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SEISMICA

Introducing the Rapid Earthquake Damage Estimation (RED-E) System for Improved Life Safety Outcomes During Earthquake Early Response in Canada

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Abstract In the wake of a major earthquake in Canada, responders can expect to encounter critical gaps in situational awareness in the first 48-72 hours that will hamper effective decision-making. To address this challenge, Natural Resources Canada is developing the Rapid Earthquake Damage Estimation (RED-E) system. This modelling system aims to produce maps of structural, human, and economic impacts within tens of minutes of a significant seismic event, similar to the United States Geological Survey's PAGER product but with enhanced details specific to Canada. This paper presents our research on optimizing the RED-E system through the User-Centered Design approach. End-user consultation throughout the development of RED-E will ensure that its outputs are practical and actionable for first responders, emergency managers, and infrastructure operators. Key findings from initial consultations underscore the need for immediate post-earthquake situational awareness, although complete understanding may take days to weeks. End-users expressed a preference for RED-E outputs in diverse formats, with road disruption modelling and secondary hazard assessments being particularly valuable. This study outlines the essential requirements for the outputs of RED-E and documents initial prototypes, showcasing the potential of the system to transform early post-seismic emergency response efforts across Canada, aiding in prioritization and resource allocation until ground-truth data become available.

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1 Introduction

The most critical period for saving lives after a major earthquake is within the first 24 to 48 hours (de Bruycker et al., 1983; Noji et al., 1990; Coburn et al., 1992). Noji et al. (1990) report that 89% of rescues in the 1988 Soviet Armenia earthquake occurred within the first 24 hours. Similarly, de Bruycker et al. (1983) found that 93.6% of survivors were rescued within 24 hours, and another 5.56% within 48 hours, following the 1980 Southern Italy earthquake (Figure 1). The survivability of trapped victims, even when their location is known, is a function of rescue capacity and time (Coburn and Spence, 2002). The most common cause of earthquake-related mortalities is structural collapse (Coburn and Spence, 2002), making early search and rescue a priority.

Effective search and rescue requires rapid development of situational awareness. Such information is, however, minimally available within the first 24 hours (Wald et al., 2008), significantly hampering emergency response efforts, as occurred in the wake of the M_w 6.9 1995 Hanshin-Awaji, Japan earthquake (Tierney and Goltz, 1997). Having information immediately after a large earthquake would allow decision-makers to prioritize rescue efforts in the most impacted areas and initiate planning for mass care for any displaced population. Recognizing the areas that experienced strong shaking and the expected impact, and developing a list of vulnerable areas or buildings within the specified impacted zones, takes up precious time for emergency managers and first responders (Turner et al., 2009). In other words, first responders and emergency managers may not know the likely locations of entrapped victims during the most critical time to save them. The current practice is that post-disaster building damage assessment is often only commenced after initial emergency response, search, and rescue; i.e., such assessment is not often used to develop situational awareness within the first few hours or days (Applied Technology Council, 2019). Preliminary information on earthquake impact is typically collected by windshield surveys, flyovers, dispatch calls and, to some extent, social media (Applied Technology Council, 2019), but such information is unlikely to be timely, complete, or reliable, especially within the first few days.

Additionally, the utilization of other tools, such as satellite imagery and Unmanned Aerial Vehicles (UAVs; also known as drones), has been considered. Although those technologies have been increasingly improving and have become more accessible in recent years, such applications during the immediate post-disaster phase

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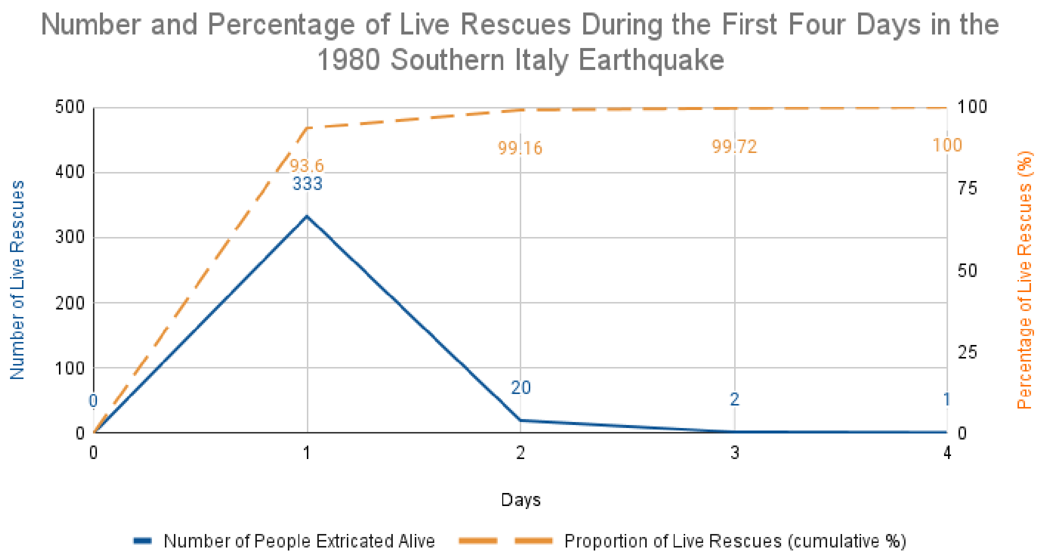


Figure 1 Numbers and percentage of individuals rescued from entrapment during the 1980 earthquake in southern Italy within the initial four days (based on data from de Bruycker et al., 1983).

have limitations, especially in Canada. Challenges in the use of satellite imagery include: (1) the timely acquisition of images, which relies on satellite revisit times, (2) the need for manual methods of image analysis, and (3) the lack of sufficiently detailed information for life-saving purposes (Diederichs, 2020). UAV operations are subject to airspace restrictions and require special permissions from authorities, which can delay the deployment (Transport Canada, 2021; Mohd Daud et al., 2022). Other constraints of UAVs include: (1) their inability to fly or capture clear images in harsh weather, dust, or smoke; (2) their limited battery life and, therefore, limited flight times; (3) the significant time needed to process and analyze large volumes of UAV data; (4) the limited availability of highly skilled personnel for effective UAV deployment (Mohd Daud et al., 2022); (5) the Transport Canada (2019) requirement for operators to maintain line-of-sight communication with the UAV. Obstacles such as buildings or terrain features will, therefore, limit the coverage area of drones during the post-disaster damage assessment.

1.1 Rapid Damage Modelling Systems: Global Examples

Rapid estimation of damage after major earthquakes can be and has been a valuable tool to assist in timely response globally. There are many international examples of rapid damage modelling systems, generally categorized by the regions they cover, including global and local systems (Erdik et al., 2011). The global modelling systems tend to be technologically robust, and the results can be validated frequently through international events (Guérin-Marthe et al., 2021). Local modelling systems are country, city, or facility-specific systems tailored to their local or facility needs, and they can include more detailed local specifics that will improve the estimation of losses and serve the specific needs of stakeholders or industrial needs (Erdik et al., 2011). Prompt Assessment of Global Earthquakes for Response (PAGER) from the United States Geological Survey (USGS) and EarthQuake Loss Assessment for Response and Mitigation (QLARM) from the International Centre for Earth Simulation are two of the best-known examples of global programs.

PAGER employs three methodologies—empirical, hybrid, and analytical—based on the availability of past fatality events, building inventories, and building code levels (Erdik et al., 2011). The empirical method, similar to the QLARM methodology, is used in regions with high mortality events but insufficient building inventory data. The hybrid method combines simplified analytical approaches with past earthquake damage statistics for areas with basic structural data, while the analytical method, suitable for countries with detailed building data, occupancy rates, structure types, and robust building code implementation, models structural responses using the Hazus capacity-spectrum methodology (Jaiswal et al., 2010).

The USGS PAGER and the FEMA Hazus teams have been working on a new prototype loss model for domestic seismic events, known as “TwoPAGER”, to supplement the current PAGER system (Wald et al., 2020). The new prototype is a combined loss model of PAGER and Hazus (Wald et al., 2020) and was developed with equity-aware data sharing in mind (Macías et al., 2023). 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 by quantifying structural, social, and economic impacts with finer spatial resolutions. The Hazus output content is too large and considered unmanageable for use by most in the response community, but is more suited for planning and disaster mitigation purposes (Wald et al., 2020). The TwoPAGER system was developed to take advantage of both systems. The intent is to provide users with more detailed loss estimates based on FEMA's spatially rich Hazus loss models and building databases to supplement the widely deployed PAGER alert product for significant domestic earthquakes. It is not intended to replace the initial PAGER alerting system but to complement it (Wald et al., 2020).

Since 2003, the International Centre for Earth Simulation has operated QLARM, providing loss estimates within 30 minutes of an earthquake exceeding magnitude 5.9 near populated areas (Wyss, 2017). Using data from GeoForschungsZentrum and the USGS, QLARM applies intensity-based vulnerability models (EMS-98) to estimate potential structural damage distribution based on shaking intensities, calibrated from as many as 1,000 past seismic events (Grünthal, 1998). The system generates outcomes for each settlement, detailing the expected percentage of buildings in five damage states, the mean damage state, and the estimated number of fatalities and injuries, along with error estimates (Guérin-Marthe et al., 2021; Erdik et al., 2011). These global rapid loss estimation systems have been valuable for understanding the severity of seismic events worldwide; they are typically intended, however, for national and international decision-making (Wald et al., 2010) and, therefore, lack details that would be useful for decision-makers in the region.

1.2 Canadian Seismic Risk and Need for a Canada-Specific Rapid Damage Modelling System

Canada is a seismically active region. At least four significant earthquakes of M_w >8 have been recorded since 1600, with 17 events of M_w7-7.9 in the same period (Lamontagne et al., 2007). 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 physical and social vulnerabilities (Hobbs et al., 2023b).

Although global rapid damage assessment systems already exist, as outlined in the previous section, it is critical to develop a Canada-specific system for several reasons. First, a Canada-specific system can make use of detailed building exposure information (Journeay et al., 2022). The system can apply Canadian-specific fragility and vulnerability curves to estimate building damage, reflecting Canadian building codes and inferred construction trends (Hobbs et al., 2023a). Second, hazard data will also be specific to Canada: the system can utilize data from the Canadian National Seismic Network (CNSN) and the Canadian Earthquake Early Warning (EEW) network, and the ShakeMaps produced by the Canadian Hazards Information Service. Third, generally, existing global damage modelling systems only present maps for hazard threats (maps of the population exposed to different levels of shaking). Creating detailed, neighbourhood-specific maps of anticipated shaking, damage, injuries, and financial loss requires a more detailed tool tailored to the local environment, which can add more value to the end-users. A Canada-specific tool will target local and regional response decision-makers: first responders, emergency managers, and Critical Infrastructure (CI) operators.

1.3 Canada's Rapid Earthquake Damage Estimation (RED-E) System

Natural Resources Canada (NRCan) is developing a Canada-specific damage modelling system, the Rapid Earthquake Damage Estimation (RED-E, pronounced like "ready") tool. A recently developed proof of concept (Hobbs et al., 2020) for the RED-E system for British Columbia (BC) contributes to a robust foundation for the system to evolve and become available in Canada nationwide. The proposed system will promptly create seismic damage and casualty estimate maps within tens of minutes of confirmation of the magnitude and location of a significant earthquake by integrating observed ground motion data from the national strong motion seismic network, parts of which recently underwent a significant upgrade for incorporation into the EEW system, with the exposure and fragility datasets from the Canadian Seismic Risk Model (Hobbs et al., 2023a,b) to estimate risk using the scenario calculators of the OpenQuake (OQ) Engine (Pagani et al., 2014). The National EEW network, which began operating in BC in May 2024 and will be fully operational in late 2025, harnesses the technology of Nanometrics Titan and Güralp Fortimus accelerometers (Cassidy et al., 2024). This EEW network, operated by NRCan, includes over 300 stations, strategically deployed in high seismic risk regions of Canada in collaboration with a partner network, which will add over 100 instruments (Cassidy et al., 2024). The RED-E system uses the exposure models and vulnerability and fragility functions that were developed for the first-generation Canadian Seismic Risk Model (Hobbs et al., 2023a) and utilizes seismic data retrieved from Canadian strong motion networks (Crane et al., 2023) in ShakeMap format, in order to generate the RED-E outputs.

