IMPACT FROM A NEARBY SEISMICALLY-ACTIVE FAULT TO SEISMIC HAZARD IN VICTORIA, CANADA

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DISCLAIMER - ERRATUM

The description of the Leech River fault (LRF) and the probabilistic seismic hazard analyses (PSHA) presented in this paper were preliminary findings. The LRF has been proven to be seismically inactive in multiple research papers (Morell et al. 2017; 2018, Li et al., 2018) and was erroneously presented as seismically active here. Rather, an area of high-angle transpressional faulting within the Leech River Valley, referred to as the Leech River Valley fault zone (LRVFZ), is the source of seismic activity (Kukovica et al., 2019). The introduced active LRF here should be considered as the LRVFZ. The geometry of the introduced active fault zone does not change.

PSHA in this paper utilized two different sets of ground motion prediction equations (GMPEs) to characterize the seismicity of the LRVFZ with fault source zone GMPEs suggesting the LRVFZ increases the Victoria hazard by a factor of 2.65. This estimation is greatly overpredicted due to an error in the input file for the EQHAZ software. The total number of entry points used to describe the fault source zone GMPEs exceeded the coded limit allowed for EQHAZ. Therefore, the presented results for the fault source zone GMPEs in Table 1 and Figure 3 do not accurately represent the total increase in hazard due to the LRVFZ. Accurate simulations of the LRVFZ with fault source zone GMPEs increase the pseudo-spectral accelerations (PSA) at Victoria on average by 11% at 10 Hz and 9% for PGA (Kukovica et al., 2019). More information regarding the seismic hazard of the LRVFZ can be found in Kukovica et al., (2019) or Kukovica, (2019).

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ABSTRACT
The Leech River fault (LRF) is situated on Vancouver Island near the city of Victoria, British Columbia, Canada. The transpressional reverse fault zone is present at surface for a length of ~60 km east to west along the southern tip of Vancouver Island. Recent paleoseismic evidence suggests at least two surface-rupturing events to have exceeded a moment magnitude (**M**) of 6 within the last 15,000 years. This fault system poses considerable seismic hazard due to its proximity to Victoria and three hydroelectric dams. We performed Probabilistic Seismic Hazard Analyses (PSHA) and Deterministic Seismic Hazard Analyses (DSHA) for Victoria with consideration of an active LRF zone. We first calibrate our PSHA methodology and successfully replicate the 2015 National Building Code of Canada (NBCC) uniform hazard spectrum for a 2% probability of exceedance in 50 years. We add an active LRF zone with magnitude recurrence parameters based on fault- and region-specific seismicity catalogues. Ground motions are calculated for the synthetic fault earthquake catalogue using Ground Motion Prediction Equations (GMPEs) based on western Canada crustal source zones (hypocentral distance metric) and fault source zones (projected fault plane distance metric). We observe up to 0.32 factor increase in the predicted motions at a frequency of 10 Hz utilizing crustal GMPEs and 2.65 factor increase utilizing fault GMPEs at 1 Hz. The DSHAs are accomplished using finite-difference 3D wave propagation simulations of a **M** 6.8 rupture with different hypocentral locations and fault geometry. The low-frequency simulations demonstrate ~20 cm/s peak ground velocity (strong shaking) is expected in Greater Victoria. Previous studies that examined economic losses in Victoria for **M** 6 or 7 Leech River fault scenario earthquakes estimate 2.5 billion to 8.5 billion Canadian dollar losses, respectively.
Keywords: probabilistic seismic hazard analysis, deterministic seismic hazard analysis, fault source zone, fault magnitude recurrence, magnitude recurrence uncertainty, Leech River fault, British Columbia.

1 INTRODUCTION

The Leech River fault (LRF) is an ~60 km transpressional reverse fault that is present at surface along the southern tip of Vancouver Island, British Columbia, Canada from Port Renfrew on the west coast to the provincial capital of Victoria in the east (Fig. 1). The fault continues eastward and offshore in the Juan de Fuca Strait and potentially connects with the Darrington-Devil's Mountain fault [1]. The LRF dips steeply between 60° [2] and 70° [3] northeast and divides Jurassic–Cretaceous schists of the Leech River Complex to the north and Eocene basalts of the Metchosin Formation to the south [4], [5]. The shallow LRF lies within the adjacent crustal system of the Cascadia subduction zone. Similar crustal systems can remain active but with recurrence intervals on the scale of 5–10 thousands of years [6].

