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Annualized Residential Earthquake Losses in the Greater Montreal Area

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ABSTRACT

Previous studies have highlighted the potential losses from a major earthquake in the Montreal Metropolitan Community (CMM). For example, losses for residential buildings were estimated at 2 to 5% of total property values when using national probabilistic hazard values or a repetition of the M5.8 September 16, 1732 earthquake nowadays at the centre of the island of Montreal. Annualized earthquake losses (AEL), which are defined as the expected annual losses, are used as a comparative regional risk indicator between various sources of natural hazards. AEL calculations were performed by software Hazus from FEMA using the 2015 national seismic hazard estimates for eight return periods from 100 to 2,500 years and a seismic microzonation map of the CMM. Economic exposure of residential building stock is based on 2018 evaluation rolls aggregated at the scale of the census dissemination areas. The AEL is estimated at 6.2 million Can$ per year and varies between 30 million and 2,000 Can$ for different dissemination areas. The AEL per dissemination area is a function of the number of buildings, their value, year of construction and site conditions, while the AEL ratio is mainly a function of the seismic hazard levels. This AEL corresponds to 31.5 Can$ per million Can$ of the building stock or two Can$ per inhabitant. This analysis will be extended to other municipalities at risk in Quebec in future studies with the latest national seismic hazard estimates.

Keywords: Annualized loss, Greater Montreal, residential buildings, Hazus, seismic risk

INTRODUCTION

Seismic hazard studies by Earthquakes Canada (Natural Resources Canada) indicate that the Montreal region has a moderate seismicity. Although located on the stable part of the North American tectonic plate, earthquakes occur within distinct bands that are the St. Lawrence Valley (including the Charlevoix area), the lower St. Lawrence and Eastern Ontario. The larger reported damaging earthquake dates of 1732 with 300 out of 400 buildings, which were mostly wood structures with walls made of timber planks, which suffered some damage to chimneys and cracked walls [1]. At this time the city counted a population of 3 000 for over 4 million nowadays in the Communauté Métropolitaine de Montréal (CMM). Later, the city hall of Montreal-East suffered damage to the masonry cladding after the 1988 M5.9 Saguenay earthquake, 300 km faraway [2]. Chouinard and Rosset [3] calculated that the site response, close to the resonance frequency of the building, could contribute to the damage to the deteriorated structure. Rosset et al. [4, 5] have developed an extensive zonation of Greater Montreal in terms of V_{s30}, the average shear-wave velocity of the top 30 m of soil, in the last decades to take into account the site response on the seismic hazard calculations. Rosset et al. ([6, 7]) analyzed the citizen-felt reports in Greater Montreal after 23 weak earthquakes (M ranging from 3.1 to 5.9) and noticed a relatively good correlation between zones with low V_{s30} values (softer soil) and highest reported intensities independently of the earthquake distance.

Yu et al. [8] have first studied damages to residential buildings in Montreal combining several ground motion prediction equations for a set of earthquake scenarios. This analysis was further complemented by consequence estimates (economical and human losses, debris, shelter needs) using both deterministic and probabilistic approaches of the seismic hazard (e.g. [5, 9]). Depending on the seismic scenario considered the results for the CMM showed that damage and the cost of damage differ between the island of Montreal and the outside municipalities mainly due to the difference in building typology between the historic centre of the CMM and its more recent periphery. This damage (from light to complete) could affect 21 to 42% of the residential buildings, 1 to 16.5% of the buildings being heavily damaged. The total cost of structural and non-structural damage could represent 1.5 to 7.1% of the total value of the residential building stock (approximately Can$196.5 billion) and that approximately 80% of this cost would be related to non-structural damage. The amount of debris generated could vary from 0.4 to 8 million tons, 60% of which was wood and brick [9]. The number of injuries is small and often insignificant. However, depending on the scenario considered, the number of people requiring hospital care could vary from several hundred to several thousand. The number of people requiring temporary accommodation could vary from 4,000 to 50,000.