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 systematic aerial, vehicular, or on-foot reconnaissance can be performed. The RED-E system can model the damage over 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, and other major damages within tens of minutes.

The RED-E system can assist emergency managers and other decision-makers in achieving many of their goals 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 in-

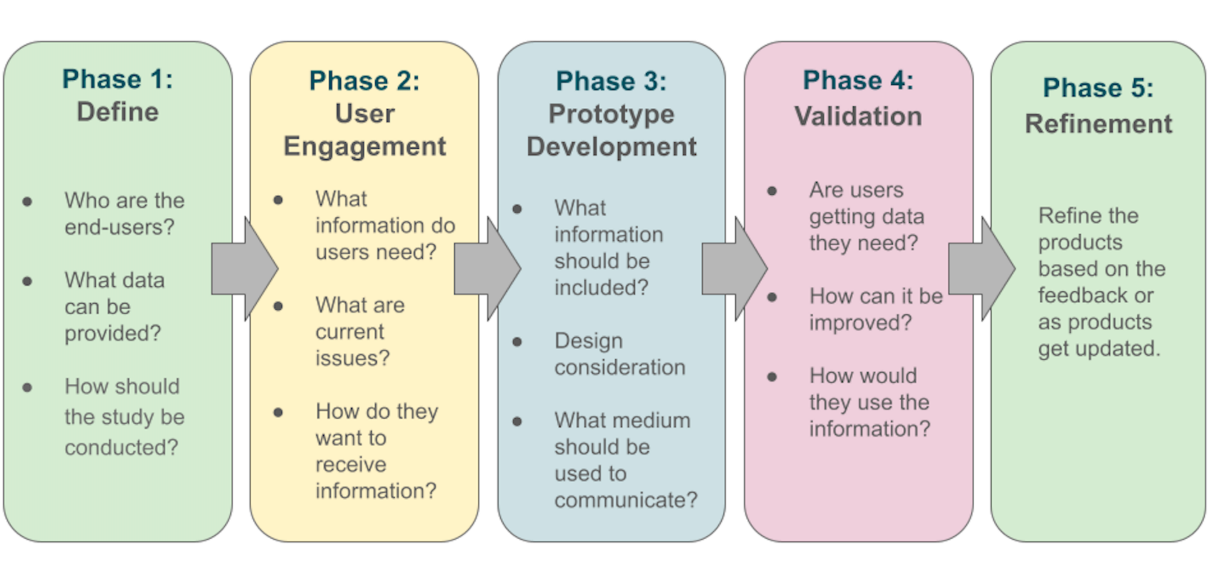


Figure 2 User-Centered Design (UCD) Framework (modified from Loos et al., 2024 and Macías et al., 2023).

clude optimizing resource allocation to maximize benefits for the greatest number of people, stabilizing situations, and initiating requests for external assistance. The RED-E tool is designed to enable end-users to operate more decisively and efficiently during the early stages of the response period.

1.4 User-Centered Design of RED-E System Outputs

This study aims to characterize the needs of end-users, including emergency managers, first responders at municipal, provincial, and national levels, and CI operators, to gain an understanding of their needs immediately after a significant earthquake by conducting informational interviews, guided by the User-Centered Design (UCD) principle. The UCD principle includes five phases: understanding the user context, gathering user requirements, developing solutions, evaluating proposed solutions, and refinement (Interaction Design Foundation, 2016) (Figure 2). The results of those informational interviews were then 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). In the UCD method, developers consider the needs, capacities, roles, and responsibilities of end-users throughout the entire design process (Twomlow et al., 2022). By following this approach, designers address the intellectual, emotional, experiential, and moral characteristics of end-users, making products more likely to be useful, comprehensible, and user-friendly (Twomlow et al., 2022; Argyle et al., 2017). Other UCD product development examples validate that UCD leads to more effective and successful products (Twomlow et al., 2022). The informational interviews are described in Section 2 of this paper, whereas Section 3 will describe the wireframe development and testing (UCD phases 3 and 4, Figure 2). Feedback on the wireframes was then solicited from two emergency management teams at municipal and provincial levels who were previously involved in the informational interviews; this feedback is summarized and discussed in Section 4. This paper is intended to support the development of a final RED-E product, and the task of developing the final product is reserved for Natural Resources Canada; therefore, building the final product was outside of the scope of this work.

2 Summarized Responses of Informational Interviews

2.1 Methodology

We conducted informational interviews with emergency managers, first responders, and CI operators to understand their needs in the first 24–48 hours after a major earthquake. During 1–2 hour virtual sessions, participants responded to 18 prepared questions. They were informed that RED-E's baseline outputs already include estimated earthquake size, depth, location, shaking intensities, damage extent, displaced populations, debris, and potential casualties. The goal was to identify additional user needs during the immediate post-earthquake period. Insights from these interviews directly informed the development of RED-E wireframes, detailed in Section 3.

2.2 Respondents' Backgrounds

The study was designed to include participants from various regions across Canada by utilizing a virtual environment. The study included 27 participants representing 12 organizations, ranging from federal to municipal levels of government, 3 Indigenous communities, 1 non-political organization, and 1 academic institution. There is often a tendency for more representation from large, well-resourced cities in conversations about seismic risk in Canada; therefore, special attention was paid to inviting participants from small communities with high seismic risk, as identified by the Seismic Risk Index (Hobbs et al., 2023b). Not all smaller communities, however, responded to the invitations, possibly due to their limited capacity to do so. 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 seismic risk than publicly appreciated. Another area the study attempted to include was the Yukon Territory; however, no emergency managers could be available due to ongoing wildfire emergencies in the summer of 2023, when this study was conducted.

Responses are grouped and summarized to improve clarity and brevity. This section focuses on key themes: situational awareness, related obstacles, information needs, and dissemination methods most relevant to RED-E product development. A full list of questions and detailed responses is available in Patchett (2024).

2.3 Situational Awareness

In response to the question "How do you gain situational awareness after a major earthquake?", most participants reported relying on windshield or walking surveys, 9-1-1 calls, and fire hall reports. Emergency managers typically depend on first responders, volunteer teams, and public reports—methods that are slow and often incomplete, even weeks post-event. Many struggled to estimate how long it would take to achieve full situational awareness, citing factors like time of day, event size, and location. Nighttime events cause additional delays. Overall, respondents agreed that credible situational awareness typically takes at least three days to several weeks, making it unlikely to identify injury locations or numbers within 24–48 hours.

When asked how they identify isolated communities post-earthquake, respondents noted that limited telecommunications, especially in remote areas, make such detection difficult. In rural areas, especially Indigenous communities, responders may know vulnerable residents and check on them directly. However, in larger municipalities or at the provincial level, isolation often goes unnoticed until survey teams arrive or calls for help are made. Windshield surveys remain the primary method of detection. Some municipalities encourage self-sufficiency and pre-position supplies, but challenges remain, especially when roads and communications are down. A key concern is avoiding scenarios like Christchurch, New Zealand, following the 2011 earthquake, where aid to isolated towns was delayed. Respondents emphasized the importance of reaching underserved communities, not just the most vocal ones.

2.4 Challenges to Gaining Situational Awareness

2.4.1 Staff Shortage

Many respondents were unsure how long it would take to respond to a major earthquake, noting that it depends on factors such as the time of day, location, magnitude, road damage, and personal readiness. If responders aren't prepared or their families need help, immediate deployment is unlikely. A few said they could respond within 10 minutes if fully ready. Some noted that even in normal conditions, first responders are stretched thin, one respondent expressing that too many 9-1-1 calls are on hold, waiting for longer than they should during normal operations. Many communities lack dedicated responders and rely on a single person to coordinate volunteers, which can delay situational awareness. Staff shortages, especially engineers and critical decision-makers, further hinder effective disaster response.

2.4.2 Prolonged Response Time

Respondents identified blocked roads and telecommunication outages as major barriers to rapid response and situational awareness. Windshield surveys and rapid damage assessments are difficult without drivable roads, and 9-1-1 is often overwhelmed, even during small earthquakes. Patrols on foot or by vehicle can take days, and information must then be relayed back, often by radio. In smaller communities, officials may go door-to-door; one municipality uses electric bikes for surveys when roads are impassable. Many Emergency Operation Centres (EOCs) and hospitals rely on walk-ins for updates, which can cause delays in gaining situational awareness and limit spatial coverage. Only a handful of local governments have trained volunteers with amateur radios, and most communities are unprepared for telecommunication failures. Functioning CI, including telecommunication, electricity, and transportation, is essential for timely situational awareness.

2.4.3 Other Obstacles

Other identified barriers include the 'rumour mill': the task of validating/countering, and addressing social media information/disinformation/misinformation would be complex and time-consuming. Many respondents commented that social media tends to pose problems rather than solutions, as it is challenging to validate the data, and people often ask for help but do not post subsequent updates to indicate whether they remain in need. Drones were also mentioned as a means to gain situational awareness, but their capacity is highly limited, as noted earlier, by the availability of technicians and equipment, restriction of aerial space near an emergency zone, and a potentially slow airspace approval process.

2.5 Critical Information Needs for Emergency Response

2.5.1 Information Content

Universally, every respondent appreciated the information that NRCan/RED-E can provide, such as the estimated earthquake size, rupture depth, and other parameters as previously listed in Section 2.1. The discussions were held with the understanding that the above-mentioned information could be provided, and respondents were then asked what additional information could be useful for them. While this paper focuses on end-user needs, some potentially valuable features, such as linear infrastructure and secondary perils, cannot yet be modelled at scale.

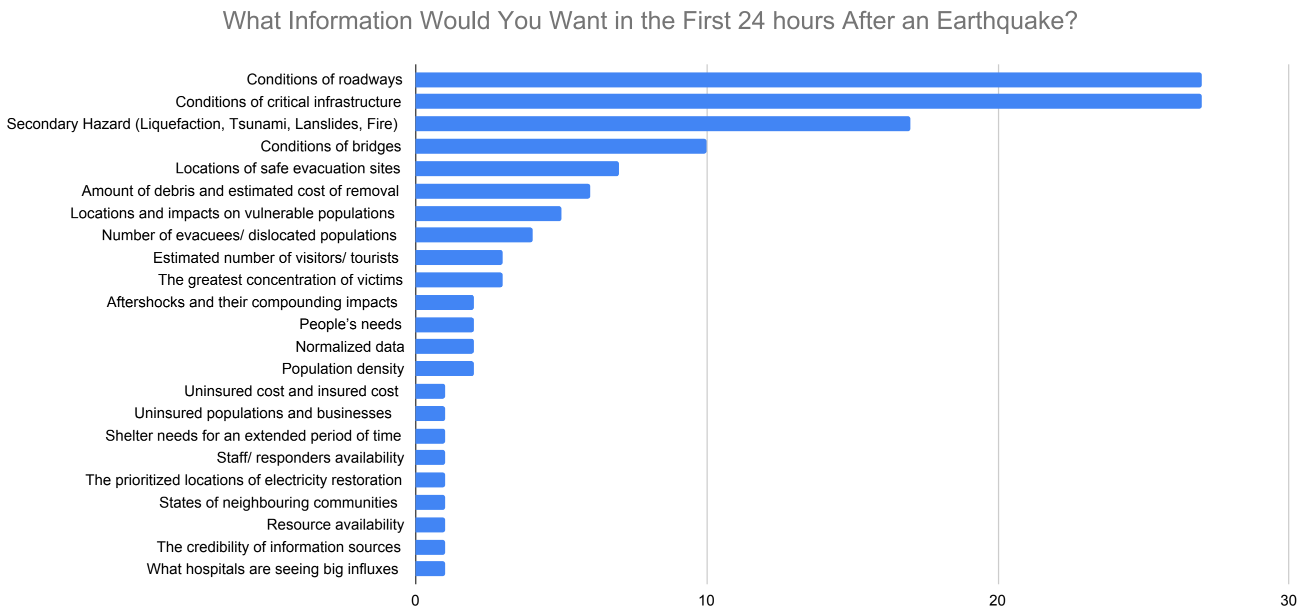


Figure 3 A summary of participants' answers to the question: "Ideally, what information would you want in the first 24 hours after an earthquake?" The X-axis shows the count of participants giving each response. The information that RED-E is capable of providing at the time of the discussion is omitted, 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 discussions were held with the understanding that the above-mentioned information could be provided, and respondents were asked what additional information could be useful.