Within the last 15,000 years, there has been evidence for Quaternary seismic activity within several strands of the LRF [2]; producing at least two earthquakes to have exceeded a moment magnitude (**M**) of 6 after Cordilleran deglaciation. This is evident from a combination of LiDAR-based scarp mapping, geomorphology, and paleoseismic trenching which determined approximately 4 m of vertical displacement in incised channel sediments and 6 m of vertical displacement of post-glacial sediments [2]. Due to other paleoseismic studies performed on nearby faults like the Darrington-Devil's Mountain fault [1], [7] and the Whidbey Island fault [8], there is greater emphasis on the importance of incorporating newly identified faults in the region in future seismic assessments.

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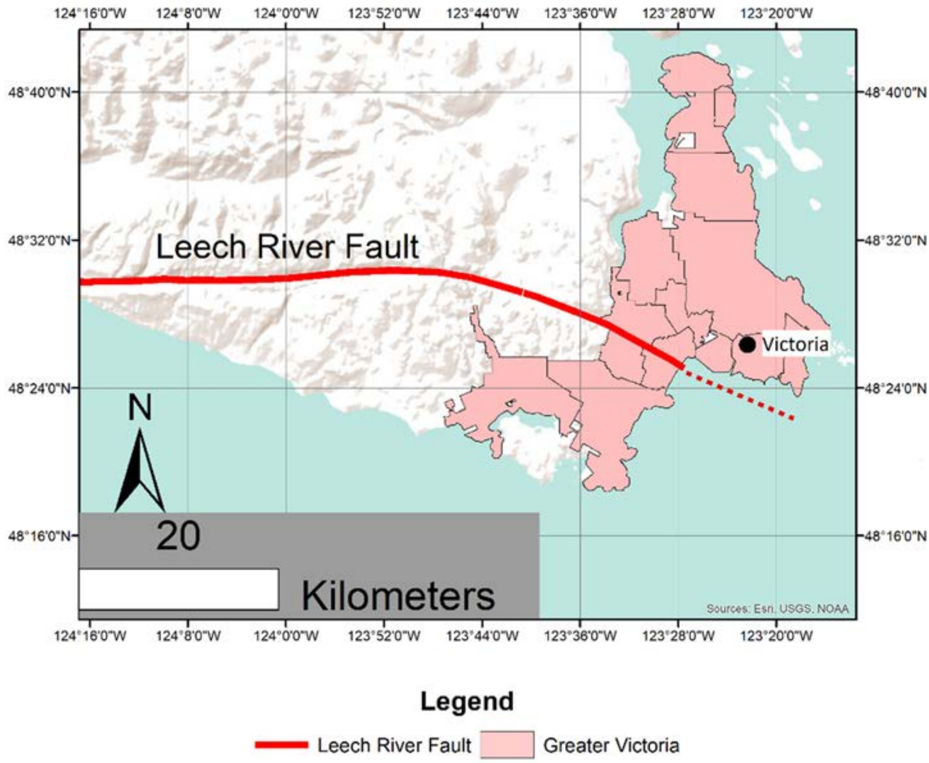

Figure 1: Terrain map of southern Vancouver Island. The Leech River fault surface (solid red line) and its offshore projection (dashed red line) are shown in relation to Greater Victoria (shaded pink area).

Due to the constant threat of earthquakes imposed by the nearby Cascadia subduction zone, which is brought on by the consistent subduction of the Juan de Fuca plate underneath the continental North America plate, the city of Victoria is exposed to the highest seismic hazard in Canada [9]. The potential for the LRF to produce two $\mathbf{M} \geq 6$ in the last 15,000 years [2] further adds to the seismic hazard of the region. There is a need for Probabilistic Seismic Hazard Analyses (PSHA) and Deterministic Seismic Hazard Analyses (DSHA) to consider this newly identified fault and its seismic hazard implications to Victoria and southern Vancouver Island. This study summarizes predicted ground-motions from seismic hazard analyses of an active LRF for the city of Victoria.

