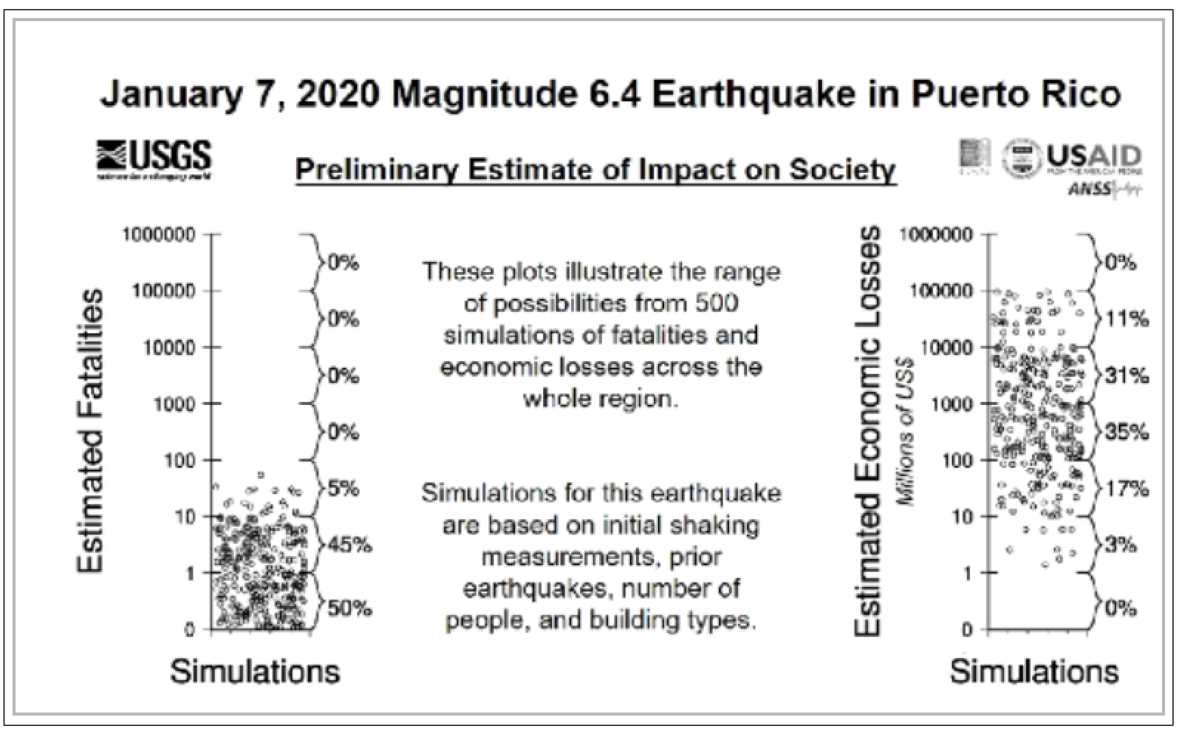


Figure 3.14: Newly proposed probability plots to showcase uncertainties (Karjack et al., 2022).

3.4.4 Social Vulnerability Index

"Social vulnerability refers to the socioeconomic and demographic factors that affect the resilience of communities" (Flanagan et al., 2011). When a disaster hits, certain groups within a community often bear a disproportionate share of the negative impacts and associated socioeconomic consequences. Lower-income households, recent immigrants, racially marginalized populations, people with disabilities, the elderly, unsheltered populations, people without means of personal transportation, and other groups whose rights and needs are not always fully met in the context of community planning or disaster risk management have limited access to support networks (Journeay et al., 2022). The socially vulnerable are "more likely to die in a disaster event and less likely to recover after one" (Lorelei, 2006). It is critical that officials recognize the increased risk of these populations during the post-disaster response and recovery phases. People described as socially vulnerable generally lack the financial ability to prepare for emergencies; thus, they often require more urgent and prolonged support. The RED-E products present combined social vulnerabilities encompassing over 20 demographic indicators (Journeay et al., 2022). Broadly, the indicators incorporate four categories: social capital (concerning family structure and community connectedness), autonomy (the ability to take actions on one's own to manage the results of hazard events), housing (shelter conditions that will influence the probability of household displacement and reliance on emergency services), and financial agency (economic means to sustain the requirements of day-to-day living during periods of disruption that can affect employment and other sources of income)(Journeay et al., 2022). The inclusion of such visually comprehensive products as a layer of information is believed to be valuable or even essential, especially for municipalities that lack resources to conduct their own socioeconomic vulnerability assessment.

3.4.5 Managing Expectations

The last question posed to participants inquired if there was any reason that they would prefer the information not to be made publicly available. Users, especially at a municipality level, would be concerned if the public could access the estimated number and locations of potential entrapments. Such information is deemed highly emotional and difficult for some. Users are concerned that the public might try to rescue the victims, but by doing so, they might put themselves in harm's way or disrupt response operations. These concerns are consistent with the results of the first informational interviews (Chapter 2), where users also revealed concerns about potential public outcry. As the public sees more information, their expectations also increase, but the response effort might not meet their expectations. If the public could see the estimated locations and the number of entrapments, such information would make the public emotionally charged and they may start criticizing the effectiveness of response operations without understanding response priorities and other variables. Participants understand that, to some degree, people will try to rescue others on their own, but they want to limit it as much as possible since such actions are unsafe. The provincial government participants were more supportive of publicizing the information so long as there is some text disclaimer so people will not be confused about what they are viewing and there will not be additional liability. All participants suggested clearly stating that the estimates are made by modelling, which comes with inherent uncertainties, and that the public should be warned to avoid hazardous areas.

While there could be some potential benefit in making the RED-E system accessible to spontaneous volunteers or users outside the emergency management field, such as the insurance industry, it is important to note that this system is designed to assist end-users rather than burden them with additional tasks during the immediate aftermath of an event when they are already overwhelmed. The majority of end-users have emphasized their preference for a public-facing version of the model that features a more general geographical scale and information, rather than detailed output being publicly available. The primary purpose of these studies was to incorporate end-user feedback into the product creation process; therefore, it is critical to respect and reflect these concerns.

The RED-E products are specifically developed for specialized personnel at this point, including emergency managers, first responders, and CI operators. However, it is possible that the product might be released to a broader audience, including the public, in future; if so, the design of the products must be modified to meet their needs, and scales need to be adjusted accordingly. For example, the study results of Loos et al. (2024) indicate that already publicly accessible products such as PAGER should be modified to become more inclusive by making the information more relatable, transparent, understandable, and shareable. If the tool is to be available to the public, it needs to be accurate and reliable, and it must come from a trusted source and not conflict with other official data from a trusted source and does not conflict with other data. Making the product publicly accessible may be aided by further studies to best understand the decision points for public users and how a non-specialized audience interprets the current version of RED-E. Launching a public-facing version of RED-E itself could also be used to raise awareness of seismic hazard and risk. When creating products for different audiences, it is vital to consider their purposes. The United States Geological Survey (USGS) is considering creating a more public-facing PAGER product and refining the existing PAGER to increase the clarity of information for specific users (Karjack et al., 2022).