The majority of participants stated the importance of telecommunication, transportation, and road conditions (Figure 3) 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 Indigenous community indicated that they have canoes to cross the river and all-terrain vehicles (ATVs) to navigate over the debris if needed, signifying their resilience. In many cases, however, first responders and emergency managers live outside the community they serve, and bridges, as well as highways, serve as arteries; the condition of key transportation infrastructure is something participants want to know immediately. Knowledge of the habitability and functionality of critical structures, particularly for infrastructure such as hospitals, is essential for planning shelter and facilitating emergency operations. The condition of natural gas lines, sewage lines, health clinics, fire halls, airports and ports is also desired immediately by end-users.

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. Many end-users prioritize response efforts based on the concentration of vulnerable populations rather than the most physically damaged areas. Understanding the impact on these groups is crucial for planning rescues and sheltering. They emphasized the need for data on individuals reliant on power-dependent medical equipment, those with disabilities or functional needs, and the locations of care homes, retirement homes, and schools in affected areas.

A few respondents also inquired about the estimated number of tourists. Tourists/visitors are difficult to account for, not easy to reach with relevant warnings (Bird et al., 2010), unfamiliar with the area, and have little connection to local communities (Becken and Hughey, 2013). For example, according to Downtown Victoria Business Association (2023), cruise ships alone bring 700,000 to 970,000 visitors annually (Mauneau, 2023), and they will need to be sheltered temporarily until it is safe for them to leave again. Many popular destinations in Canada attract a large volume of tourists, and these cities and townships must consider the consequences of emergency responses.

The Ontario Ministry of Municipal Affairs and Housing values estimated loss data on uninsured homeowners, tenants, small businesses, farms, and non-profits. The ministry currently financially supports the uninsured population during sudden, unexpected, extraordinary (in a historical sense), widespread, and expensive natural disasters (Ontario Ministry of Municipal Affairs and Housing, 2018). Having rapid access to the likely number of uninsured and/or low-income individuals impacted by a major earthquake can facilitate an expedited approval process.

After an earthquake, emergency managers focus on setting up EOCs, assessing staff capacity, and planning for rescue, evacuation, and shelter. They must identify safe evacuation routes and prioritize survey areas. To establish shelters and group lodging, they need in-

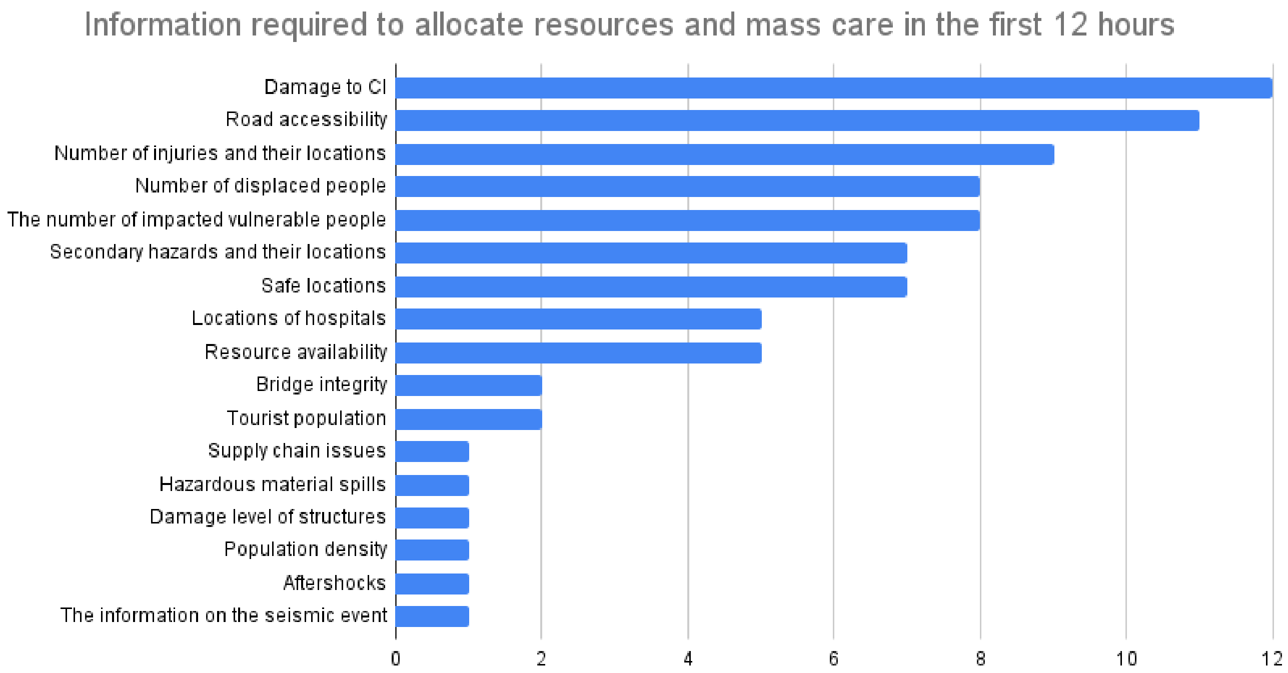


Figure 4 A summary of participants' answers to the question: "What information is needed to determine mass care needs and allocate supplies within the first 12 hours?". The X-axis shows the count of participants giving each response.

formation on available buildings, their conditions, and the number of nearby displaced people (Figure 4). They also require the locations and functionality of healthcare facilities. RED-E modelling can help identify potential safe zones, allowing faster planning and prioritization of shelter sites and evacuation routes.

Respondents emphasized the importance of data on secondary disasters, such as liquefaction, landslides, and debris, as well as their associated removal costs. Tsunami risk was a recurring concern, with one noting RED-E would lose value if it excluded tsunami impacts. Some also wanted information on aftershocks and their compounding effects, though these cannot yet be modelled at scale. Currently, RED-E does not include linear infrastructure, telecommunication disruption, or CI functionality, but these are future goals.

Interviews also explored data needs for mass care and supply allocation within 12 hours. Key information includes damage to CI (roads, bridges, power, water, gas, sewage), road accessibility for evacuation and responders, injury counts and locations, displaced populations, vulnerable individuals, and tourist numbers. Medical providers need CI status, patient demographics, and injury severity. Access to roads, ports, and airports is essential for planning rescues and delivering supplies.

2.6 Information Dissemination

2.6.1 Preferred Format of RED-E Outputs

Most end-users (70%) prefer RED-E information in GIS-compatible formats to integrate with their existing emergency operation systems. Local compatibility is crucial, as not all municipalities use provincial GIS systems and may have customized layers (e.g., hazardous materials, sacred sites). Indigenous communities, in particular, value control over sensitive data and may not use GIS at all.

Many also want one- or two-page PDF summaries, similar to PAGER or QLARM, with static maps and key information for field use during telecommunication outages. Text summaries are valued for reporting and communication via radio or satellite when networks are down. Overall, users prefer receiving information in multiple formats, such as GIS, PDFs, and text, for increased redundancy and accessibility.

Some users trust NRCan as the source due to its scientific credibility, including Indigenous communities with federal ties. However, concerns were raised about the reliability of federal websites during high-traffic periods, citing past outages. It is worth noting that the system was upgraded since the last outage during the 2001 Nisqually earthquake, but this belief persists. Clear user contact points for feedback were also requested.

For spatial scale, municipalities prefer neighbourhood-level data, while provinces are satisfied with regional summaries.

2.6.2 Foreseeable Challenges of RED-E Integration

Some end-users anticipate challenges integrating RED-E, citing limited staffing, technical capacity, and potential indirect costs for training and system upkeep. Small municipalities especially highlighted the need for regular training with simulated earthquakes, though only if RED-E can incorporate real-time data. Provincial governments may face added security-related requirements, such as using Canadian servers and undergoing

Figure 5 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?" The X-axis shows the count of participants giving each response.

lengthy approval processes.

2.6.3 Concerns about RED-E Outputs

The study inquired about concerns on the *potential* data dissemination to the public, although public release is not within scope at this time. Most respondents expressed concerns about the results being made publicly available (Figure 5).

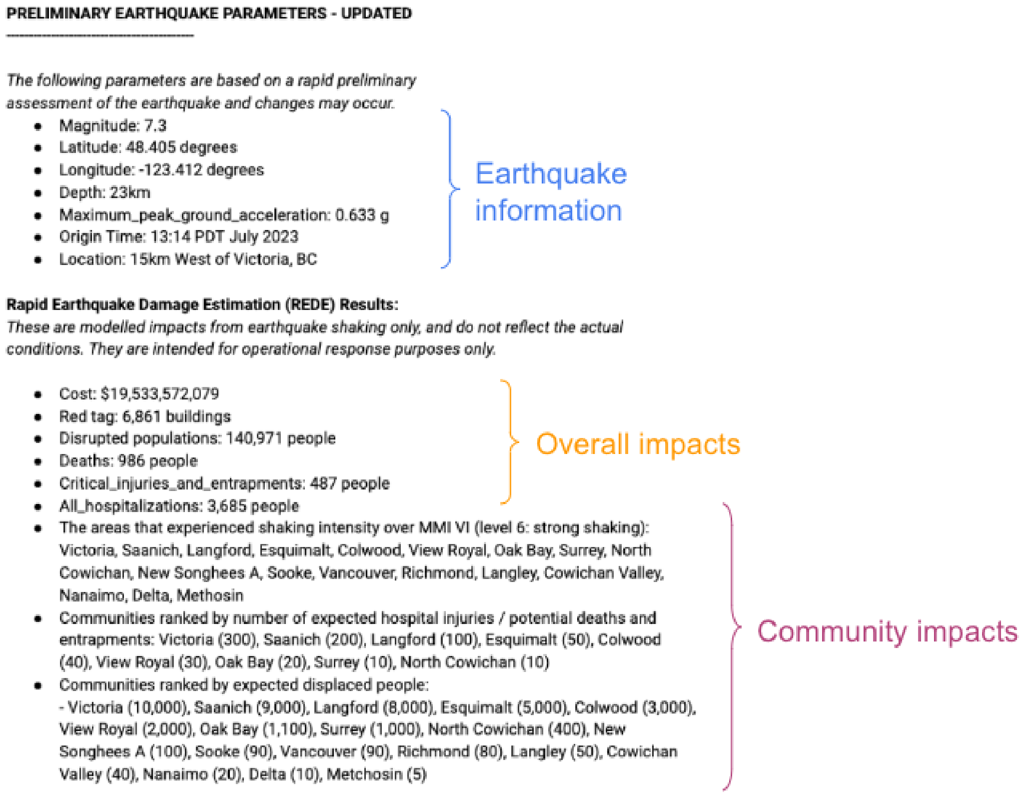
End-users are concerned that publicly sharing RED-E data could lead to misinterpretation, believing that RED-E is ground-truth instead of modeled. They worry that misinformation on social media, and resulting panic, may hinder rescue efforts and raise unrealistic public expectations for rescue operations. Additional concerns include the rise of disaster tourism (both physical and online), which can cause system overload, and, lastly, potential data inaccuracies that may undermine public trust. Indigenous communities have emphasized the importance of data privacy and retaining control over their own information, highlighting the need to respect sovereignty in order to build nation-to-nation trust.

End-users support having separate RED-E outputs for internal and public use. Summarized formats, such as PAGER or QLARM, are considered most suitable for the public. They recommend consulting with experts who are trained to discern what information should be made public, as well as conducting expert review before public release to avoid conflicting information. They also suggest limiting access to sensitive data, such as fatality estimates, through password protection or security clearance, to prevent emotional distress and misuse.