2 PROBABILISTIC SEISMIC HAZARD ANALYSES

The purpose of PSHA is to determine the probability of exceedance for a specific ground motion amplitude at a site by integrating over all earthquakes for all source zones and their associated ground motions for a specific temporal period [10]–[12]. The frequency of exceedance (γ) for a specific site is calculated based on a given ground motion amplitude (y) [10]. This is performed at a desired return period through the summation of all activity rates of a specific source zone expressed by the equation:

$$\gamma(y) = \sum_i v_i \iiint f_M(m) f_R(r) f_E(\varepsilon) P[Y > y | m, r, \varepsilon] dm\, dr\, d\varepsilon, \tag{1}$$

where v_i represents the activity rate v of source i, f_M and f_R represent the probability density functions for magnitude and distance, respectively. The term $P[Y > y|m,r,\varepsilon]$ represents the probability of the predicted ground motion (Y) for a given magnitude (m), distance from source (r), and randomness (aleatory variability, ε) to exceed the desired ground motion amplitude (y) [7], [13].

Our PSHAs are performed using EqHaz software [14] developed at the University of Western Ontario, which utilizes Monte Carlo simulation to solve the Cornell-McGuire method expressed in eqn (1). Our PSHA implementation is validated by replicating the 2015 National Building Code of Canada (NBCC) ground motions at different return periods prior to the introduction of the LRF as a seismic source [13]. The national seismic hazard model consists of five seismic source zones within a 500 km radial area of Victoria. These source zones capture seismicity that occurs in the subducting Juan de Fuca plate, the overriding North American plate and the subduction interface related to the Cascadia subduction zone. Our PSHA implementation was calibrated to be within 11% at 0.1 Hz of the 2015 NBCC ground motions [13].

The LRF is then added as a fault source zone defined by known fault geometry [2], [3]. The LRF seismicity rate is poorly determined because none of the recorded seismicity has been conclusively identified as generated by the fault. Hence, there is large variability in magnitude-recurrence values for the LRF fault source zone. In this study, three different seismicity catalogues are used, in addition to adding the two potential **M** ~6 Quaternary events [2], to define three sets of magnitude recurrence pairs. The seismicity rate is determined from: (a) seismicity catalogues of the national network [15]; (b) from an earthquake relocation study [3]; and (c) determined from earthquake events occurring in the upper 10 km of the crust on the southern tip of Vancouver Island [16]. For catalogues (a) and (b), we develop a hybrid model which utilized a characteristic-magnitude model for larger earthquakes, and an exponential-magnitude model for smaller earthquakes [13].

In our PSHA implementation, synthetic earthquake catalogues for a duration of 1 million years are generated according to seismicity rate parameters via the Monte Carlo method for each source zone. Regional Ground Motion Prediction Equations (GMPEs) are used to predict ground motions for each generated synthetic earthquake catalogue. Two sets of GMPEs were used for the LRF source zone catalogue: (1) GMPE for crustal source zones with a point-source hypocentral distance (R_{hypo}) metric; and (2) GMPE for fault source zones with a projected-fault Joyner-Boore distance (R_{JB}) metric. Uncertainty in seismicity rate of the LRF (panels (a), (b) and (c) in Figs 2 or 3) and associated GMPE (Fig. 2 versus Fig. 3) is examined in the six PSHAs.

The contribution of the LRF to the Victoria uniform hazard spectrum (UHS) for a 2475 year return period strongly depends on the GMPE used and less so on the variability in the fault seismicity rate. When the crustal GMPE is used (Fig. 2), the LRF significantly contributes to seismic hazard above ~5 Hz (analysis C). The impact of adding an active LRF zone is negligible at lower frequencies but increases the predicted motions by a maximum factor of 0.3 at higher frequencies (≥ 5 Hz) amongst the three fault seismicity rates (Table 1). When fault GMPEs are used to calculate LRF earthquake ground motions, the LRF becomes the dominate source zone driving Victoria's seismic hazard at all frequencies (Fig. 3). The maximum factor increase in predicted motions is 0.3–2.0 amongst the three seismicity rates for the LRF (Table 1). These significant increases in predicted motions are likely due to the very small distance between source and the Victoria site, within the fault projection of the LRF.