An informational vacuum can cultivate mistrust in authority and science (Fallou et al., 2020). Based on end-user feedback, clear information needs to be provided to explain how the modelling is done, its benefits and limitations, the inherent uncertainties modelling carries, and an explanation of the terms used. Including links in the products, leading to more detailed information, and offering educational workshops online and offline could be helpful options for users who wish to learn more about the technical aspects of modelling processes. It is essential to communicate the capacity of seismology and the modelling limitations, to regulate user expectations from recognized authoritative and scientific institutions and to retain the trust in seismology science and the institutions themselves, as such anxiety can enhance the expectation for scientists to find solutions (Fallou et al., 2020). Furthermore, these anxieties can open up the room for misinformation or conspiracy theories if left unmanaged (Fallou et al., 2020). The study further states the value of timely acknowledgement of a significant seismic event with attributed information such as magnitude, location and felt intensities; the provision of post-earthquake safety tips and ongoing updates is also an effective way to reduce public anxieties, especially as aftershocks are not uncommon after large earthquakes (Fallou et al., 2020). However, determining what information is appropriate for a certain audience require further investigation to tailor the products for the audience.

3.4.6 Providing Educational Resources for Users

Communicating the modelling processes helps end-users understand the limitations and recognize where the uncertainty comes from. End-users might benefit from informational workshops to know what metrics are involved in the social vulnerability indicators or why the data RED-E requires to produce its outputs (e.g., ground motion data) becomes more accurate over time following the initial rupture, for example. Including links in the products leading to more detailed information, holding educational workshops in person, or recording such workshops to make them more widely accessible online could be valuable options for users who wish to learn more about the technical aspects of modelling processes. The study conducted by Karjack et al. (2022) indicates the effectiveness of an improved understanding of hazards and motivation for preparedness by helping people learn how earthquakes happen (Karjack et al., 2022). RED-E products could serve as an essential medium to promote personal disaster preparation and build community resilience in the future.

3.4.7 More Accurately Represented Population Census and Housing Data

Another important avenue for future research is to obtain more accurate population and housing data for First Nations communities, which are typically underrepresented in the Canadian Census yet underpin current exposure inventories (Smylie and Firestone, 2015; Saku, 1999). Census data are the most widely used and essential sources of information as they provide comprehensive pictures of the characteristics of the people in the community (Trevethan, 2019), and they serve as one of the critical exposure data inputs for RED-E modelling processes. However, there are some challenges to address regarding the First Nations census data. First Nations tend to be underrepresented because the Indigenous indicator is based on self-identification, and there has been some undercounting due to the non-participation of some reserves. Transient First Nations populations between reserves and cities and between jurisdictions can contribute to inaccurate population counts, leading to the inflated size of some towns/cities or people that are not recorded in the census at all; First Nations communities responsible for providing services on reserve may be underfunded because of the uncounted transient population (Trevethan, 2019). Another study indicates that the current Indigenous social statistic data are unequally represented, leading to quality challenges contributing to a significant underestimate of inequities in health determinants, health status, and healthcare access between Indigenous and non-Indigenous people in Canada (Smylie and Firestone, 2015), which can lead to underrepresented social vulnerability in the RED-E output.

3.4.8 RED-E is an Evolving Product

User Centered Design (UCD) is an iterative process. In addition to incorporating the feedback obtained through this study, additional commentary should continue to be sought after the product launch. The subsequent study can be conducted by using finalized products to solicit feedback to evaluate the user's ability to comprehend the data accurately and make decisions based on the products and to test the product's usability using scenario cases. It might be possible to gain a larger volume of feedback by conducting survey-based studies or making workshop/presentation videos as RED-E products are launched and further developed to make the survey process more scalable. The study followed the UCD principles, and conducting informational meetings, building wireframes, and receiving feedback on RED-E wireframes are the first and critical steps in the process of refining the RED-E system.

3.5 Limitations

Given the investigators' language limitations and time constraints, this study phase involved two teams of emergency managers from BC's municipal and provincial governments. BC is an English-speaking region known for its high seismic activity.

3.6 Conclusion

An aspiration of the RED-E system is to help enable more rapid and effective mobilization of disaster response immediately after a significant earthquake. Experiences from past seismic events and feedback from informational interviews indicate that gaining situational awareness immediately after a damaging earthquake can be time-consuming and challenging. However, the importance of immediate response within 24-48 hours for life-saving purposes is validated through many studies (de Bruycker et al., 1983; Noji et al., 1990; Coburn et al., 1992) and past events. Rapidly available (within tens of minutes) modelled information on human, structural and economic losses can be a helpful guide to gauge the severity of the impacts on the affected communities and regions. The study's objectives were to create wireframes and receive feedback on them, culminating in the current report with steps to finalize the product.

Reflecting on the comments received during the informational interviews (Chapter 2), three wireframes of RED-E products were developed: text, static, and dynamic, and feedback was solicited from two teams of emergency managers at municipal and provincial levels. The most critical feedback received, which can be incorporated into RED-E immediately, is the inclusion of definitions of terms, features like ports, airports, hazardous materials, etc., information on injuries that are separated into different levels of injury severity, separated debris materials, colour-blind friendly bivariate choropleth maps to display two variables without compromising the space, closer geographic extent for the static product (for the second page), and possibly the inclusion of impacted demographics and ranked impacts for the text format at neighbourhood scales. Suggestions that will be considered as modelling capabilities expand are the inclusion of CI information and secondary perils. Overall, all the wireframes were well-received by end-users with the understanding that secondary hazards and CI infrastructural losses are not included in the model at this point, validating the usefulness of RED-E products and confirming that it is ready for operationalization in Canada in the next few years.

Chapter 4

Conclusion

This thesis discusses the importance of gaining situational awareness quickly after significant earthquakes for emergency managers, first responders, and Critical Infrastructure (CI) operators, as the decisive hours following such events are crucial for rescue operations. It explores the usefulness of the prospective Rapid Earthquake Damage Estimation (RED-E) system in Canada to model damage, fatalities, and economic losses based on shaking intensity maps and risk assessment using the OpenQuake engine software. The future Canadian RED-E system aims to leverage Canada's Seismic Risk Model, ShakeMap outputs that leverage the Earthquake Early Warning seismic networks, and consultations with end-users to provide timely decision-making support during these critical hours.

This thesis has extensively explored global examples of rapid disaster modelling systems, clarified the motivation and rationale behind the development of the Canadian RED-E system and introduced its current status (Chapter 1). The study was conducted using the User-Centered Design (UCD) principles to guide RED-E design and implementation decisions. The first phase of the UCD process is to define the target users, the tool's capability, and the strategy of research procedures. The second phase of UCD requires user engagement to learn the end-user needs, goals, and issues they may face within the 24-48 hours following a large earthquake, as well as to examine how the RED-E tool could assist the situation (Chapter 2). Based on the feedback gained from the end-users, three wireframes for the system were created (UCD phase 3), and these wireframes were presented to end-users to validate the value of the products and receive more comments in order to enable further improvements (UCD phase 4, Chapter 3).

In Chapter 1, the study established that developing a Canadian RED-E system is essential for several reasons. Other global rapid damage modelling systems effectively communicate impact scale quickly, while RED-E offers additional value to Canadian end-users by providing details on smaller geographical scales, the number and location of displaced people, the impacted number and location of socially vulnerable populations, and various levels of injuries, which can greatly benefit local responders.