Education is a critical component if RED-E is made public-facing. Respondents emphasized the importance of clearly communicating the system's modelling uncertainties and limitations to avoid misinterpretation. They recommended explicitly stating that RED-E outputs are modelled data, not confirmed facts, and educating the public before the system is launched. To protect privacy and reduce the risk of attracting disaster tourists, they also advised displaying data at a scale that avoids revealing sensitive or overly localized information.

2.7 Other Comments

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 as responders collect and upload them. Others expressed concern over how often data will be updated to minimize uncertainty and keep the system outputs current and relevant, and asked who will be updating it. They also wanted to know the uncertainty of the modelling results. One respondent asked for normalized data to gain a better understanding of the impact scales.



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. They are intended for operational response 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 people:
  - Victoria (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 6 Annotated wireframe of the RED-E product in text format. Coloured text will not be part of the final product. The numbers shown here are mock-ups for illustration purposes only.

3 RED-E Product Wireframes

Based on user feedback (Section 2), wireframes were developed to demonstrate potential RED-E functionality. The intended users are emergency managers, first responders at all government levels, and Critical Infrastructure (CI) operators; the tool is not currently designed for public use. Interviews emphasized key data needs, such as those listed in Section 2.1, along with additional desirable information (e.g., telecom and road disruptions, secondary hazards), which are not yet scalable to model.

The study's main goals were to conduct interviews, assess user needs, create wireframes, and gather feedback, following a user-centered design (UCD) approach. In response, three RED-E formats were developed: text, static PDF, and dynamic GIS. These formats allow information sharing regardless of communication system status. The wireframes are conceptual and may not reflect the final RED-E product. As a sample scenario case, wireframes used the risk model results of an $\mathrm{M_w}$ 7.3 full rupture of the Leech River fault, 15 km west of downtown Victoria (Morell et al., 2018; Harrichhausen et al., 2021, e.g. Figures 6, 7); where these results were not available, dummy values are used. For example, the values of the expected range of estimated fatalities in the static wireframe (Figure 7) and some values in the text format are not model results but are included for illustrative purposes only.

3.1 Text Version

The text format is the most straightforward and readily accessible product, even during low-bandwidth times (Figure 6). It is inspired by and adapted to be more readable than the messages sent by the United States Tsunami Warning Centers (https://www.tsunami.gov/). Potential users of RED-E (Section 2.2) 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 information on the seismic event itself, including estimated magnitude, location (in longitude and latitude, depth, and a general location description, e.g., 15 km west of downtown Victoria), maximum ground motion 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 or shelter-seeking people, fatalities, critical injuries and entrapments, and the number of hospitalizations. It also includes community impact, which lists the areas that experienced shaking intensity over MMI VI (level 6: strong shaking), communities ranked by the number of expected critical injuries requiring hospitalization/potential deaths/entrapments, and communities ranked by number of people expected to be displaced.

3.2 Static Version

The static product is a dashboard in PDF format with comprehensive visuals such as maps, tables, descriptions of the event, and the estimated losses (Figures 7, 8, 9, 10). The usefulness of the PDF format for post-earthquake communications was validated by Loos et al. (2024), who demonstrated the criticality of a highly shareable format for post-earthquake products where a combination of text and images can easily be shared internally within a response organization, externally to affected populations, and generally on media platforms.

The initial "summary" page of the static version includes overview maps and overall estimates for impacted areas (Figure 7), while the subsequent "community" pages convey the municipality-specific results.

The summary page includes:

- Disclaimer that information shown is based on modelling, not ground-truth data
- Colour-coded impact level (red, orange, yellow, and green) based on the Earthquake Impact Scale (Wald et al., 2011)
- Seismological overview information (estimated magnitude, location, origin time, and depth)
- List of impacted communities (communities with more than 2 critical injuries, which require immediate hospitalisation, and/or entrapment/fatalities)
- Colour-coded impact summary table, consisting of fatalities, critical injuries, displaced populations, numbers of buildings in different damage levels (collapsed, complete, and extensive), and economic impact. Each value includes uncertainties at the 5^{th} and 95^{th} percentiles of all modelled outcomes. Assignment of colours is generally guided by the Earthquake Impact Scale that has been implemented for the USGS PAGER product (Wald et al., 2011), augmented for the displaced population based on the tentative thresholds of 50,000 for red ("international response"; e.g. the 2016 Fort McMurray, BC fire evacuation which resulted in the relocation of 90,000 people (Public Safety Canada, 2016)), 20,000 for orange ("national-scale impact and response": e.g. the 2023 Yellowknife wildfire, which triggered 20,000 people to evacuate (Ljunggren, 2023)), 5,000 for yellow (regional impact and response; e.g. the 2023 flood in Merritt, BC, which caused caused 7,000 people to relocate (Norwell, 2023)), and 1,000 for green ("little to no impact").
- Three maps of estimated severe injuries (critical hospital, entrapment, and fatalities combined), estimated displaced population, and severely damaged buildings (collapsed, complete, and extensive combined)
- Link to dynamic RED-E version
- Contact information

Three different examples of the community-specific page of the static RED-E were created (Figures 8, 9, 10) to solicit feedback on what should be included. All three versions have maps of critical injuries and entrapment/potential death, displaced populations, and debris and bridge conditions, but the three versions are differentiated by the presence of an impact summary table (Figure 8), a damaged buildings map (Figure 9), or a social vulnerability map (Figure 10). The maps on the summary page used the census subdivision boundaries, approximately equivalent to a municipality scale, whereas the maps on the community page used the settlement area boundaries, approximately equivalent to a neighbourhood or postal code or Forward Sortation Area of postal code.

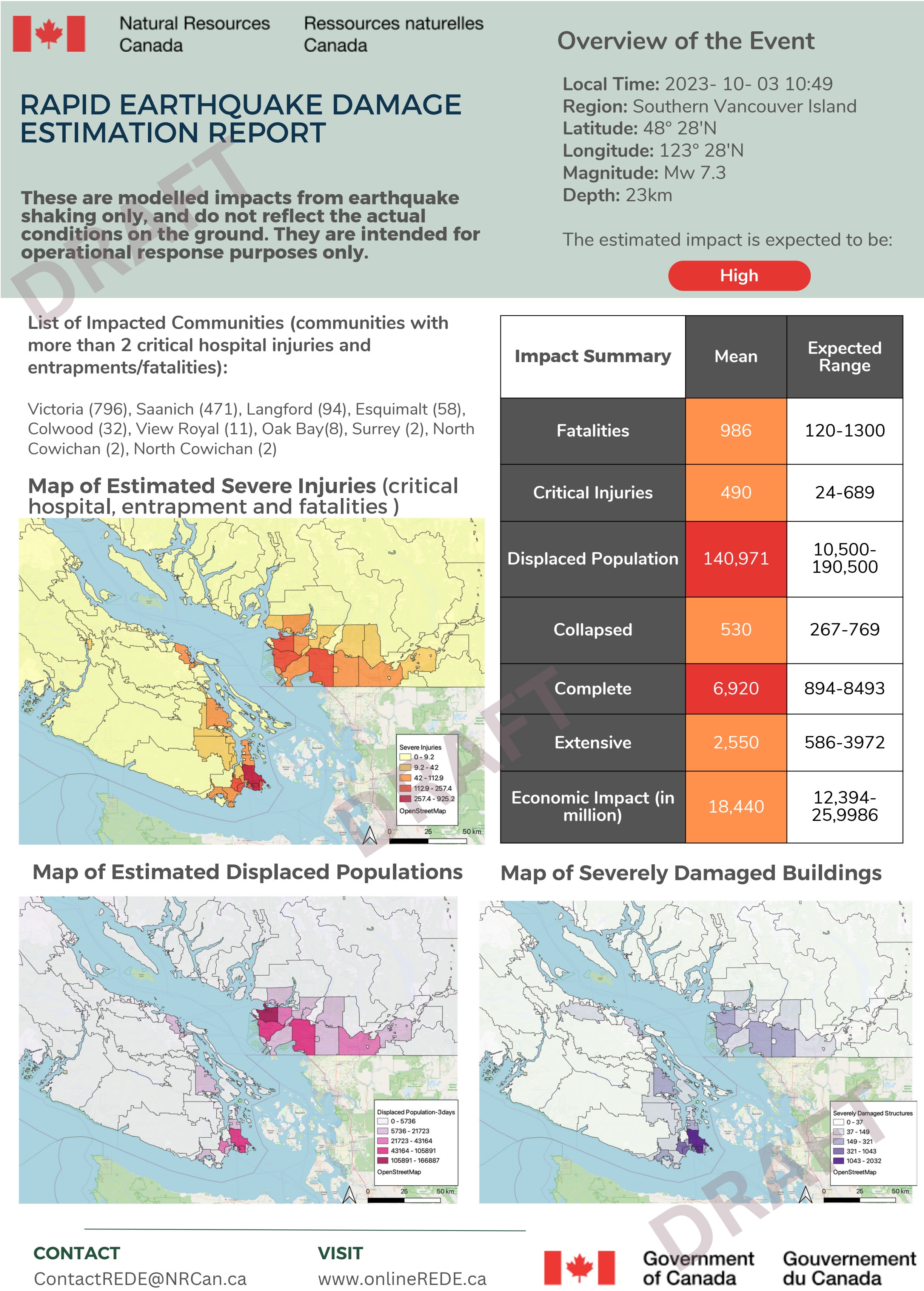
3.3 Dynamic Version

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. Many emergency management teams use provincial GIS portals. Some well-resourced communities or groups may also have local mapping systems with their own data layers of CI, hazardous materials, or identified vulnerabilities. It is envisioned that the API version of the dynamic RED-E format will allow users to extract data for their own portals. The dynamic GIS version could also be independently hosted through a federal platform, such as the national Earthquakes Canada website, as an interactive map with multiple data layers. Examples of larger scale, "zoomed out" views, which envelop the whole impacted region, are shown in Figure 11, while Figure 12 showcases examples of smaller scale/"zoomed in" views, at the municipality level. Users of the dynamic version will see a disclaimer displayed before using the site and are given the ability to view or hide the layers and features that may or may not be useful for them.

In addition to maps, the dynamic version could ideally also have bar charts showing the building types contributing to each variable, similar to NRCan's RiskProfiler website (accessible at https://RiskProfiler.ca), and impact summary tables. This version could also include some features such as city boundaries, bridges, major highways, hospitals, ambulances and fire stations.

4 Participants' Feedback on Wireframes

The RED-E wireframes presented in the previous section were presented to two groups who had been involved in the informational interviews: one local government and one provincial government. Herein, summarized responses from the wireframe review sessions are provided, including detailed suggestions from end-users on how the wireframes could be improved. Each virtual 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