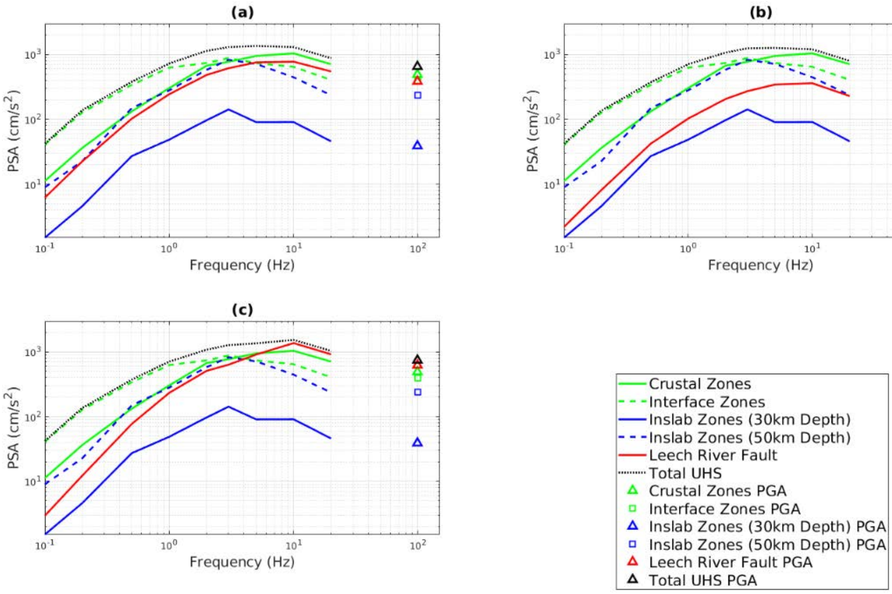

Figure 2: UHS curves for Victoria at a 2475 year return period considering three sets of LRF seismicity rates (panels (a), (b) and (c)) and calculated using crustal GMPEs.

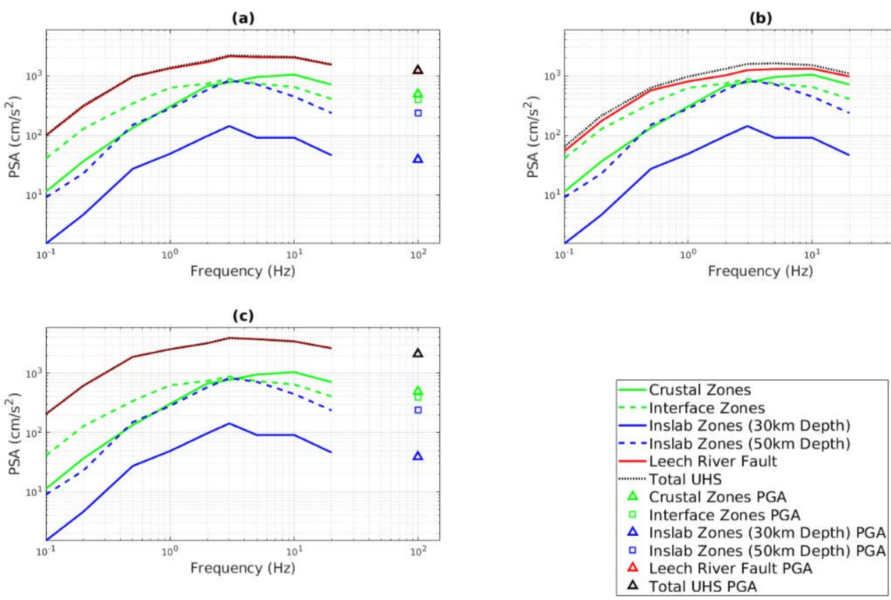

Figure 3: UHS curves for Victoria at a 2475 year return period considering three sets of LRF seismicity rates (panels (a), (b) and (c)) and calculated using fault GMPEs.

Table 1: Maximum factor increase in ground motions at a 2% probability of exceedance in 50 years.

Fault activity rate	Crustal GMPE	Fault GMPE
Analysis A	0.04 at 1 Hz, 0.12 at 10 Hz	0.97 at 1 Hz, 0.80 at 10 Hz
Analysis B	0.02 at 1 Hz, 0.04 at 10 Hz	0.39 at 1 Hz, 0.30 at 10 Hz
Analysis C	0.02 at 1 Hz, 0.32 at 10 Hz	2.65 at 1 Hz, 1.98 at 10 Hz

3 DETERMINISTIC SEISMIC HAZARD ANALYSES

In contrast to PSHA, DSHA defines the maximum ground motion from a single earthquake event [12]. Several parameters of the earthquake rupture model including rupture directions, propagation velocities, hypocentral depth and slip distribution along the fault can be varied for each DHSA. Thus, DSHAs provide the opportunity to examine uncertainty in the fault rupturing process of a large LRF earthquake.