The repeat of the 1732 earthquake nowadays could lead to 12% of the building stock suffering extensive and complete damage, this value decreasing to 1.2% for the municipalities outside Montreal. The total monetary loss would amount to 12% of the value of the portfolio in Montreal and around 0.04% outside Montreal, non-structural damage accounting for 80% of total damage on average. Debris generated from damage is estimated at 7 million tons, wood and brick materials representing more than 65% of the total [5].

Following these deterministic analyses of the risk to residential buildings, an approach taking into account the probability of exceedance of different levels of ground motion from all possible earthquake events has been tested. It is based on (1) Annualized Earthquake Loss (AEL), which is the estimated long-term value of earthquake losses for the building stock in a given year, and (2) Annualized Earthquake Loss Ratio (AELR), which expresses the estimated AEL as a fraction of the replacement value of the building stock. For that, we use the tool Hazus, developed by US Federal Emergency Management Agency (FEMA), widely used in the USA for fine-grained risk analysis of various natural hazards [10] and the FEMA approach for annualized loss estimates [11]. The latter consists in multiplying the economic losses by the corresponding annual probability of occurrence and summing the result of this calculation for several return periods. Such an analysis requires data on the seismic hazard (peak and spectral accelerations) for different return periods (or probability of occurrence), on the nature of the soils (loose soils that can modify ground motions), on the buildings (number and geographical distribution) and their characteristics (building materials, structural systems, etc.). The inventory of residential buildings is the one used in our previous studies with 2018 data following the Hazus taxonomy and associated fragility models from the Capacity Spectrum Method to estimate the building damage [10].

METHOD

The approach to calculate the AEL

The average annual loss considers two components of earthquake risk: (1) the probability of occurrence of an earthquake for a given region (i.e. the level of ground motion) and (2) the consequences of these ground motions in terms of physical damage and economic losses. It takes into account the damage caused by all return periods and allows to integrate the relative weight of each earthquake damage according to the return period. AEL calculation consists of multiplying the economic losses by the corresponding annual probability of occurrence and summing the result of this calculation for several return periods following the FEMA approach [11] and formula:

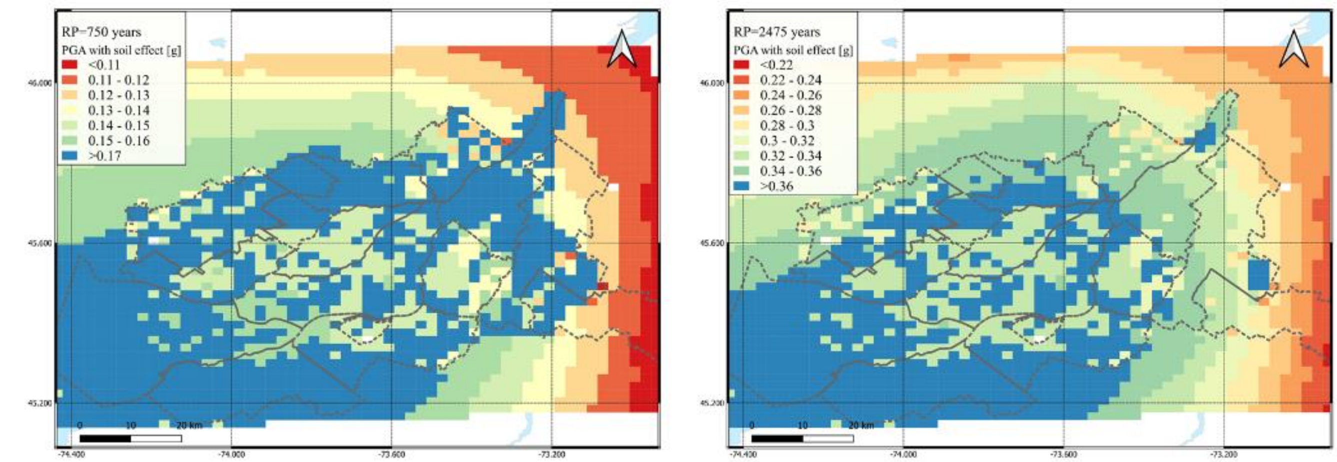
$$\mathbf{AEL} = \boldsymbol{P_{2500}} \times \boldsymbol{L_{2500}} + \sum_{\boldsymbol{i}} (\boldsymbol{P_i} - \boldsymbol{P_{i+1}}) \times \frac{\boldsymbol{L_i} + \boldsymbol{L_{i+1}}}{\mathbf{2}} \tag{1}$$

Where P_i is the annual probability for a return period i RP_i (P_i=1/RP_i) and L_i the calculated loss for the return period i. The return periods i are 100, 250, 500, 750, 1,000, 1,500 and 2,000 and 2,500 years.