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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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VISIT
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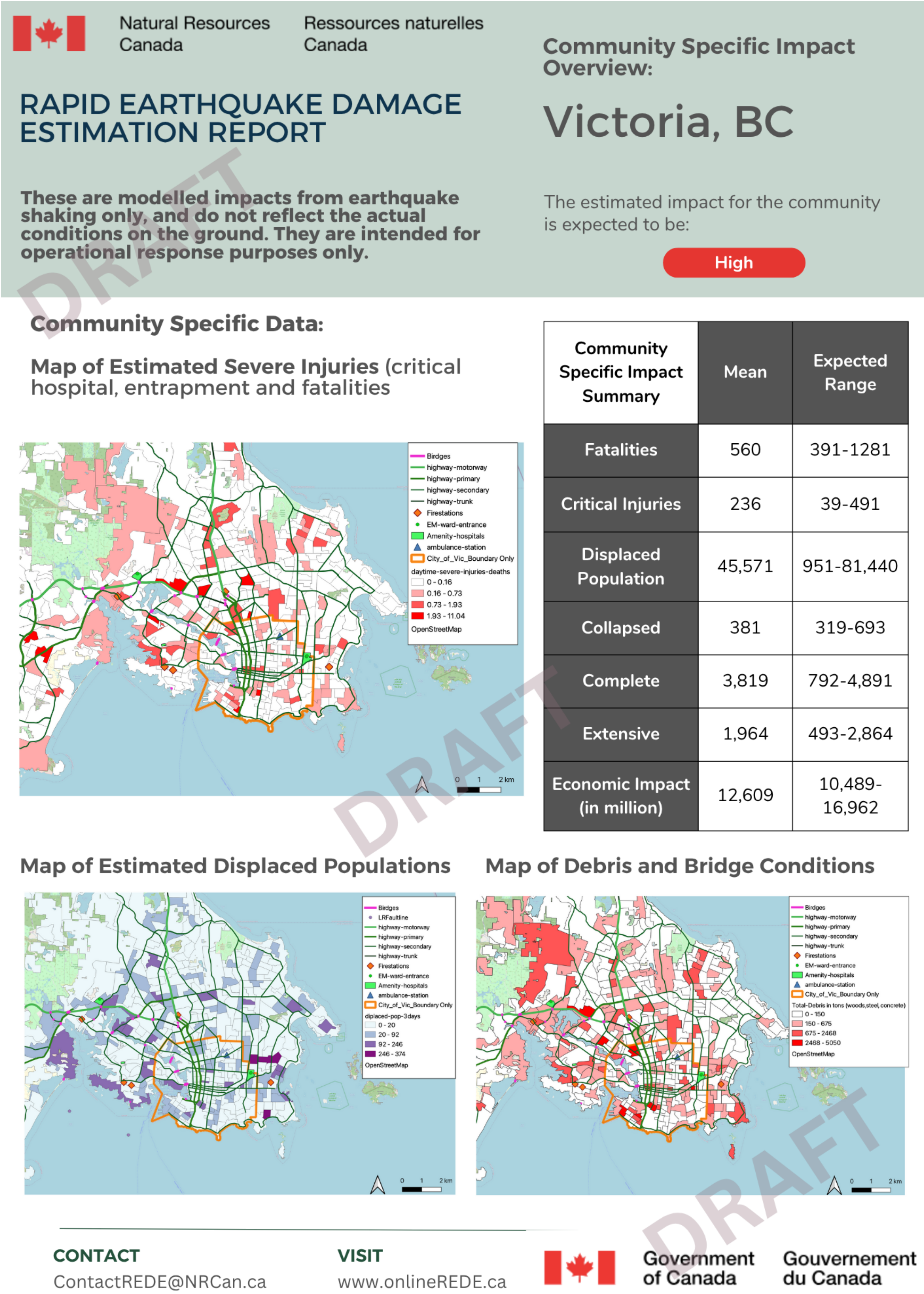
Figure 7 The summary page of static RED-E, which contains summarized information on the seismic event and estimated impact results for all impacted areas, presented at the subdivision level.



Natural Resources Canada | Ressources naturelles Canada

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

DRAFT

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

DRAFT

Map of Estimated Displaced Populations

Map of Debris and Bridge Conditions

DRAFT

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Figure 8 The community page of static RED-E: version 1, containing estimated impact results (maps of severe injuries, displaced populations, and debris and bridge conditions) with municipality-specific information summarized in a table.

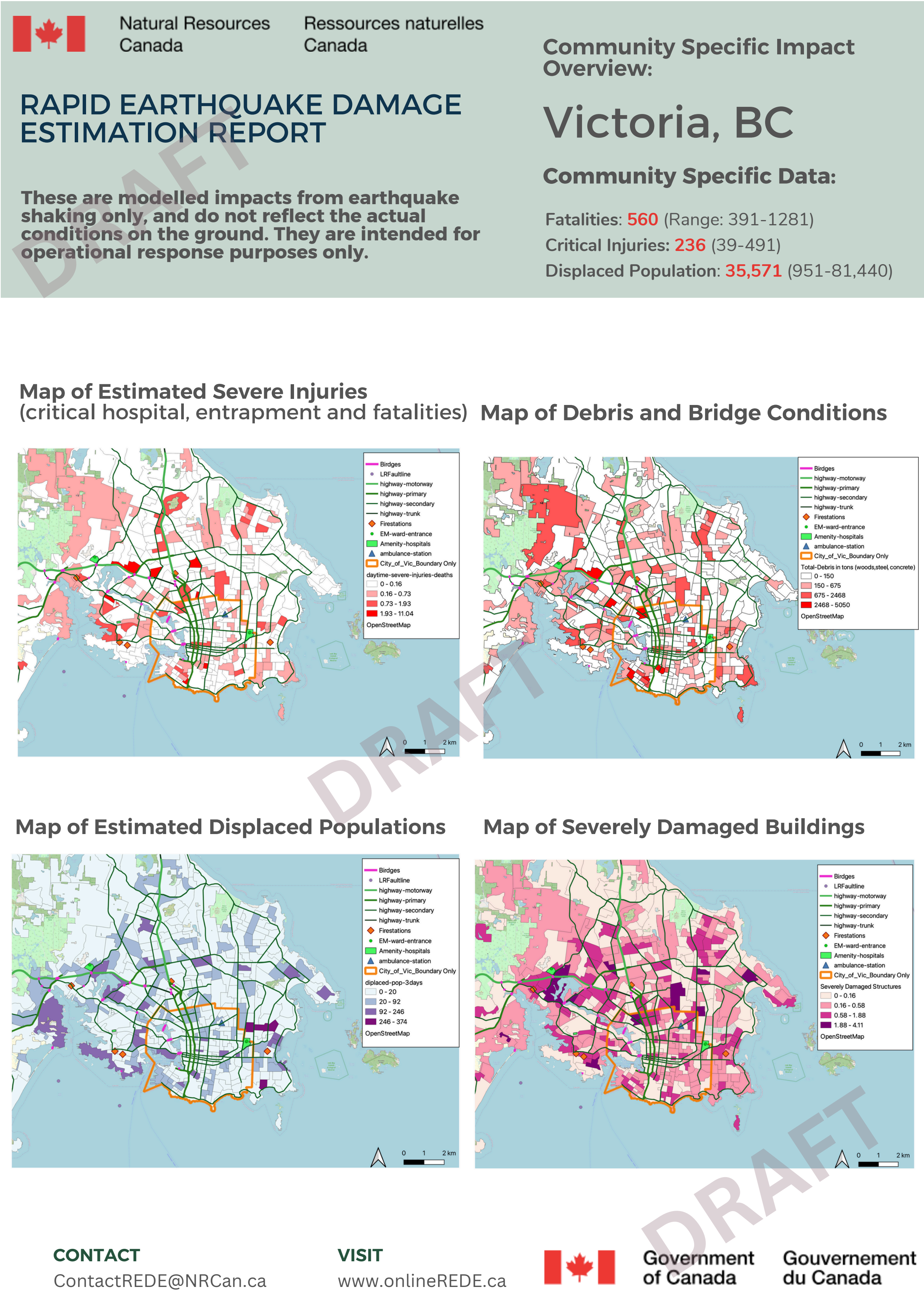

Figure 9 The community page of static RED-E: version 2, containing estimated impact results (maps of severe injuries, displaced populations, debris and bridge conditions, and severely damaged buildings).

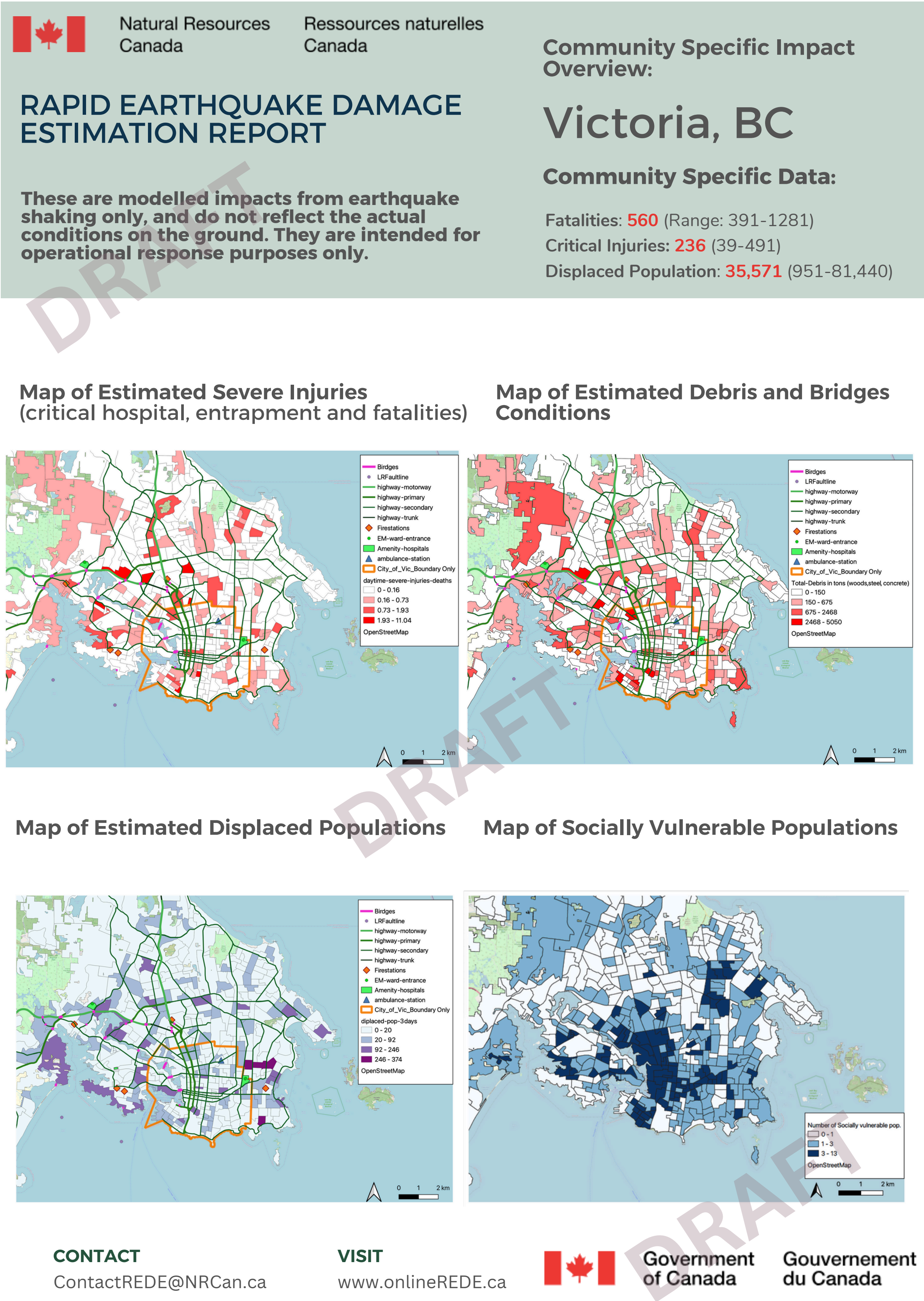

Figure 10 The community page of static RED-E: version 3, containing estimated impact results as maps of severe injuries, displaced populations, debris and bridge conditions, and socially vulnerable populations. A map of socially vulnerable populations is included here instead of severely damaged buildings as seen in version 2.