Moreover, although Canada uses USGS's ShakeMap and EEW software to create similar products, adopting USGS's PAGER system for Canada would not be more practical or feasible since the PAGER system is not necessarily designed to be modifiable or adaptable by other countries. Moreover, Canada has already devoted significant resources to developing its own comprehensive risk model based on the Sendai Framework mandate, which is readily accessible on RiskProfiler.ca. By integrating near-real-time seismic parameters, RED-E outputs can be easily generated for end-users. Enhancing resiliency and response capacity at the societal level can be further strengthened by leveraging this valuable and regionally appropriate product. The RED-E output will be customized specifically to meet the needs of Canadian end-users, utilizing detailed building exposure data and applying Canadian-specific fragility and vulnerability curves to estimate damage.

Chapter 2 presented the design, content, and outcomes of end-user informational interviews. To understand the end-users' real-world situations, needs, and the problems the product aims to address in the immediate aftermath of a major earthquake, engaging with the end-users is essential, and reflecting their voices at the early stage of product development is critical for developing well-serving and eventually indispensable products. The study engaged with representatives from various organizations at different levels of government, Indigenous communities, non-political organizations, and academic institutions and ensured representation from diverse backgrounds and regions across Canada. The interviews, conducted via virtual meetings, involved 27 participants who each answered 18 open-ended questions over 1-2 hours.

Key findings from Chapter 2 include the desire for multiple communication channels for the RED-E system, the potential for the system to assist in prioritizing rescue efforts, and the identification of obstacles to gaining situational awareness, such as road blockages and telecommunication loss. Information desired by end-users within the first 24-48 hours includes critical infrastructure damage, displaced populations, injuries, secondary hazards, and safe evacuation locations.

The majority of end-users expressed concerns regarding the potential for a public-facing RED-E if it were to be made. These concerns include the potential for the public to misunderstand the modelled data, cause panic, and have heightened rescue expectations. The aim of RED-E is to help emergency response end-users work more effectively by providing useful modelled data to them, not complicating their work; thus, it is critical to reflect on the end-users' concerns. End-users expressed a preference for dynamic maps, PDF formats, and simple text for receiving RED-E information, with a focus on usability and accessibility. Integration challenges for end-users include staffing capacity, technical issues, and training costs.

Chapter 3 represents the third and fourth phases of UCD. It showcased three wireframes developed for the RED-E system (UCD phase 3). These wireframes are conceptual outlines of the future interface, focusing on prioritizing content and functionalities. Feedback comments on the wireframes by end-users are also included in this chapter (UCD phase 4). Feedback on the wireframes was gathered from emergency management teams who previously participated in the informational interviews. This feedback was then analyzed and discussed. The insights from these interviews confirm the significance of the RED-E products.

Key findings from Chapter 3 include the following. End-users prefer receiving maps of potential entrapments, severe injuries, fatalities, displaced populations, and debris over building damages. Maps of collapsed buildings are helpful but less valuable than those focusing on life safety, as some collapsed buildings may be empty depending on the hours of the seismic event. Saving lives is the priority for end-users, making potential entrapment maps crucial immediately after an event. Receiving RED-E reports quickly is valuable for municipalities or provinces/territories to request funding or resources, as waiting for ground-truth data can take hours or days. Providing separate injury levels based on severity is useful for directing appropriate responses and resources accordingly. Demographic information on displaced populations is also valuable for planning reception centres tailored to different demographics. RED-E products should utilize bivariate choropleth maps displaying two pieces of information, such as the concentration and location of both the displaced population as well as the socially vulnerable population, especially for static versions, to maximize the limited space. It's also crucial to choose colour-blind-friendly palettes for inclusivity. Additionally, it is important to consider communicating uncertainty levels in modelled results, which can be helpful for their decision-making processes.

Overall, many users are optimistic about the system's potential value, despite its current limitations in modelling secondary hazards and impacts on critical infrastructure. For the provincial governments, this tool can allow them to act proactively to foresee the needs of local governments before receiving requests, e.g., to approve financial assistance or external help where estimated losses exceed local capacity. For the local government, it can be a prioritization tool to initiate the response effort and identify safe locations to house displaced populations. Based on the informational meetings, the end-users would highly appreciate having the RED-E tool as it can be a helpful guide to fill the gap until ground-truth data becomes available. The statement is especially true if the tool implements users' recommendations, as expressed herein. The user-centred design methodology and the findings of this research may also be of interest to other agencies outside of Canada who are developing or refining similar rapid damage assessment tools.

Appendix A

This is a complete list of questions and answers from a survey to solicit feedback from end-users. A subset of these data were provided in Chapter 2.

A.1 "Could you briefly explain your role after experiencing a significant earthquake?"

Most responded with the same answers: setting up Emergency Operation Centres (EOCs), connecting with colleagues, and developing plans for rescue, evacuation, and shelter needs are the leading answers.

- Setting up EOCs
- Contacting colleagues
- Understanding their capacity (a part of situational awareness); how many firefighters are available. Which fire halls are still standing and functioning?
- Communicating with the public about where to evacuate and what happened
- They will try to secure the transportation routes to get people in and out, and they will decide which one would be the best to send the people out to validate it, to at least establish one route of evacuation, and depending on the

community needs and damage level they will identify and decide what areas need to be inspected first to send out the heavy urban search and rescue teams.

- Keeping people safe: we discourage people from entering dangerous buildings even if their friends or relatives are inside and ask them to rely on the first responders, but they are usually delayed.
- Reviewing the states of bridges
- The role is still undecided; the government is relatively new

A.2 "After an earthquake, when are you expected to report for duty?"

Many respondents are expected to report for duty as soon as they are able.

A.3 "Currently, how do you expect to gain situational awareness after a major earthquake?"

Most responses suggest that situational awareness will be developed based on 911 calls and windshield surveys conducted on foot or by vehicles, if possible. Multiple answers are shown here. Drones are mentioned, but their capacity is limited by the availability of technicians, restriction of aerial space near an emergency zone, a potentially slow approval process, and small quantities of available drones.

For transportation sectors, they have post-disaster assessment protocols to identify bridges that meet criteria such as over a certain magnitude threshold, distance from the epicentre, built year, etc., and they prioritize them to send bridge area managers to review, and depending on their review results they may send assessment teams; however, in reality, if earthquakes are significant, timely review of these identified bridges might not be possible. They are currently building tools to identify the bridges to prioritize recovery.