Concretely, it corresponds to the area below the loss curve expressed as a function of the earthquake return periods. The FEMA approach consider two hypotheses; 1) that economic losses associated with ground motions with return periods greater than 2,500 years are no larger than those for 2,500 years and 2) that economic losses associated with events with return periods less than 100 years are small enough to be neglected.

Seismic hazard and exposure model

For this study, the calculated peak ground acceleration (PGA) and spectral acceleration Sa(T) for the period T of 0.3 and 1.0s come from the fifth generation of the Seismic Hazard Model of Canada (SHM5). Halchuk et al. [12] describe in detail the model. Seismic hazard values are first extracted for site class C sites (V_{s30}=450m/s) for the different return periods in a grid format including the CMM region using the Canadian gridded data [13]. The resolution of the grid (10 by 10 km) is not enough to define precisely the hazard in the smallest dissemination areas within the CMM and necessitated an interpolation at a higher resolution. For that, we first tested interpolation method over an available sampling grid with higher resolution (5 by 5 km) and performed a cubic spline interpolation (polynomial interpolation of degree three) to obtain 2 by 2km grid of hazard points. The hazard grids are then corrected from the site conditions using the V_{s30} map developed by Rosset et al. [5]. The soil effect is added to the probabilistic hazard map using a foundation factor F(T) based on the corresponding soil conditions. The applied correcting factors F(T) are based on the updated NBCC 2015 [14] and adjusted on the PGA and the spectral periods T (e.g. F(T=0.2s)) using site class and PGA_{ref} (0.8×PGA when the ratio Sa (0.2)/PGA < 2.0 and PGA otherwise). The PGA values calculated for a return period of 750 years (Figure 1a) and 2475 years (Figure 1b) provide a direct illustration the site conditions greatly affect seismic hazard distribution. Indeed, most of the regions are in site classes B (760<V_{s30}<1500m/s) and C (360<V_{s30}<760m/s), the amplification is equal or less than 1.0 decreasing the original PGA. In the northern and eastern part of CMM, some regions have site classes D and E (V_{s30} lower than 360 m/s), which will have a large amplification factor. This indicates that the softer soil amplifies more ground motion. Similar trends are observed for Sa(0.3s) and Sa(1.0s)



(a) *(b)*

Figure 1. Distribution of PGA (in g) with the CMM following the SHM5 and including the site condition for the return periods of (a) 750 years (b) 2475 years. From original hazard data in Halchuck et al. [13] and V_{s30} data in Rosset et al. [7].

Our dataset of residential buildings in the CMM includes more than 870 000 lines with the geographical location, the built year, the number of dwellings, the number and surface of the floors, the tax value and other useful information (Registre Foncier du Québec, 2018). A first building inventory carried out on the island of Montreal, district by district, helped to differentiate the development of the real estate stock in the suburbs and in the centre of the island. Unreinforced masonry (URM) includes all buildings with more than five dwelling units built before 1945 and all buildings built before 1875. Light wood frame (W1) includes all buildings with fewer than five dwelling units built after 1875. Concrete moment frames (C1) include buildings with more than five dwellings built between 1945 and 1995. Finally, shear concrete frames (C2) include buildings with more than five dwellings built after 1995. The number of stories distinguishes between Low (1 and 2 stories), Middle (3 to 7 stories), and High-rise (more than seven stories) construction. These rules helped to define the type of construction, which were tested in a sample of areas. In parallel, the number of dwellings serves as an indicator of the occupancy types. Property data with the same geographical location are aggregated into a single multiplex. The table 1 shows the percentages of buildings by construction and the occupancy types according to the Hazus taxonomy. One note that 81% of the wood constructions (W1) are single-family homes (RES1) and that the concrete constructions (C1 and C2) are mostly multiplexes (RES3C to F). Unreinforced masonry constructions of 1 or 2 floors (URML) are for 20% single-family houses and for 85% multiplexes of 3 floors and more (URMM). Duplex and triplex are either wood-frame or masonry construction.