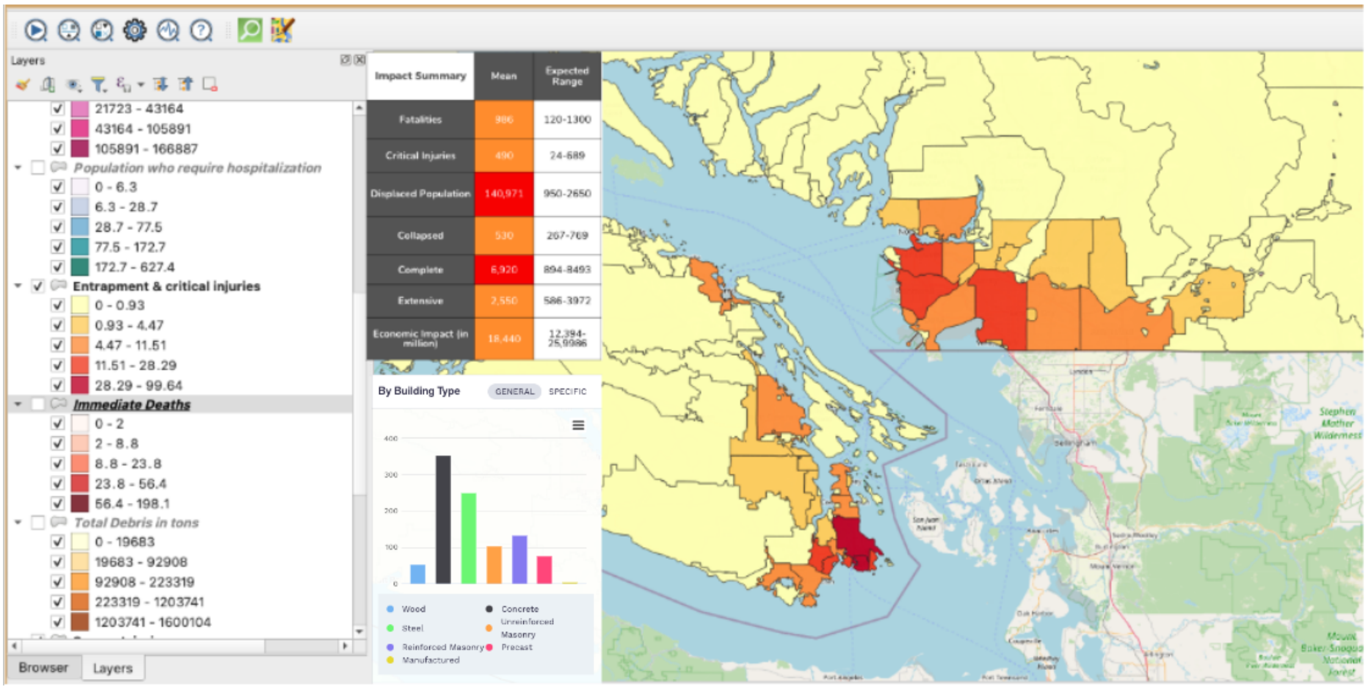

Figure 11 A zoomed-out view of the dynamic RED-E version. An example of an impact summary can be seen by selection options within the sidebars, and census subdivision-specific information is displayed as users select polygons on the map. This image was shown to participants in order to demonstrate the functionality of the interactive maps in the dynamic version, rather than to focus on specific values, which are shown for illustrative purposes only.

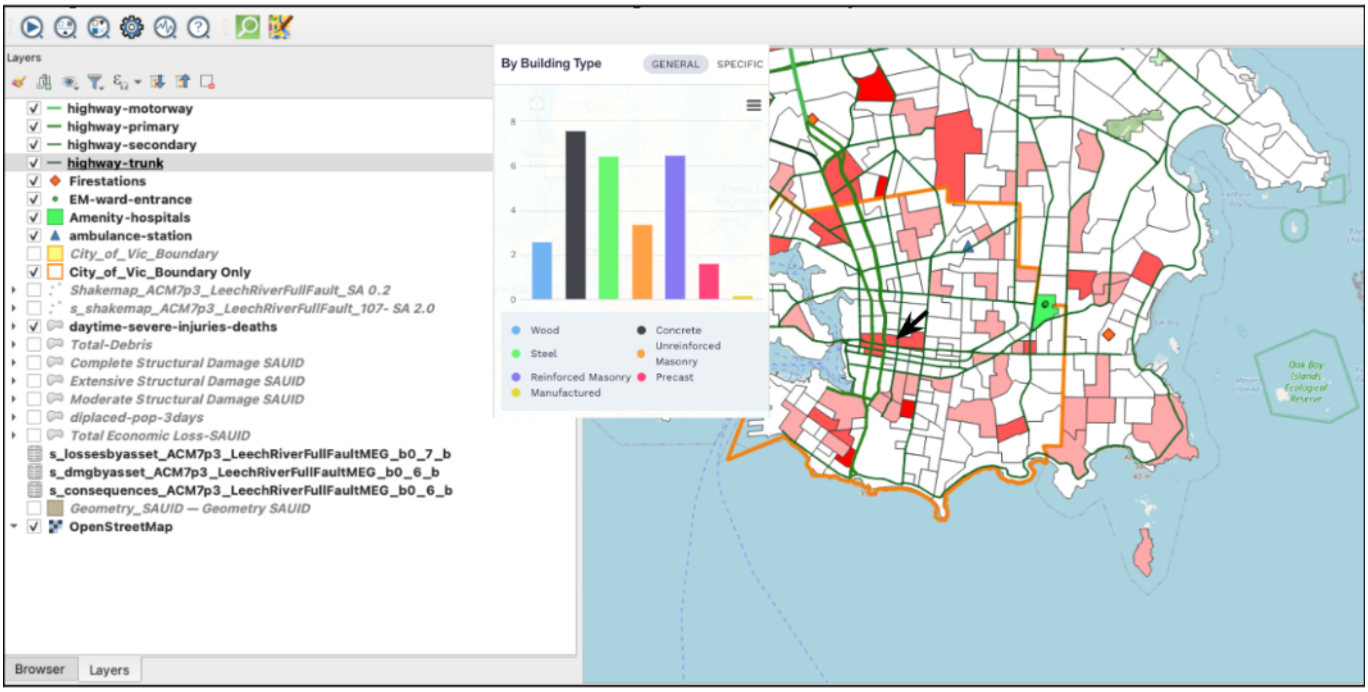

Figure 12 The map zoomed in to the neighbourhood level showing the neighbourhoods with severely damaged buildings. As users click the neighbourhood polygon, more detailed data in bar graphs, such as what types of buildings are severely damaged, the age of severely damaged buildings, and types of occupancy (residential, commercial, etc.) would appear, similar to the information provided by https://RiskProfiler.ca. This image was shown to participants to demonstrate the functionality of the interactive maps rather than to focus on specific values, which are shown for illustrative purposes only.

products. Complete responses are available in Patchett (2024).

Overall, the text format (e.g., Figure 6) was appreciated by all users as it is simple, short, and straightforward. It is communicable using amateur radio, satellite phones or commercial radio in the case of a telecommunication breakdown. Ranked impact data helps end-users assess severity. For provinces, it highlights which municipalities need the most support and which can offer mutual aid. At the municipal level, responses vary based on impact scale (e.g., sheltering 100 vs. 1,000 people) and the text format effectively conveys this scale.

Both municipal and provincial users also acknowledged the value of the static format, particularly appreciating visuals like maps that illustrate the scale and severity of impacts. They found both the summary and community pages valuable, as they serve different purposes for different users. One team was open to a longer version of the static RED-E to include more information, while the other preferred a concise format, noting that two pages per community were sufficient.

In general, for end-users, having maps of potential entrapments and severe injuries, fatalities, displaced populations, and debris is more valuable than a map of damaged buildings, as their priority is to save lives. For example, pre-code commercial buildings might collapse but will likely be empty if the event occurs at night.

Depending on the event's scale, municipalities may need provincial or federal support. RED-E is valuable because it provides rapid impact estimates, allowing faster funding or resource requests, well before ground-truth data are available. It helps users identify and communicate expected response gaps.

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, and require different resources. For example, fatalities need to be dealt with by coroners. Critical injuries require rapid hospitalization, while first-aid-level injuries can be treated at home or on site. Entrapments require support from the Heavy Urban Search and Rescue (HUSAR). Similarly, the information on the debris should be categorized into materials since different material types require different removal procedures. Users also requested the inclusion of definitions of terms, and data layers for features like ports, airports, hazardous materials, etc.

Similar to the earlier stage of end-user engagement (Section 2.5.1), respondents expressed a desire for information on secondary hazards (tsunami, liquefaction, landslide, and fire) to be provided if possible. Currently, RED-E cannot model tsunami impact using the OpenQuake Engine; it may be possible, however, to implement the OpenQuake Engine Liquefaction Calculator in the future (Yilmaz et al., 2021). These users suggested that a simple potential inundation zones layer could be helpful even if tsunami modelling is unavailable. For local end-users, a closer geographic extent for the community page of the static product would be more beneficial.

Users noted the need for multiple reception centres tailored to different demographics, such as seniors or families, due to varying care needs. Inclusion of demographic data on displaced populations, especially at the neighbourhood level, is essential. They also suggested using bivariate choropleth maps to show two data types in one map. For example, one map could illustrate the number and location of displaced populations as well as the distribution of socially vulnerable populations (Figure 13). Using bivariate maps helps save space in static RED-E products. To ensure inclusivity, it's important to employ a color-blind-friendly approach.

5 Discussion and Future Work

In this study, we sought to include participants from across Canada's seismically active regions, but the investigators' language limitations restricted participants to those in areas where the official language is English. The study covers many areas of Canada by utilizing a virtual meeting environment. Future engagement can expand to include participants from other areas.

5.1 Inclusion of Critical Infrastructure (CI)

Potential RED-E users value impact estimates on CI, including transport networks, bridges, ports, pipelines, and hazardous material facilities. Identifying road blockages is a key priority for future RED-E updates. There are prior global examples of network impact modelling from seismic events, such as works by Cho et al. (2001), Costa et al. (2017), and Poudel et al. (2023). The new linear infrastructure module for the OpenQuake Engine could be used to investigate the effect of earthquakes on roads, specifically in terms of damage to onramps and highway bridges in Canada, and on other linear CI such as water mains and power lines. This approach could be used in RED-E to address end-user feedback from this study.

5.2 Visualization of Uncertainty

In the feedback versions, uncertainties were shown as numerical ranges. Participants suggested visualizing these uncertainties would better support decision-making. Past studies support this, showing that visualized uncertainty helps narrow expectations and increases confidence in decisions (Joslyn and Savelli, 2010; Schneider et al., 2022). Figure 14 shows two examples from the PAGER system and an associated study. Both demonstrate the probability of modelled fatalities and economic losses. The scatter plot versions had been revised based on suggestions made by cognitive scientists and led to significant improvement in understanding of the uncertainties by both technical and public users (Karjack et al., 2022).

5.3 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. This includes 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 (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-earthquake response and

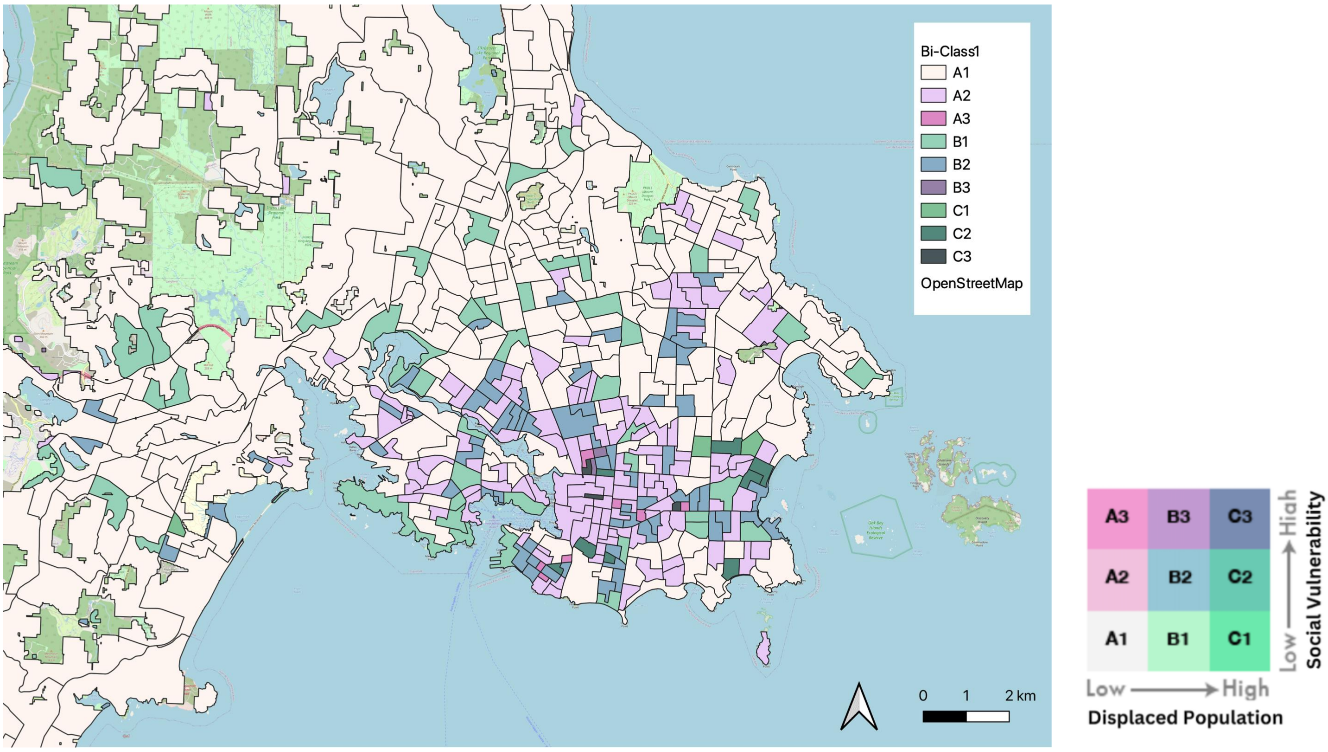

Figure 13 An example of a bivariate choropleth map displaying both the displaced population and social vulnerability for the city of Victoria, BC. The legend is modified from Stevens (2015).