- First responders or staff (Firefighters, police, ambulance, etc.) would go on foot or by vehicle to conduct windshield assessment and report the damage on their fire halls (status reports); some communities would go door to door: crews on foot conduct windshield assessments and report back; they would go into the predetermined high-risk area to see, but only if they are safe (no tsunami and flood risk) to enter the area; they would walk (patrol) or drive to gain situational awareness based on the pre-identified fragility of buildings and priorities; the patrols would have to report in through radio, or would have to return to an area where they can get telecom access, which would delay things. (16 responses)
- Phone calls; 911 calls; their system can locate the cellphone that calls come from to identify the location, but in the likely large event that the communication network is down, it won't work well, so if that's the case, it would be units going out to assess the situation. (10)
- Rapid Damage Assessment tool from BC Housing or similar portal; one of municipalities' downtown core holds aging infrastructure and buildings, so they will likely start there; trained public workers will conduct building rapid damage assessment as well, but for the safety reason, it might not be possible to send them to a certain area (possibly 3 to 4 teams of two members will be sent out in the district ideally in vehicles. They will not be sending anyone to low-lying areas due to tsunami concerns. They might not send them out due to safety reasons without protecting shelters); Ontario has a provincial disaster assessment team known as PDAT; a lot of it would rely on those lower levels of government to communicate upwards; push notification with the survey would be disseminated to staff to understand their availability to report and form teams to conduct a visual survey of infrastructure, and if the communication is live, then they will report back the conditions through their web-based application, and they have identified the high-risk area of the bridge for the highways. (10)
- Drone; drones are available if they request but very limited in number and technicians, and many are unsure how much they can rely on them, and the area they can fly is restricted. (7)

- Social media, but the rumour mill is a genuine concern and problem. (4)
- Media; press events, notices, bulletin boards (4)
- If a major earthquake occurs, it would be at the provincial level activation; thus, they use Common Operating Picture (COP) that connects with the province to share and receive information; information from the province, regional dispatch centre, or communication with neighbouring municipalities; they rely on the province to share data to gain situational awareness. (4)
- Volunteer radio teams and local radio stations; they could receive information by radio like their ham radios, and they also have an emergency management radio system. (3)
- People come to the hospitals, reception centre, and security office, and they also bring information or send emails. (3)
- Remote sensing data from NRCan (2)
- Security camera (1)
- They have a traffic camera network across the province to gain situational awareness if the telecommunication is still up (1)
- Use an app to gain information from the public; this is a community app to exchange information with residents (1)
- Communicating with larger surrounding districts (1)
- They use their alerting systems or websites to communicate with people, but they can't gain situational awareness quickly at this point. (1)

A.4 "What are the current obstacles to gaining situational awareness quickly?"

- Undrivable roads, highways or bridge conditions/accessibility; loss of airports, ports, rail, or other transportation means; many city staff don't live in the city; especially bridges are bottlenecks; many travel to where they work from outside cities and without bridges, they can't get there; one road in and out; if it's disrupted it would have a significant impact, but they are outside of their jurisdiction perhaps requiring previously MOTI (the Ministry of Transportation and Infrastructure); if this road is disrupted they will require help from the province; response from engineers to get back to them takes time; about 60% of employees work outside of where they serve (23)

- The loss of telecommunication networks: causes a time lag in reaching out to the necessary staff and officials and grasping situational awareness; without telecommunication, there isn't much they can do other than drive to the communities (10)

- Lack of available and qualified staff: capacity issues of first responders; even on regular days, staffing challenges; Too many calls are on hold, and they are waiting for days even on regular days; many communities lack in capacity to handle a large disaster; there might be only one person reporting, with many volunteers- getting situational awareness quickly can be problematic and time-consuming; availability of trained staff/engineers; lack of personnel to make crucial decisions; some other staff who are decision-makers might not be as prepared as emergency managers might be, which can hinder decision-making processes and hamper the response (10)

- Lack of electricity/power (5)

- Damage to critical infrastructure: sewage, water, power (3)

- Rumour mill: validation of the social media information would be complex and takes a long time (2)

A.5 "Realistically, how long do you expect it will take to gain credible and complete situational awareness after a major earthquake? Does this timeline change if there is a significant disruption to roadways?"

The time it takes to gain complete and credible situational awareness seems to depend on the size of the event, location, and time of the day. The quotes below explain well why. Everyone except one respondent answered yes to the second part of the question: "Does this timeline change if there is a significant disruption to roadways?"

"How long it takes to gain complete and creditable situational awareness depends on the time of the day. If it happens during the day on weekdays, they would respond immediately, but it won't be the case at night and on a weekday. It takes many hours if that happens at 3 am on Sunday, but they plan to install some cameras in the specific facilities to gain situational awareness soon. If the event happens at night, they need daylight to know what happened really, so it would take a lot longer to gain some information; it probably takes weeks to gain it."

How long it takes to grasp all of the bridge conditions is challenging to answer since there are over 3,000 bridges in BC, and if events occur in remote areas, it will take longer to survey. The timeline depends heavily on road conditions.

- 3 days to weeks: Depending on the availability of telecommunication networks and road disruption, it could take days; depending on the event, but at least 72 hours (3 days) to gain a decent picture of the situation, and a complete and credible picture would take weeks; for rural areas (since they lack existing transportation infrastructure, one damaged highway would be detrimental, whereas urban areas can find alternative routes), it could take up to weeks; within a day (16-24 hours) for general ideas and 72 to 96 hours to have a much better picture of situational awareness; the military would take days to deploy: about

5 days to deploy (15)

- Unknown: communities rely on two bridges to connect with other communities; can't serve certain communities if bridges are down; the majority of key personnel commute outside of the community and road disruption would mean they won't make it to the community to do their work; it depends if they have telecommunication and road network working (6)
- 24-48 hours; within a day or two they should know enough to set priorities; "with a large scale [of] earthquake, you're going to continue to deal with the problems that you have at hand. But after the first 24 hours, you should have a plan as to what your priorities are and what you're going to be capable of and make some hard decisions as to we're not going to be able to do that. Also calling in other resources" (4)
- 12 hours (1)
- The community only has 70 homes, and they can walk and check on everyone door to door within two to four hours (2)

A.6 "How do you share collected data, and who do you share it with?"

- Share with neighbouring municipalities and provinces, and the province may share with the federal government if necessary. They share collected data with neighbouring municipalities over the radio, or they might just visit them in person to share the collected data. They will also share with provincial or federal governments, but it depends on what their legal department says.
- Through COP or provincial calls: Emergency Planning Secretariat (EPS) would be on the calls with the province, and the province usually has a lot of data/information from the CI operators (BC Hydro, MOTI for transportation, Drive BC, etc.), and they also sit in on calls with hospitals, too, but municipalities or First Nation (FN) communities will not share their data unless it's necessary. They share their communities' data with only their leadership and keep it within

the organization, but there is a non-profit organization that advocates for FN communities' needs, and they will share some data if it's necessary to get some support from the province or others. Many sit in on calls with the province to gain regional situational awareness.

- All FN communities involved in this study share data with First Nations Emergency Services Society (FNESS) Emergency Planning Secretariat (EPS), and with EMCR if necessary and ask for support from them if needed.

A.7 "How quickly do you expect to be able to deploy first responders after a major earthquake?"

Most could not provide definitive answers to "How quickly do you expect to be able to deploy first responders after a major earthquake?" since the response time depends on the time of day, size of events, epicentral locations, and individual circumstances.