We use a 3D finite-difference anelastic wave propagation simulation software developed by Olsen, Day and Cui known as AWM-ODC [17] which has fourth-order accuracy in space and second-order accuracy in time. It utilizes a cubic mesh that is discretized to five nodes per minimum shear wavelength. This work uses the same base elastic 3D model as previous earthquake scenario simulations in the region [18], [19]. The base elastic 3D model is originally extracted from the Pacific Northwest 3D velocity model [20]. The uniform grid size of the physical model is 250 m, with a minimum V_s of 625 m/s. Hence, the maximum resolvable frequency of our 3D ground motion simulations is 0.5 Hz (2 s period).

Figs 4 and 5 present peak ground velocity (PGV) maps for two different **M** 6.8 LRF simulations. The kinematic rupture model (slip distribution) is a modified version of the 1994 **M** 6.8 Northridge earthquake with an 18 km fault length [19] which is simulated in two different hypocentral locations with varying fault orientation. There is little difference in PGV between the two scenarios, either 22 cm/s (Fig. 4) or 19 cm/s (Fig. 5) corresponding to very strong perceived shaking or a Modified Mercalli Intensity VII [21].

We are currently developing additional earthquake rupture scenarios specific to the Leech River fault. We have selected earthquakes with similar magnitudes, fault dimensions and geodetic/stress rates to the LRF, including the 2011 **M** 6.3 Christchurch, New Zealand earthquake [22] and the 2010 **M** 7.0 Haiti earthquake [23]. Simulating the 2011 **M** 6.3 Christchurch earthquake is of particular interest because of similar building stock in Victoria and Christchurch and potential similarities in resulting damage. A suite of earthquake scenarios are being developed to examine the regional variability in predicted ground motion for Victoria and the Greater Victoria region for future large LRF earthquakes.

4 RISK IMPLICATIONS OF THE LRF HAZARD

Assessing the seismic risk associated for a given region incorporates the potential natural hazard with the exposure and vulnerability of population and infrastructure for the area of study [24]. Our seismic hazard analyses of the LRF capture uncertainties in the fault seismicity rate, associated predicted ground motions, and rupture characteristics. This LRF hazard variability can be incorporated into seismic risk assessments for the Greater Victoria region.

Previous HAZUS risk assessments of **M** 6–7 LRF scenarios have been accomplished [24], [25]. A **M** 7 partial 30 km rupture of the LRF [24] is expected to be very damaging, with a large amount of buildings (64%) reaching extensive levels of damage. Complete damage

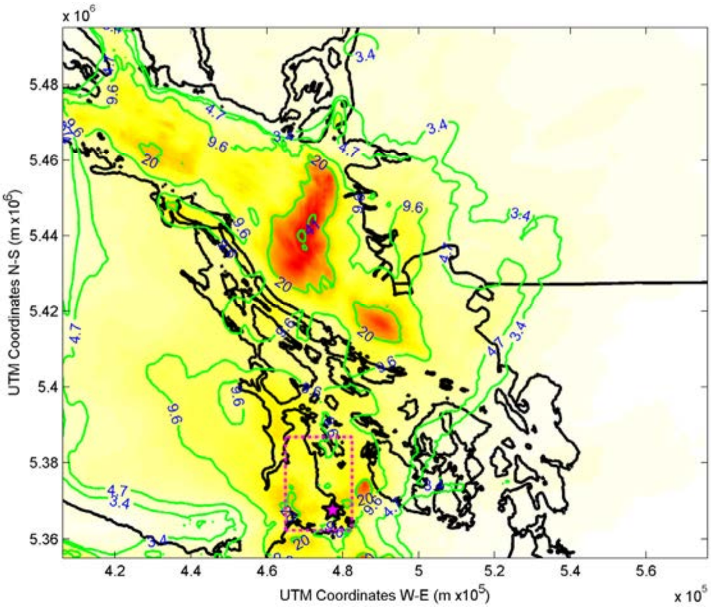

Figure 4: Contoured PGV (cm/s) map for **M** 6.8 LRF rupture. The projected fault plane and hypocenter are shown by the dotted–dashed box and star, respectively. Coastline and international border are shown by black lines.