Table 1. Percentage of buildings by construction and occupancy types.

Occupancy types	**Construction types following the Hazus taxonomy**												
	W1	**URMM**	**URML**	**S1L**	**MH**	**C3L**	**C3H**	**C2M**	**C2L**	**C2H**	**C1M**	**C1L**	**C1H**
RES1	80.5	-	19.8	-	-	-	-	-	-	-	-	-	-
RES2	-	-	-	-	100	-	-	-	-	-	-	-	-
RES3A	10.7	-	34.6	-	-	-	-	-	-	-	-	-	-
RES3B	4.9	-	26.2	-	-	-	-	-	-	-	-	-	-
RES3C	2.9	5.4	17.7	99.6	-	-	-	11.8	65.4	-	3.5	72.6	-
RES3D	0.8	9.9	1.4	-	-	54.5	-	13.7	21.9	3.4	27.0	18.4	16.4
RES3E	0.2	84.4	0.3	0.4	-	45.5	100	64.1	9.0	93.1	59.8	7.5	78.9
RES3F	-	0.3	-	-	-	-	-	10.5	3.8	3.4	9.8	1.4	4.7
Number of buildings	796 179	226	51 762	3 652	5 794	8	2	169	4 338	136	955	9 241	254
% of the total	91.2	<0.1	5.9	0.4	0.7	<0.1	<0.1	<0.1	0.5	<0.1	0.1	1.1	<0.1

For the Montreal region, three levels of seismic design code are applied to residential buildings based on the built year; 1970 is the year to differentiate building's code level because the capacity-based design and structural ductility considerations have been introduced for building seismic design at this date. Thus, structures built before 1970 are defined as pre-code. In 1990, new seismic requirements in several design standards are introduced. The buildings built between 1970 and 1990 are defined as low code. The highest level of seismic design considered for residential buildings constructed after 1990 is defined as moderate code. W1 houses are distributed equally in three thirds among the three code levels while steel (S) and unreinforced masonry buildings are in pre-code. Concrete frame buildings consist of 18%, 44% and 38% in pre-, low- and moderate code, respectively. For mobile houses (MH), the distribution is estimated around 11%, 69% and 20%.

The property assessment roll provides the property value assigned to the buildings included in the assessment unit. The total building value of the residential built-up area is estimated to be around Can$196.5 billion. The ICLR (Institute for Catastrophic Loss Reduction) provided us with the ratio of the content value of residential buildings to their property value for the years 2016 to 2019, by Forward sortation areas (CatIQ database). The average ratio in the CMM for 2018 (the year of the property roll data) is 54±7%. The value of the building content is estimated at Can$99 billion for a total building value of Can$196.5 billion, which gives a total residential portfolio of Can$295.5 billion. Single-family houses represent more than 65% of this total, with duplexes and triplexes accounting for 13.7 and 8.4%, respectively. The mean value for the 6,116 DAs is about Can$48 million with a standard deviation of the same order of magnitude. The first quartile is 29 million and the third quartile is 51 million.

Hazus uses the Capacity Spectrum Method to calculate the fragility curves used to estimate the building damage [10]. The intersection of the building capacity curve for a given building type and its respective demand spectrum define the peak building response in terms of spectral displacement or spectral acceleration. The building capacity curve, also known as a push-over curve, is the lateral displacement response of a given building type to increasing lateral load. Design capacity, yield capacity, and ultimate capacity are the three controlling points that describe each curve. The demand spectrum is the damped earthquake spectrum, which will be reduced for effective damping greater than 5%. The fragility curves are analytically defined by the median value of peak ground displacement (PGD) and the variability associated with that damage state. For each given damage state, the fragility curves are defined as a continuous lognormal distribution function with a median value and a logarithmic standard deviation. The values used to generate the fragility function for each building type and level of damage are the ones provided in Hazus [10].