- As soon as they are able; this is after making sure they are physically and mentally well, and their family members are okay and not in danger, and there are no immediate needs at home. Response time is difficult to imagine; people might expect us to be there no matter what to help them, but that's not always the case (7)
- Depending on the time of day, if during the day, we're going to be activating immediately, but slower on weekends and during the night (2)
- Depending on the road condition, their locations and their families' well-being and locations, and the communication network (2)
- Within hours (2)
- For a small event like an apartment fire, the volunteers can come within half an hour, but for a major event, it would take at least 2 hours to set up a reception centre; set up an EOC within 24 hours (2)

- Unknown: many people commute out of their homes, and responding to the community could be challenging, especially if the roads are not drivable (3)
- Unknown: some communities don't have in-house first responders; they have contracted first responders (firefighters), but they are farther from the community, and if their own community is also impacted, then it makes it unlikely that they can come and help the smaller community even though they are required to help them; many first responders and emergency managers don't live in the community they serve, and it makes it challenging to be deployed right away (3)
- They will be communicating with each other within 10 minutes at max and coming up with a plan (1)
- The first response would be out within half an hour (1)

A.8 "Are the response teams deployed to the most disrupted areas or based on other prioritization systems?"

Most responders will be dispatched based on the British Columbia Emergency Management System (BCEMS) guideline. Other critical priorities are vulnerabilities of the impacted population, stabilization of the situation to protect the public, and how they can maximize the good with limited resources. Smaller FN communities don't have the capacity to dispatch response teams as they wish until they grant permission from the province to fund the teams.

- Based on BCEMS:
    1. Ensure the health and safety of responders
    2. Save lives
    3. Reduce suffering

4. Protect public health
5. Protect infrastructure
6. Protect property

- Life, safety, and property = basically the same as BCEMS; the first priority is the responder's safety, and the second is rescuing lives; this is because the responders are assets, and they might not always send the responders to the most disrupted area, but they might if it is also the highest concentration of vulnerable populations to benefit the greater good; not solely dependent on building damage but if there were people in the building they would send the response team there (6)
- They consider the vulnerability levels as well as impact levels, vulnerability of people and population density. People with rich resources and large backyards and without tall buildings next to them will not be the first on the priority list (4)
- Where can I do the most good with the resource: maximum benefit with using the current resource; where can you make the most benefits with the resource we have that would also be a priority; how to serve the greatest number with available resources; first they need to gain the situational awareness to utilize the limited resource; they want to go where most good can be done based on the resources they have and decisions will be made at DOC (Department Operation Centre) or EOC, but the vulnerability of population also would play a part; greater risk and the best allocation of resources: deployed to the most disrupted areas based on the report if many people's lives are at risk (4)
- Stabilization of situations that can harm many people might also get prioritized too (1)
- Vulnerability: Many communities don't have first responder capacity within the communities but have contract with neighbouring municipalities, and response will prioritize their response based on risk and will be dispatched based on 911 calls. Some FN communities are considered high-risk, and they will be prioritized (1)
- 911 calls (1)

- For many FN communities, they require approval from the province to fund the first response, and then they can receive help from neighbouring municipalities.
- Not based on the BCEMS, but based on the relationships of responders and receiving communities: "I mean, even just accessibility is a big one or like how close the relationship is between who's deploying the responders and who's receiving the responders? That kind of stuff makes a difference on how they're deployed and who, like how, who, and where they're deployed"

A.9 "What information is needed to determine mass care needs and allocate supplies within the first 12 hours?"

- Damage to critical infrastructure: telecommunication, power, water, food, natural gas:
  - "Drinking water in this town comes from the nearby island, and the damage to their water pipe in the seabed would be a serious concern."
  - What services are available and where
  - "Having information on damage to critical infrastructure is absolutely and incredibly valuable."
  - Identified blackout zones (12)
- Road accessibility/evacuation routes:
- How can we take people out of place and let them transport; any accessible roads? Or must be airlifted?
- Marine ports, airports
- Scope of scale impacts on major roadways

- Identified road blockage = they need alternative routes. If there is none, then an external agency like the province needs to come and approach from the other side (11)

- Number of injuries, their locations, and demographics:
  - The provincial medical sector estimates the number of injuries using their own means. They identify the impacted area, the population in the area, and the percentage of people impacted by the event to determine the estimated number of injuries
  - Who needs care, and what levels of injuries? Are they children, adults, or family? Because certain hospitals provide care for children but not for adults. They need to be sent out to different places to get their care, and it also depends on the levels of their injuries and the care they need; the scale of injuries (8)

- Number of displaced people or people in need:
  - How many people need shelter and basic necessities to survive
  - They don't have enough blankets and cots for all the people they are currently housing (7)

- The number of impacted vulnerable people:
  - How many people are at home and reliant on medical equipment that needs power, and what are their locations
  - Number of people with special needs
  - Elderly people who have functional needs or deaf and hard of hearing
  - Impacted vulnerable population areas, care homes, elderly homes, schools
  - Vulnerability and resilience of the community themselves (is resiliency something quantified beforehand to be included in the algorithm) (8)

- Secondary hazards and their locations: landslides, liquefaction, fire, floods, tsunami (7)

- Safe locations: Locations community centres or reception centres are habitable, functionable, and accessible and their capacity:

- Where and how big are the reception centres What's structurally available and if they have all the services they need; where is safe and available (large facilities for group lodging), and what are conditions of these facilities; standing facilities with service running (7)

- Locations of hospitals: locations of hospitals and an indication of their functionality; clinics and other health care facilities; damage to hospitals, clinics, and fire halls (5)

- Resource availability: what's available? Water, electricity, food, and other necessities (5)

- The time of day: it means there could be lots of people Did the event occurr close to the residential area at night or the office area in the daytime? (3)
- Bridge integrity (2)
- Tourist population (2): visitors who normally don't live in the area and are not familiar with the area
- Supply chain issues (1)
- Hazardous material spills (1)
- Damage level on structures; high confidence in the damaging impact would be great to plan ahead (1)
- Population density (1)
- Aftershocks (1)
- The information on the seismic event, size, shaking levels on the map, the basic cause of earthquake, depth, and location (1)

A.10 "Does the need for mass care change over time (24 to 48 hours)?"

All of the respondents said yes

- Things would change over 24-48 hours because resources from the federal government (army, etc.) would become available
- "The first issue would be assisting people immediately after the event, and the next would be letting them evacuate from the campus, and I would say a couple of days then, like people just need to be sheltered and have enough essentials. But then, after all, after a week or 2, frustration would be completely different. I think people would be needing different things... like a month later, they would be needing their childcare back again, and then, like, those different things could be needed too."
- Response to recovery; different needs

A.11 "Is there a certain level of confidence you need to have when making these decisions?"

- Generally, they would rather be safe than sorry regarding reacting to the estimated numbers.
- It is important that the estimated data come from credible sources - as long as the information comes from reliable sources based on well-established science, they can act on the estimated numbers.
- FN communities will contact EPS and FNESS to confirm the information before making decisions.

A.12 "How do they identify isolated communities that can't ask for help?"

In general, provincial governments will not know about the isolated communities until they are notified; there is no way for them to identify them. However, they can send teams to check on them to see if they are ok. At municipal and FN community levels, they can identify them through windshield assessment.

A.13 "Ideally, what information would you want in the first 24 hours after an earthquake?"

Every interviewee wanted to know the information RED-E can provide including the estimated earthquake size, rupture depth, hypocentral location, shaking intensities in various locations, time of the event, estimates of damage extent on structures, and number of injuries or potential fatalities in the community. The discussions were held granted that the above-mentioned information could be provided and asked what additional information could be useful.