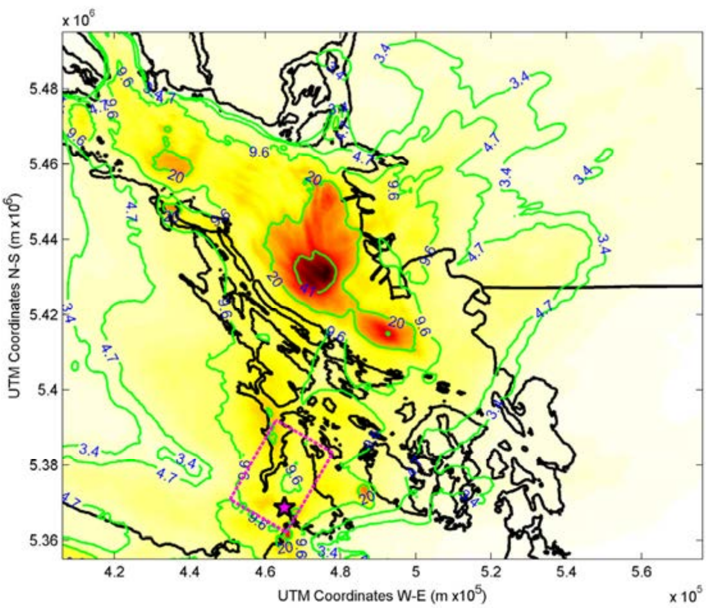

Figure 5: Contoured PGV (cm/s) map of a **M** 6.8 LRF rupture. The projected fault plane and hypocenter are shown by the dotted–dashed box and star, respectively. Coastline and international border are shown by black lines.

(3%) is localized to concrete and masonry buildings of the downtown core, which is analogous to concentrated damage in downtown Christchurch following the 2011 **M** 6.3 earthquake. It is expected that water pipelines would be reduced to 25% of normal serviceability and sewer pipelines would be lost completely. In [25], a 13 km length **M** 6 scenario and a 30 km length **M** 7 scenario result in $1.8 billion and $5.9 billion Canadian dollars, respectively, in direct economic impacts. This Level 1 analysis is limited to direct economic impacts to the residential general building stock, shelter requirements, and debris clean-up for scenarios at 2 am (maximum building occupancy). For a Level 2 analysis, economic impacts increase to $3.5 billion and exceed $11 billion for the **M** 6 and 7 scenarios, respectively. These direct economic impacts include structural and non-structural building damage, business inventory loss, relocation cost, business income loss, rental income loss, and wage loss. In all cases, non-structural building damage is the dominant economic impact.

5 CONCLUSIONS

Our study analyzed hazard contributions of an active LRF for the city of Victoria, British Columbia in probabilistic and deterministic seismic hazard analyses. PSHAs demonstrate an increase in the total seismic hazard for Victoria with the greatest increase related to the location of Victoria within the projection of the fault plane. For a 2% probability of exceedance in 50 years (2475 year return period), spectral accelerations at 10 Hz frequency are increased by an average factor of 0.16 or 1.03 for GMPEs applicable to western Canada crustal areas (using R_{hypo} as the distance metric) or fault source zones (using R_{JB} as the distance metric), respectively. For the same return period, 1 Hz spectral accelerations increased by an average factor of 0.03 for GMPEs applicable to western Canada crustal areas, and 1.34 for GMPEs applicable to fault source zones. Performing DSHAs for two different **M** 6.8 LRF scenarios with varying fault orientation and hypocentral location demonstrated consistent strong shaking for the Greater Victoria area.

We demonstrate that the seismic hazard in Greater Victoria can change significantly if the LRF is considered to be a seismically active fault. This paper examined variability in predicted earthquake ground motions due to current uncertainties associated with the LRF including the fault seismicity rate, appropriate ground motion prediction equations and associated distance metrics, and rupture characteristics of individual large earthquakes. Previous HAZUS risk assessments of **M** 7 LRF scenarios [25] demonstrate this event will be very damaging with $5.9 billion dollars in damage to the residential building stock but could exceed $11 billion dollars considering other direct economic impacts such as business income and wage losses. The seismic hazard in Greater Victoria is highly variable depending on whether the Leech River fault is seismically active. Risk assessments will need to capture this hazard variability to provide robust risk or loss estimates in future.

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