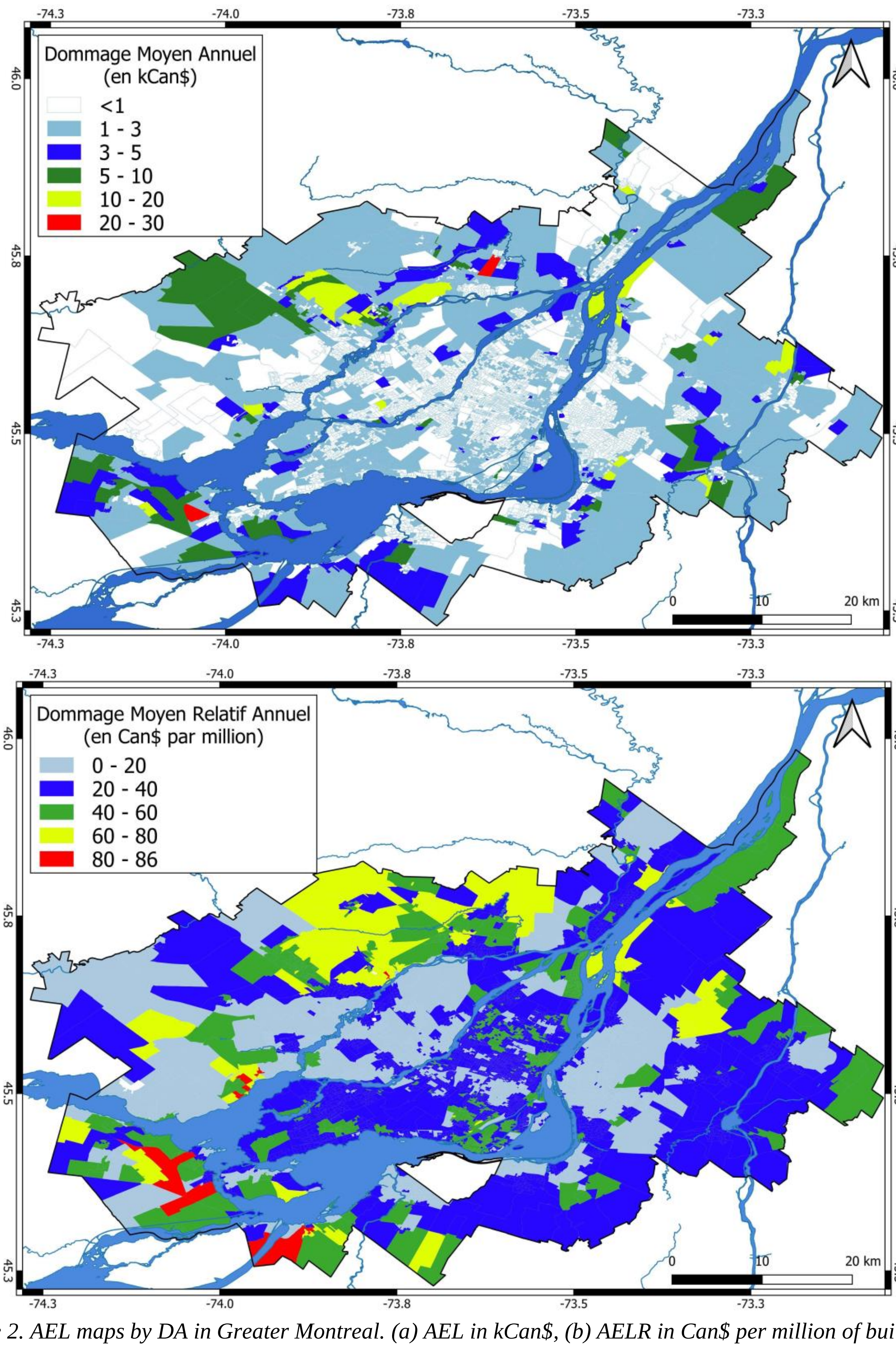
RESULTS

Estimated AEL and AELR

The estimate of the annualized earthquake loss is calculated from the annual loss values for the different return periods considered. Table 2 provides with the annual and annualized values at each return period. 53% of the AEL is due to the return periods higher than 1,500 years with the largest percentage for the 2,500 years RP (37%), all other values being between 5-13%. AEL in Greater Montreal is about 6.18 million Can$ and 93% of the DA have a value lower than 2,000 Can$ and 16 DA have values higher than 10,000 Can$ as shown in the map in Figure 2a. The AEL ratio compares the AEL value with the value of the built environment. It is estimated around Can$31.45 per million of building value. The map in Figure 2b shows this distribution of AELR by DA and indicates that most of the values are in the range of 20-40 Can$ per million with three DAs with values higher than 80 Can$. In addition the