Universally, the information on the road conditions was highly desired for conducting the initial windshield survey on foot or by vehicle and the area of power and telecommunication outages. Telecommunication, transportation and road conditions are keys to situational awareness, resource allocation, and evacuation efforts. Identifying safe sites next to heavily impacted areas is also critical information for their planning process. Structures' habitability and functionality are the information they seek and value. Bridges mainly serve as bottlenecks, and their importance deepens for more remote communities and on highways. For remote districts, the drivable road condition becomes more valuable since they lack the grid of roads and have only a few roads or sometimes only one road in and out of the communities; thus, the modelled conditions of roads are a critical piece of information to them. Damage extent, locations, and seismic information are considered given and removed from the list below. Another piece of information they value is the conditions of Critical Infrastructure

(CI), including the extent of power and telecommunication outages, water, natural gas, sewage availabilities, hospitals, clinics, fire halls functionality, and airport and port serviceability. The location and extent of liquefaction and landslides, debris, and the cost of debris removal are also valuable information for them. The topic of the tsunami was brought up many times; some feel strongly about including tsunami impact. One person indicated it would "negate the RED-E's value if it doesn't include the tsunami impact."

Additionally, many interviewees highlighted the importance of grasping the damage to vulnerable populations. Some information that is especially valuable for the Housing Ministry is the modelled number of uninsured low-income or vulnerable people. They financially support the uninsured population during sudden, unexpected, extraordinary (in a historical measure), widespread and expensive natural disasters. If they can have a modelled number of people impacted by the major earthquake, it can expedite the approval process. Similarly, the number of displaced people is also valuable for planning purposes. First responders are especially keen to know the greatest concentration of the victims, not the most damaged empty buildings but the people in damaged buildings. Aftershocks and compounding impacts of aftershocks are mentioned a few times and can be helpful information for them.

- Conditions of roadways: accessibility; the best evacuation routes and transportation routes for resources. Utility partners need to know the road conditions to assess the recovery time; "Transportation impacts would be valuable. In all honesty, that significantly impacts the health system as far as patient care and the ability to deliver the correct goods and supplies". Road condition/disruption: some regional districts have roads managed by the Ministry of Transport and regional roads; they would like to have information on these: Identified road blockage = they need alternative routes; if there is none, then an external agency like the province needs to come and approach from the other side (27)

- Conditions of critical infrastructure; telecommunication, power, water, hospitals, sewage etc.; having a tool to share that between all organizations involved would be valuable; An electrical shortage would be the main concern; Infrastructure information would be very useful - not currently in place; they are spread out for small communities; Information on critical infrastructure to help make decisions for later; detailed understanding of hospitals that might be standing but may or may not be functioning. If the facilities have power and water, airports' health, bridges, roads, telecom system, water, and sewage system; location of functional clinics; availability of services: electricity, water, sewer, functioning ports; is there any communication or transportation available; drinking water availability, sewage, natural gas, power, hospitals, clinics; standing facilities with service running; scope of scale impacts on major roadways, infrastructure, and communication impacts; damage to hospitals and fire halls; power and telecommunication outage; availability of medical services; impacts on communication infrastructure; identified blackout zones; impacts on municipal/public infrastructure, not privately owned infrastructure; publicly owned bridges, roads, water, waste treatment facilities; condition of underground infrastructure, which is harder to see and important to know: location of water main breaks; more shared information from the private sectors such as BC Hydro, Fortis BC etc for the critical infrastructure would be great; condition of dams (27)

- Secondary Hazards (liquefaction (6), tsunami (5), landslides (3), fire (1), hazardous material spillage): locations of liquefaction and its extent; tsunami: tsunami damage and even a vague inundation zone would be useful for them; they said it would negate the value of the tool if it doesn't include the tsunami impact, even the general area of impact without the toll of injuries and impacted buildings; landslide generated tsunami; tsunamis from both subduction zone and landslide; Natural gas leak and fire (17)

- Bridge; condition of bridges; bridge safety/condition (10)

- Locations of safe evacuation sites (reception centre and group lodging): safety of the locations where we are sending the people to group lodging, reception centre, EOC etc.; safe transportation routes; what's not damaged to use it safely; locations where medical mobile units can be deployed safely but close enough to people in need, but these medical mobile units are to identify people and triage, with only small capacity to treat people; safe location to occupy; no liquefaction, pipe bursting to flood, ground failures, cracks; shelter availability: "How is the damage to the surrounding area for outpatients to go home to?" They need to know if such triage can be done or not: "Can they discharge people?"; "Do they have their shelters to go back to?" Especially medical service providers want to know these two questions (7)

- Amount of debris and estimated cost of removal: the amount of debris would be good to know so they can assess the capacity of their landfill to take it (6)
- Locations and impacts on vulnerable populations: health or medical conditions of community members; the number of people who might need medical assistance within 24-48 hours (e.g. dialysis); Location and numbers of vulnerable/prioritized populations like elders who are previously identified; elder centers; the vulnerability factor is essential; since it's about their ability to self-sustain, some provinces have the map of such vulnerable population as a GIS layer: elders, ESL, families with young children, and people who rely on public transit; which neighbourhoods are impacted, and what are their levels of impact; vulnerable populations who are uninsured: lower income and rental population; not those in big mansions who have financial means to support themselves and recover (5)
- Number of evacuees/dislocated population; shelter needs: "Your tools looking at shelter needs. That would be a very [big] interest to us as well" (4)
- Estimated number of tourist population; if the incident happens during the day more population as many as 600,000 more people might be affected than at night, and they need to look after them if they can't leave (3)
- Structural damage and building conditions; are they habitable; structural damage, main floor, and furnace damage for uninsured people (3)
- The greatest concentration of victims: want to see the greatest concentration of victims; not the greatest number of damaged empty buildings but buildings with people in them; the number of injuries and locations (3)
- Number of injuries: how many people need care and how much care they need (2)
- Aftershocks and their compounding impacts (2)
- People's needs: what sort of resources do they need? Medical needs? Protection from elements? Food? Water? Shelter? And how much; number of evacuees who need resources (2)

- Normalized data (2)
- Population density (2)
- Uninsured cost and insured cost (1)
- Uninsured populations and businesses: how many small businesses, homeowners, tenants, and small farms are impacted, and how many are not insured (1)
- Shelter needs for a more extended period of time (1)
- How many staff/responders are available and can be deployed (1)
- The prioritized locations of electricity restoration (1)
- They want to have a sense of whether situations are worsening or getting better (1)
- States of neighbouring communities: because they will be sharing resources with their neighbouring communities, being able to see their conditions would be valuable (1)
- Resource availability (1)
- The credibility of information sources (1)
- Hospitals' capacity: what hospitals are seeing big influxes (1)

A.14 "At what scale (geographical coverage and details) would you want this (above-mentioned) information?"

Many didn't answer this question directly but mentioned that they would like this information to be GIS consumable, giving them options to zoom in and out as they wish.

- Zoom in and out: Covering a larger geographical scale to know the impacted area, but the ability to zoom in to gain the details would be amazing; more data is always better; have the ability to pick and see their municipalities of interest (7)
- Neighbourhood levels: Don't have to be street level but general neighbourhood area, municipality; neighbourhood level or census track kind of level (5)
- Municipality/First Nation's territory level (1)
- Regional/provincial/territorial scale (2)

A.14.1 "How would you like to receive RED-E information?"