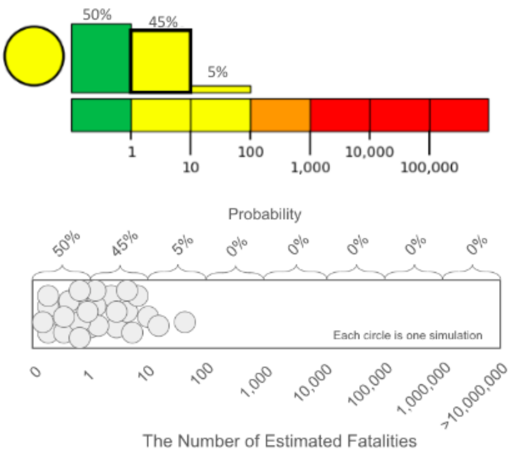

Figure 14 Two ways to display uncertainties/probabilities in estimated impacts. Top: histograms, as currently used by the USGS in PAGER. Bottom: Probability plots modified from Karjack et al. 2022. The example outputs are estimated fatalities following the 7 Jan 2020 M6.4 Puerto Rico earthquake.

recovery phases, as 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 this information as a data layer is believed to be valuable or even essential, especially for municipalities that lack resources to conduct their own socioeconomic vulnerability assessment.

5.4 More Accurately Represented Population Census and Housing Data

An important avenue for future research is to obtain more accurate population and housing data for Indigenous communities, which are typically underrepresented in the Canadian Census that underpins current exposure inventories (Smylie and Firestone, 2015; Saku, 1999). The census is one of the most widely used and essential sources of information as it provides a comprehensive picture of the characteristics of the people in the community (Trevethan, 2019) and it serves as one of the critical exposure data sources for RED-E modelling processes via the Canadian Seismic Risk Model (Hobbs et al., 2023a). Challenges exist with census data for Indigenous Peoples due to underrepresentation from self-identification and low participation on some reserves. Transient populations moving between reserves and cities can lead to inaccurate counts, inflating urban populations or omitting individuals entirely. As a result, Indigenous communities may be underfunded for services due to uncounted residents (Trevethan, 2019). Another study indicates that the current Indigenous social statistic data are unequally represented, stemming from misclassification and systematically embedded non-response biases and sampling errors in census data, 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.

5.5 Public Data

Throughout both stages of end-user engagement, participants raised concerns about making RED-E outputs public. They feared it could trigger public panic, raise unrealistic rescue expectations, and encourage unsafe self-rescue attempts that may interfere with official operations. While they acknowledge some people will act independently, they prefer to minimize this risk. Provincial representatives were more open to public release, provided a clear disclaimer explains the data are modelled estimates and warns against entering hazardous areas.

Public access could benefit spontaneous volunteers and sectors like insurance and engineering. However, the lack of a national credential system for securely sharing RED-E with emergency personnel adds complexity. Since RED-E is currently designed for professional users, broader public release would require modifications and further discussion. As an example of improvement, the study results of Loos et al. (2024) indicate that publicly accessible products such as PAGER should be modified to become more inclusive by making the information more relatable, transparent, understandable, and shareable. Making the product publicly accessible may be aided by further studies to understand the decision points for public users and how a non-specialized audience interprets the current version of RED-E. Marketing to launch a public-facing version of RED-E itself could be used to raise awareness of seismic hazard and risk. Similarly, the 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). End-users want clear explanations of the modelling process, benefits, limitations, terms, and uncertainties. Including links to detailed information, plus offering workshops or short videos, can help users understand technical aspects. Clear, timely communication reduces post-disaster anxiety (Lamontagne and Flynn, 2014; Fallou et al., 2020). Regulating public expectations through trusted scientific institutions is essential to maintain trust, as public anxiety can increase pressure on scientists to find solutions (Fallou et al., 2020). Providing post-earthquake safety tips and ongoing updates is also an effective way to reduce public anxieties, especially as aftershocks are common after large earthquakes (Fallou et al., 2020).

5.6 RED-E is an Evolving Product

User-Centered Design (UCD) is iterative. Beyond this study's feedback, continued input should be gathered after RED-E's launch. Future research may assess users' ability to understand and apply RED-E data and broader feedback may be collected through surveys or workshops as the tool evolves.

6 Conclusion

The RED-E system aims to support faster, more effective disaster response after major earthquakes. Past events and interview feedback show that gaining situational awareness is often slow and difficult. Rapidly available modelled data, on human, structural, and economic impacts, can help assess severity within minutes. This study conducted preliminary interviews, developed wireframes, gathered user feedback, and outlined next steps to finalize the tool.

Key findings from the informational interviews include:

- Following a large earthquake, gaining complete and credible situational awareness is time-consuming, assumed by most to take at least three days to weeks, and challenging to cover the entire affected region adequately.
- The three most frequently identified obstacles to gaining situational awareness were road blockages, loss of telecommunication, and staff shortages.
- The three most desired pieces of information within 24-48 hours of the disaster were the condition of CI, the number and locations of displaced people, and injuries.
- When communications are down and communities become isolated, impacts can only be assessed by travelling to them. The RED-E system could help the province, territory, or federal government proactively identify such isolated communities and start attempting to communicate with them.
- 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 and data types for the public versus official end-users.

Recommendations:

- The RED-E products should be communicated in multiple formats.
- Results should be provided in absolute and normalized terms. For example, casualties should be reported as the total number of casualties and as the number of casualties divided by residents in the neighbourhood/municipality/region.

- RED-E should provide the ability to add ground-truth data as they become available.

Three wireframes of RED-E products were developed, based on the comments received during the informational interviews: text, static, and dynamic, and feedback was solicited from two teams of emergency managers at municipal and provincial levels. Some critical input received, which can be incorporated into RED-E immediately, is: the inclusion of definitions of terms; data layers for features like ports, airports, hazardous materials, etc.; information on injuries that are separated into different levels of casualties; debris materials presented by classification; colour-blind friendly bivariate choropleth maps to display two variables without compromising space; closer geographic extent for the community page of the static product; and possibly the inclusion of information on the impacted demographics and ranked neighbourhoods according to the severity of impact for the text format. Suggestions that can be considered in the near future are the inclusion of CI information and secondary hazards.

All wireframes were well-received, and users see RED-E as highly valuable for immediate post-earthquake response. End-users need to communicate impact estimates and capacity gaps when requesting aid, and RED-E helps identify these gaps. For provincial governments, it enables proactive support by anticipating local needs. For local governments, it serves as a tool to prioritize rescues, submit support requests, and locate safe areas for displaced populations. Based on interviews and feedback, users strongly support RED-E, especially if it incorporates their recommendations, as it helps bridge the gap until ground-truth data are available.

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Data and Code Availability Statement

Masked and anonymized data from our informational interviews and prototype feedback sessions are available in Patchett (2024).

References

Applied Technology Council. Post-disaster building safety evaluation guidance. Technical Report FEMA P-2055, 2019. https://www.fema.gov/sites/default/files/2020-07/fema_p-2055_post-disaster_buildingssafety_evaluation_2019.pdf.

Argyle, E. M., Gourley, J. J., Flamig, Z. L., Hansen, T., and Manross, K. Toward a User-Centered Design of a Weather Forecasting Decision-Support Tool. *Bulletin of the American Meteorological Society*, 98(2):373–382, Feb. 2017. doi: 10.1175/bams-d-16-0031.1.

Becken, S. and Hughey, K. F. Linking tourism into emergency management structures to enhance disaster risk reduction. *Tourism Management*, 36:77–85, June 2013. doi: 10.1016/j.tourman.2012.11.006.

Bird, D. K., Gisladottir, G., and Dominey-Howes, D. Volcanic risk and tourism in southern Iceland: Implications for hazard, risk and emergency response education and training. *Journal of Volcanology and Geothermal Research*, 189(1–2):33–48, Jan. 2010. doi: 10.1016/j.jvolgeores.2009.09.020.

Cassidy, J. F., Brillon, C., Seywerd, H., Crane, S., Kaya, Y., and Hassani, B. Canadian strong motion monitoring and data access. In *18th World Conference on Earthquake Engineering 2024, Millan, Italy*, 2024.

Cho, S., Gordon, P., Moore II, J. E., Richardson, H. W., Shinozuka, M., and Chang, S. Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Urban Earthquake. *Journal of Regional Science*, 41(1):39–65, Feb. 2001. doi: 10.1111/0022-4146.00206.

Coburn, A. and Spence, R. Earthquake Risk Modelling. *Earthquake Protection*, page 311–352, Sept. 2002. doi: 10.1002/0470855185.ch9.

Coburn, A., Spencer, R., and Pomonis, A. Factors determining human casualty levels in earthquakes: Mortality prediction in building collapse. In *Proceedings of Earthquake Engineering, Tenth world conference, 1992 Balkema, Rotterdam*, pages 5989–5994, 1992.

Costa, C., Silva, V., and Bazzurro, P. Assessing the impact of earthquake scenarios in transportation networks: the Portuguese mining factory case study. *Bulletin of Earthquake Engineering*, 16(3):1137–1163, Oct. 2017. doi: 10.1007/s10518-017-0243-2.

Crane, S., Seywerd, H., Adams, J., Bird, A., Kolaj, M., and Perry, C. National Earthquake Early Warning for Canada. In *Canadian Conference - Pacific Conference on Earthquake Engineering 2023 Vancouver, British Columbia*, 2023.

de Bruycker, M., Greco, D., Annino, I., Stazi, M. A., de Ruggiero, N., Triassi, M., de Kettenis, Y. P., and Lechat, M. F. The 1980 earthquake in southern Italy: rescue of trapped victims and mortality. *Bulletin of the World Health Organization*, 61(6):1021–1025, 1983.

Diederichs, A. Geodetic methods of mapping earthquake-induced ground deformation and building damage. Master's thesis, University of Victoria, 2020. http://hdl.handle.net/1828/12031.

Downtown Victoria Business Association. 2023 Annual report on downtown Victoria, 2023. https://downtownvictoria.ca/downtownvictoria.ca/uploads/2023/06/DVBA-Report2023-002.pdf. Accessed: 2024-03-05.

Emergency Management BC (EMBC). The Provincial Earthquake Immediate Response Strategy (PEIRS), 2022. https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/emergency-preparedness-response-recovery/embc/plans/peirs.pdf. Accessed: 2024-03-05.

Erdik, M., Şeşetyan, K., Demircioğlu, M., Hancılar, U., and Zülfikar, C. Rapid earthquake loss assessment after damaging earthquakes. *Soil Dynamics and Earthquake Engineering*, 31(2):247–266, Feb. 2011. doi: 10.1016/j.soildyn.2010.03.009.

Fallou, L., Bossu, R., Landès, M., Roch, J., Roussel, F., Steed, R., and Julien-Laferrière, S. Citizen Seismology Without Seismologists? Lessons Learned From Mayotte Leading to Improved Collaboration. *Frontiers in Communication*, 5, Aug. 2020. doi: 10.3389/fcomm.2020.00049.