- COP or other GIS consumable product: hrough the Common Operating Picture (COP) portal would be ideal; GIS would be great: COP they access daily; straightforward; COP is heavily used during the major event (big activation), and the provincial system can consume stand-alone systems as a custom application; it would be a massive detriment if it weren't consumable on that platform (COP); for the Ontario government: the product needs to be able to integrate in their Disaster Land GIS platform (19)
- PAGER type: PDF product would be most easily shared through emails to elected officials, other subject matter experts and the public; PDF format is very comprehensive and easily sharable, which is excellent; would be good for many First Nations responders and it would be helpful for them as they sit in the regional coordination calls; printing out option is good/ valuable; PDF type of image could be circulated quickly through apps like connect rocket for indigenous communities; however, maps/GIS are not actionable; PDF formats are great, so they can be distributed and taken to other places; basic information to be emailed out early on would be helpful; a PDF with maps and tables provides comprehensive visuals; it helps users to get a quick snapshot of what the likelihood of certain things is and to kind of understand like, what is the gravity of the situations (15)
- Multiple formats: anyways they can receive the data they want to receive; several different options are good; more the better because some communities

are really connected to the federal government, but they haven't built those relationships with the province yet; more options are better for redundancy (12)

- The stand-alone system from NRCan works fine, too, as long as the site is made to fulfil the needs of all visitors without being overwhelmed (6)
- The option to enlarge and print would be good as a plot or on the standard A4 size sheet because it may need to be delivered to the field where they might not have telecoms or the ability to download it on their phone (5)
- A table summary of all the results would be valuable to report concisely; lists of impacts; allow them to scale and respond appropriately, and a comprehensive report summary; the simple text is valuable (4)

A.15 "Are there any concerns about the results of our tool, which are hypothetical, being available to the general public?"

The majority of respondents did not feel comfortable sharing details of estimated damage results openly with the public due to concerns that causing panic might hinder response efforts, bout public misinterpretation of data, and promoting unrealistically high response expectations. In terms of disaster tourists, there were concerns of both in-person and online disaster tourists impacting the response effort negatively by physically blocking the roads and taking up the bandwidth online. Most responders wanted to have separate public-facing information and more detailed information for the people in the specialized field.

- Public misunderstanding of the modelled data as ground-truth data:
- If the information is open to the public, then we need to ensure that the data is clearly labelled as modelled data and not circulated on social media as ground-truth damage data

- Misinformation during the disaster is expected, and they fear that openly having too much information can be confusing
- They might miss that it's a model
- Concerned that people misinterpret the data as real data, not modelled. However, many people, for example, the critical infrastructure owners, province, local government center, and the first responding community, would benefit from open access to the data. But it's important that it is clearly labelled that it's a model, not real data.
- "I worry about their ability to understand. Understand those scales." (6)

Fear of causing unnecessary panic, which might counter the rescue or evacuation effort:

- There's a risk of people being provided with information that may counter the response efforts. If people take that information and make their own decisions based on it, it might go against some greater interest in moving people. We want transparency, but we are concerned that it would raise panic and hinder response processes.
- "When we had that tsunami warning, people heard there was a tsunami warning, and everyone panicked and drove up to the top of mountains, which was unnecessary and just caused major other impacts. So yeah, I think it's good for them to have information as long as they have the education and know what to do with it".
- Concerned that if all of the information is available to the public, everyone will rush into getting the available resources and services, and that would make the system overwhelmed.
- Modelled numbers of fatalities or critical injuries might be too emotionally triggering to be available publically (6)

Heightens the rescue expectations that might not be met:

- “When people see their area identified as a damaged zone, their expectations would also go up without understanding prioritization, which can be problematic. When the information is presented to the public, they would ask how the authorities are responding and managing that itself could be problematic.”
- “They will be extremely vocal when they feel they are not receiving equitable services after seeing the model maps because they don’t see themselves as communities richer than others. It’s a good tool but cannot be perceived as a decision. The public has a hard time understanding the scale that EM needs to deal with.”
- “I worry that if this information gets out and somebody sees that they’re impacted or potentially impacted again, that’s going to create that anxiety and expectation that okay, like, what’s the city doing?”
- “General information can be available to the public, but when it’s compiled as a list of weaknesses, we create targets. It’s sort of a final assessment of risk or weakness that comes concerning for people. Suppose you know all of the weaknesses of structure. You have a target list. So, like, the information that we deal with and building our maps and stuff like this is all public information, but once we compile it into something and say, this is an area of risk because of one bridge or something that’s a target, and that becomes a problem.” (4)

Loss of confidence and trust:

- If the information becomes available, but the estimation is not accurate, then it can lead to a loss of public trust/confidence (2)

Disaster tourists and disruption of response efforts:

- Curious people causing more damage or taking up resources or virtual disaster tourists that want to see images of damages ending up crashing the page, and it would no longer be available for people who need it; creating traffic and people are putting themselves at risk; concerned that they might behave in ways that counter rescue/response efforts.

- The information that would be shared with the public could have different scales and details to avoid disaster tourists (4)
- Privacy concern: especially for First Nation communities (4)
- No, I don't see any issues (2)
- House insurance concern (1)

A.15.1 Suggestions and comments for this question:

- Have security clearance to use the tool
- The information must come from a reputable source; such as the province or federal governments.
- The public could have different scales and details to protect privacy and to avoid the disaster tourists. Creating internal documents/GIS portal with details for people in the specialized field and summarizing information for the public-facing products; separating a public-facing site and the internal site makes sense; a PAGER type of general situation report might be the best for the public; when people zoom in, the information might get misinterpreted as real data.
- The functionality or capacity of hospitals can be communicated after the verification and permission of the province or other authority.
- If the tool is to be available to the public, it needs to be accurate and reliable and ensure that it comes from a reliable/trusted source and does not conflict with other data.
- NOAA's tsunami maps and how they make them available to the public might be a good example.
- Ask for experts' opinions: provincial governments have teams of dedicated information officers to decide on what information should be available to the public.

- Uncertainty about the model needs to be communicated clearly: "I like the idea of that kind of thing being publicly available, you know, and I also understand the limitations of any kind of model that it's as good as the data that goes in. And that data, I know for a fact, will never be perfect".
- Even if the system is open to the public, only those concerned or people who work in the field might only use it; there is much information available online, but only people in the field use it.

A.16 "Do you foresee challenges integrating a tool like our Rapid Earthquake Disaster Estimator in your agency? If so, what might be?"

- Staffing capacity challenges: human resource, staffing capacity, and if there's a financial component attached to it, they'd have to go through mayor and Council approval. And then also our privacy department and any information has to be hosted on Canadian servers and that kind of stuff; as a First Nation, they offer broader services to community members than municipalities, and it can be challenging, especially some being relatively new governments (6)
- Technical capacity: if the system requires a new skillset to use (5)
- Cost: The system is free, but there might be an indirect cost to train staff etc.; the cost can sway the decision-making process; financial consideration on training, updating, and subscription (5)
- Security clearance or approval: our privacy department and any information have to be hosted on Canadian servers; approval to use this tool can possibly take a while. Disseminating information has to go through a robust vetting process. The challenge of being fully integrated and using it as a recognized tool and being approved as an authoritative source of information for us, might take a while (2)

- All of the (Mainland Coastal Salish) communities will likely have a lack of human, financial, and technical resources and capacity (1)
- Not really (2)

A.17 "Based on our briefing, do you have any suggestions or tweaks that might make our tool more useful to someone in your position?"

Training component: "You, or whoever is the expert in this, should sit there and present what this means and how to read it. Even in advance,"; training would be excellent for staff to know what they are looking at; training with simulated earthquakes would be good and refresher training; training might be needed if there is a component to add ground-truth data (6)

User-friendly interface; the system should be user-friendly and intuitive for many users or similar to what they are using already and uses the existing skillset in the organization (4)

Having everything on the one system is valuable, so they don't need to prioritize monitoring several systems; if it can be integrated into their existing system, that would be even better, COP has everything they need in one system, and that's valuable; a big part of what the COP was based on: having everything we need in one location. So we don't have to balance between and keep track of many different websites and products. So it's all in one spot and easy to use; it would be a huge detriment if it weren't consumable on that platform (COP); how easy is it to integrate the existing mapping?

Have the option to add ground-truth data as the situation evolves to keep the system relevant; to have options to indicate that this model was accurate, not accurate, etc. or worse than it was modelled or better than the model, etc.; ability to see or add a real-time photo as it comes up. Maps (GIS) are great; it would be excellent if that system had the ability for us to verify or like correct, or you know the information. We're going to be driving those areas reasonably quickly, and we would realize that something is actually not as bad or not.

Normalized data; using the census unit for population data would be good- "This is horrendous, but compared to what we saw in the rest of the city, it was almost negligible." (2)

GIS consumable at local government level to allow them to integrate their local layers

Ensure to learn and research from the other countries who already have systems practiced.

The information should come from NRCan directly if this is something they produced since it will be branded and we know it has a scientific background; rather than NRCan- province and municipalities; NRCan equals more credibility; stand-alone system from NRCan is good. They use both COP and their internal GIS system, too, so if the layer is integrative, that's good.

Provincial governments get the information from the USGS due to reliability issues. There was a time when NRCan's web servers were not sized for the capacity of website hits. It's a part of my job and continuity of operations. We need to ensure the site can handle the large volume of visitors for. something like the major earthquakes. Canada's website gets a lot of hits on an earthquake day and that's what they need to be sized for. It wasn't at one point, whereas the USGS was, so they became a bit more trusted in that respect.

Inequality in data; some cities had financial means to hire technicians to conduct their own research to find out their soil study/ vulnerability study. However some others are dependent on the publicaly available resources. How are these incorporated and resolved?

Considerations of vulnerabilities such as physical, financial, cultural, etc. would be good to have

How frequently the data are updated is key to increasing modelling accuracy. One of the respondents commented that during the provincial-wide exercise, the modelling data they received included inputs that were at least 5 years old- they commented that it does not represent their communities appropriately since there have been a lot of changes to it. If the estimated number is based on obsolete data, it is not as useful for them.

Who do they contact if they have questions about the data's ambiguities and how they can receive them?

Ownership of data: if the data were introduced as an extra layer, this would be outside of their ownership of the data they have been using. What happens if anything needs clarification or needs tweaking or refinement, that we have that kind of clear point of contact

Also, understanding how the data would be updated and refined. How often would the data be updated, and by whom?- they want to ensure that the data they are using are current and relevant.

Reliability of the system; they seek ground-truth data; not sure how they can use modelled data to make decisions, but it would serve as a primary estimation.

The system should follow the KISS (Keep It Super Simple) principle in terms of both technology and user experience; GIS would need trained people to use, there should be no cost, and easy access is good if the user can select the area of interest and get the information that would be amazing like Saanich, Victoria, Oak Bay etc. and generate PAGER like information.

"We want to send crews out to to a wreckage like, here's the map. Go and check this area. And again, it's I see this as a prioritization tool. And let's go and validate the information".

Be clear on what's included and not included and where uncertainly or inaccuracy may come from

A.18 Other Comments:

- As a First Nation (FN), they have a lot more responsibility than municipalities since the FN governments need to provide their members with education, medical services, and social services in addition to the other services they provide for non-members such as sewage water etc. They manage their own fishing and look after their lands. For FN to manage all governing duties with a smaller capacity can be challenging, including emergency management work and they are also a relatively new government.

- One of the FN communities is small and walkable within 1.5 hours and 2 hours maximum. They also have ATVs to go around and bobcats (heavy machinery to move debris); undrivable roads are not applicable for them. They also have canoes to cross the river in case the bridge is unsafe.

- Clear definitions of terms: for example, what is considered "red-tagged" buildings or "dislocated populations" or "shelter-seeking populations".

- They will rather be safe than sorry in terms of reacting to the estimated numbers- as long as the information is coming from credible sources based on rigorous studies they can act on the estimated numbers.

- How are other countries using similar systems, and what is their feedback?- This would be my homework to look into this information

- How is the population census data or housing data collected, and do they represent indigenous populations well? When the flood event occurred in 2018, the map they used didn't consider the First Nations people who lived outside the dikes, right? So they are not within the dikes, which puts them at a higher risk during an earthquake of different hazards, like flooding, liquefaction and things like this. It depends on how they're pulling population data. The population data was based on MSP numbers, and it was not fully inclusive

- "The ability to have real-time, like your tool is incredibly beneficial for a response"

- Ensuring that the product is GIS consumable is vital; e.g. the data can be shown through the COP system

- Not everyone uses the COP portal; thus, RED-E products should apply to all GIS formats at provincial to local levels.
- Separating or having the ability to choose what data would be included in the pubic-facing maps would be great
- Tsunami impact inclusion: "Is there any integration or incorporation of broad level impacts of the tsunami?"
- Maps are really good for creating situational awareness but the lag time for larger scale maps are not great
- Integrating Drive BC information to improve situational awareness; Drive BC has good real-time information of the road- is it possible to include them?
- "I think this (tool) is just an additional piece of information that would be extremely valuable for making more informed decisions."
- Levels of confidence matter, even if the census data is not up to date; if the model has a high confidence level of damage in a particular area, they would use that data and act on it.
- They wanted to know about the refreshment time: the refresh rate of the information
- Does USGS have a tsunami component, and why not? Tsunami information was in high demand, and they wanted to know why it could not be added.
- Disaster response takes so many stakeholders from different levels of government to private sectors. A tool like this, if it can inform multiple stakeholders about the situation can be very helpful; for example, a telecommunication company would know the road condition better to assess if they can repair the damage soon or not or they can find out ways to repair it. It would be helpful for planning for all sectors and stakeholders.
- Training would be nice, especially if there would be a component on adding real data on top of it to confirm the modelling result, but if it is one way push, then it is probably very straightforward forward and no training is needed; they already use USGS PAGER and NRCan site

- “It’s a really exciting tool. And having that estimator could be incorporated into response”.
- The tools should be simple, user-friendly and not require any training.
- If they can add their own layers at the local level, that would be useful. For example, the ammonia buffer zone won’t be available anywhere else.
- “How is the tool going to be updated?” And how are we going to consider that sort of ever-changing risk (with aftershocks)?”

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