Flanagan, B. E., Gregory, E. W., Hallisey, E. J., Heitgerd, J. L., and Lewis, B. A Social Vulnerability Index for Disaster Management. *Journal of Homeland Security and Emergency Management*, 8 (1), Jan. 2011. doi: 10.2202/1547-7355.1792.

Goda, K., Wilhelm, K., and Ren, J. Relationships between earthquake insurance take-up rates and seismic risk indicators for Canadian households. *International Journal of Disaster Risk Reduction*, 50:101754, Nov. 2020. doi: 10.1016/j.ijdrr.2020.101754.

Grünthal, G. *EMS-98 (European Macroseismic Scale)*. The ESC Working Group, 1998. https://www.gfz-potsdam.de/en/section/seismic-hazard-and-risk-dynamics/data-products-services/ems-98-european-macroseismic-scale.

Guérin-Marthe, S., Gehl, P., Negulescu, C., Auclair, S., and Fayjaloun, R. Rapid earthquake response: The state-of-the art and recommendations with a focus on European systems. *International Journal of Disaster Risk Reduction*, 52:101958, Jan. 2021. doi: 10.1016/j.ijdrr.2020.101958.

Harrichhausen, N., Morell, K. D., Regalla, C., Bennett, S. E. K., Leonard, L. J., Lynch, E. M., and Nissen, E. Paleoseismic Trenching Reveals Late Quaternary Kinematics of the Leech River Fault: Implications for Forearc Strain Accumulation in Northern Cascadia. *Bulletin of the Seismological Society of America*, 111(2): 1110–1138, Jan. 2021. doi: 10.1785/0120200204.

Hobbs, T., Kaya, Y., Journeay, M., Singh, G., Bird, A., Cassidy, J., van Ulden, J., and Rotheram, D. Improving Situational Awareness During Early Earthquake Response Using Existing Seismic Risk Models to Rapidly Estimate Damage. Nov. 2020. doi: 10.1002/essoar.10504844.2.

Hobbs, T. E., Journeay, J. M., Rao, A. S., Kolaj, M., Martins, L., LeSueur, P., Simionato, M., Silva, V., Pagani, M., Johnson, K., Rotheram, D., and Chow, W. A national seismic risk model for Canada: Methodology and scientific basis. *Earthquake Spectra*, 39(3):1410–1434, May 2023a. doi: 10.1177/87552930231173446.

Hobbs, T. E., LeSueur, P., and Journeay, J. M. Characterizing seismic risk across Canada. In *Canadian Conference - Pacific Conference on Earthquake Engineering 2023 Vancouver, British Columbia*, 2023b.

Interaction Design Foundation. User Centered Design, 2016. https://www.interaction-design.org/literature/topics/user-centered-design#4_phases_in_user-centered_design-2.

Jaiswal, K. S., Wald, D. J., Earle, P. S., Porter, K. A., and Hearne, M. Earthquake Casualty Models Within the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) System. In *Human Casualties in Earthquakes*, page 83–94. Springer Netherlands, Dec. 2010. doi: 10.1007/978-90-481-9455-1_6.

Joslyn, S. and Savelli, S. Communicating forecast uncertainty: public perception of weather forecast uncertainty. *Meteorological Applications*, 17(2):180–195, June 2010. doi: 10.1002/met.190.

Journeay, M., Yip, J. Z. K., Wagner, C. L., LeSueur, P., and Hobbs, T. *Social vulnerability to natural hazards in Canada*. 2022. doi: 10.4095/330295.

Karjack, S., Brudzinski, M. R., and Shipley, T. F. Assessment of the General Public's Understanding of Rapidly Produced Earthquake Information Products ShakeMap and PAGER. *Seismological Research Letters*, 93(5):2891–2905, July 2022. doi: 10.1785/0220210318.

Lamontagne, M. and Flynn, B. W. Communications in the Aftermath of a Major Earthquake: Bringing Science to Citizens to Promote Recovery. *Seismological Research Letters*, 85(2):561–565, Mar. 2014. doi: 10.1785/0220130118.

Lamontagne, M., Halchuk, S., Cassidy, J. F., and Rogers, G. C. *Significant Canadian earthquakes 1600-2006*. 2007. doi: 10.4095/224164.

Ljunggren, D. Canada wildfire: all 20,000 Yellowknife residents evacuating, Aug. 2023. https://www.reuters.com/world/americas/canada-wildfires-crews-battle-stop-blaze-yellowknife-evacuates-2023-08-17/. Retrieved on Jun 7, 2024.

Loos, S., Karr, M., Macías, M., Knodel, E., Wald, D., Ludwig, K., Peek, L., and Lee, P. Publicly available yet not fully accessible: strategies for sharing post-earthquake loss information, Proceedings of the 18th World Conference on Earthquake Engineering 2024. 30th June–5th July, Milan, Italy. In *Proceedings of the 18th World Conference on Earthquake Engineering 2024. 30th June–5th July, Milan, Italy*. 2024.

Lorelei, J. Addressing social vulnerability to hazards. *Disaster Safety Review*, 4(2), 2006.

Macías, M., Sabine, L., and Elizabeth, R. Designing earthquake scenario exercises to evaluate actionable earthquake impact products [Poster]. Publisher: Colorado School of Mines Graduate Research Symposium, 2023. Accessed: 2024-03-05.

Mauneau, E. Victoria sees record number of cruise passengers in 2023, despite fewer ships, Oct. 2023. https://www.cheknews.ca/victoria-sees-record-number-of-cruise-passengers-in-2023-despite-fewer-ships-1174565/.

Mohd Daud, S. M. S., Mohd Yusof, M. Y. P., Heo, C. C., Khoo, L. S., Chainchel Singh, M. K., Mahmood, M. S., and Nawawi, H. Applications of drone in disaster management: A scoping review. *Science & Justice*, 62(1):30–42, Jan. 2022. doi: 10.1016/j.scijus.2021.11.002.

Morell, K. D., Regalla, C., Amos, C., Bennett, S., Leonard, L., Graham, A., Reedy, T., Levson, V., and Telka, A. Holocene Surface Rupture History of an Active Forearc Fault Redefines Seismic Hazard in Southwestern British Columbia, Canada. *Geophysical Research Letters*, 45(21), Nov. 2018. doi: 10.1029/2018gl078711.

Noji, E. K., Kelen, G. D., Armenian, H. K., Oganessian, A., Jones, N. P., and Sivertson, K. T. The 1988 earthquake in Soviet Armenia: A case study. *Annals of Emergency Medicine*, 19(8):891–897, Aug. 1990. doi: 10.1016/s0196-0644(05)81563-x.

Norwell, J. Living in Merritt is like living on an active volcano, says city manager, as concerns loom over flood risk, Nov. 2023. https://www.cbc.ca/news/canada/british-columbia/lytton-flood-risk-frustration-1.7031873. Retrieved on Jun 7, 2024.

Ontario Ministry of Municipal Affairs and Housing. Guidelines to apply for Disaster Recovery Assistance for Ontarians (DRAO), 2018. https://www.ontario.ca/document/guidelines-apply-disaster-recovery-assistance-ontarians-drao/1-introduction-program-guide#section-0. updated May 2022.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M., and Vigano, D. OpenQuake Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model. *Seismological Research Letters*, 85(3):692–702, May 2014. doi: 10.1785/0220130087.

Patchett, M. Characterization of end-user needs to optimize the development of the Rapid Earthquake Damage Estimation (RED-E) system in Canada. Master's thesis, University of Victoria, 2024. https://hdl.handle.net/1828/16441.

Poudel, A., Pitilakis, K., Silva, V., and Rao, A. Infrastructure seismic risk assessment: an overview and integration to contemporary open tool towards global usage. *Bulletin of Earthquake Engineering*, 21(9):4237–4262, May 2023. doi: 10.1007/s10518-023-01693-z.

Public Safety Canada. Canadian Disaster Database, 2016. https://cdd.publicsafety.gc.ca/dtprnt-eng.aspx?cultureCode=

en-Ca&eventTypes=%27WF%27&normalizedCostYear=1&dynamic=false&eventId=1135. Retrieved on June 7, 2024.

Saku, J. C. Aboriginal census data in Canada: a research note. *Canadian journal of native studies*, 19(2), 1999.

Schneider, M., McDowell, M., Guttorp, P., Steel, E. A., and Fleischhut, N. Effective uncertainty visualization for aftershock forecast maps. *Natural Hazards and Earth System Sciences*, 22(4), Apr. 2022. doi: 10.5194/nhess-22-1499-2022.

Smylie, J. and Firestone, M. Back to the basics: Identifying and addressing underlying challenges in achieving high quality and relevant health statistics for Indigenous populations in Canada. *Statistical Journal of the IAOS*, 31(1):67–87, 2015. doi: 10.3233/sji-150864.

Stevens, J. Bivariate Choropleth Maps: A How-to Guide, 2015. https://www.joshuastevens.net/cartography/make-a-bivariate-choropleth-map/.

Tierney, K. J. and Goltz, J. D. Emergency response lessons learned from the Kobe. University of Delaware Disaster Research Center, Preliminary Paper, 1997.

Transport Canada. Knowledge requirements for pilots of remotely piloted aircraft systems 250 g up to and including 25 kg, operating within Visual Line-of-Sight (VLOS) - TP 15263, 2019. https://tc.canada.ca/en/aviation/publications/knowledge-requirements-pilots-remotely-piloted-aircraft-systems-250-g-including-25-kg-operating-within-visual-line-sight-vlos-tp-15263.

Transport Canada. Where to fly your drone, 2021. https://tc.canada.ca/en/aviation/drone-safety/learn-rules-you-fly-your-drone/where-fly-your-drone.

Trevethan, S. Strengthening the availabiligy of First Nations data. 2019. https://www.afn.ca/wp-content/uploads/2019/05/NCR-11176060-v1-STRENGTHENING_THE_AVAILABILITY_OF_FIRST_NATIONS_DATA-MAR_25_2019-FINAL_E.pdf.

Turner, L. L., Wald, D., and Lin, K.-W. A ShakeCast User's Observations on the Benefits of Situational Awareness for Seismic Risk Management. In *Improving the Seismic Performance of Existing Buildings and Other Structures*, page 1235–1240. American Society of Civil Engineers, Dec. 2009. doi: 10.1061/41084(364)113.

Twomlow, A., Grainger, S., Cieslik, K., Paul, J. D., and Buytaert, W. A user-centred design framework for disaster risk visualisation. *International Journal of Disaster Risk Reduction*, 77:103067, July 2022. doi: 10.1016/j.ijdrr.2022.103067.

Wald, D., Earle, P., Allen, T., Jaiswal, K., Porter, K., and Hearne, M. Development of the US Geological Survey's PAGER system (Prompt Assessment of Global Earthquakes for Response). In *The 14th World Conference on Earthquake Engineering: October 12-17, 2008, Beijing, China*, pages 1–8, 01 2008.

Wald, D., Jaiswal, K., Marano, K., Bausch, D., and Hearne, M. PAGER–Rapid assessment of an earthquakes impact [Fact Sheet], 2010. doi: 10.3133/fs20103036.

Wald, D. J., Jaiswal, K. S., Marano, K. D., and Bausch, D. Earthquake Impact Scale. *Natural Hazards Review*, 12(3):125–139, Aug. 2011. doi: 10.1061/(asce)nh.1527-6996.0000040.

Wald, D. J., Seligson, H. A., Rozelle, J., Burns, J., Marano, K., Jaiswal, K. S., Hearne, M., and Bausch, D. A domestic earthquake impact alert protocol based on the combined USGS PAGER and FEMA Hazus loss estimation systems. *Earthquake Spectra*, 36(1):164–182, Jan. 2020. doi: 10.1177/8755293019878187.

Wyss, M. Report estimated quake death tolls to save lives. *Nature*, 545(7653):151–153, May 2017. doi: 10.1038/545151a.

Yilmaz, C., Silva, V., and Weatherill, G. Probabilistic framework for regional loss assessment due to earthquake-induced liquefaction including epistemic uncertainty. *Soil Dynamics and Earthquake Engineering*, 141:106493, Feb. 2021. doi: 10.1016/j.soildyn.2020.106493.