AEL per inhabitant is 1.6 Can$ and per building 7.1 Can$. These parameters that correlate building density and population density with annualized earthquake loss are useful from a socio-economic perspective.

Table 2. Annual and annualized loss by return periods.

Return period (years)	Loss (in million Can$)		% of the Total AEL
	Annual	Annualized	
2500	5,720.91	2.288	37
2000	4,471.57	0.509	8
1500	2,989.01	0.634	10
1000	1,795.67	0.789	13
750	1,084.10	0.475	8
500	555.52	0.549	9
250	90.12	0.646	10
100	6.23	0.289	5



(a)

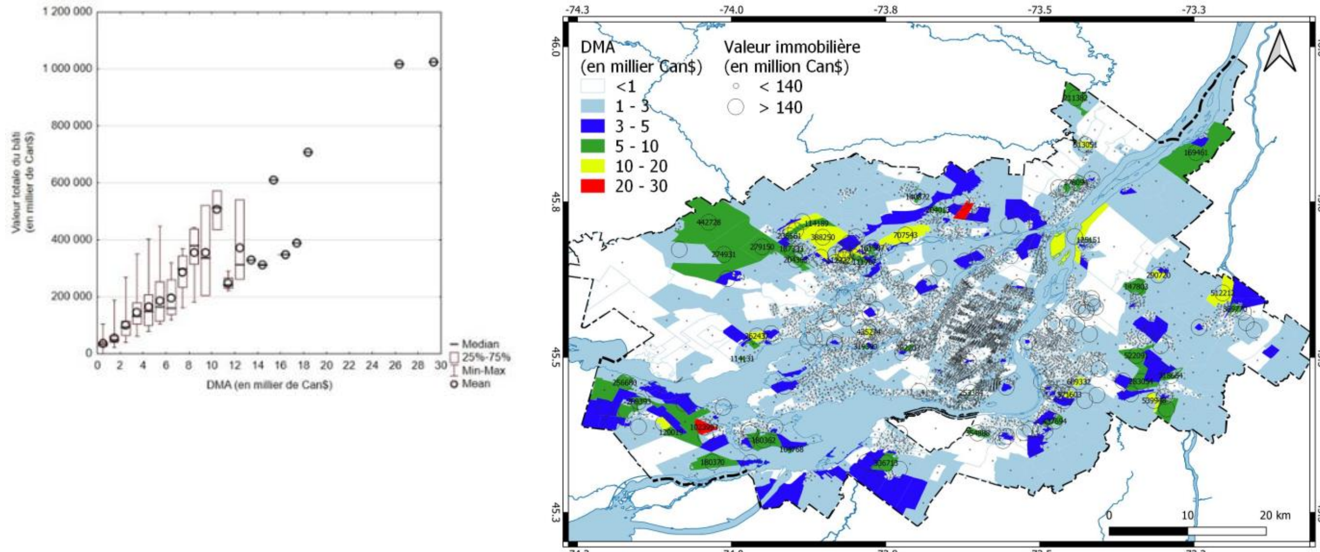
(b)

Figure 2. AEL maps by DA in Greater Montreal. (a) AEL in kCan$, (b) AELR in Can$ per million of building value.

Correlated parameters to AEL and AELR

The graph in Figure 3a shows the relationship between the values of AEL grouped by steps of 1,000 Can$ and the total value of the building (structure and contents). A positive relationship between the AEL and the total value of the building is observed.

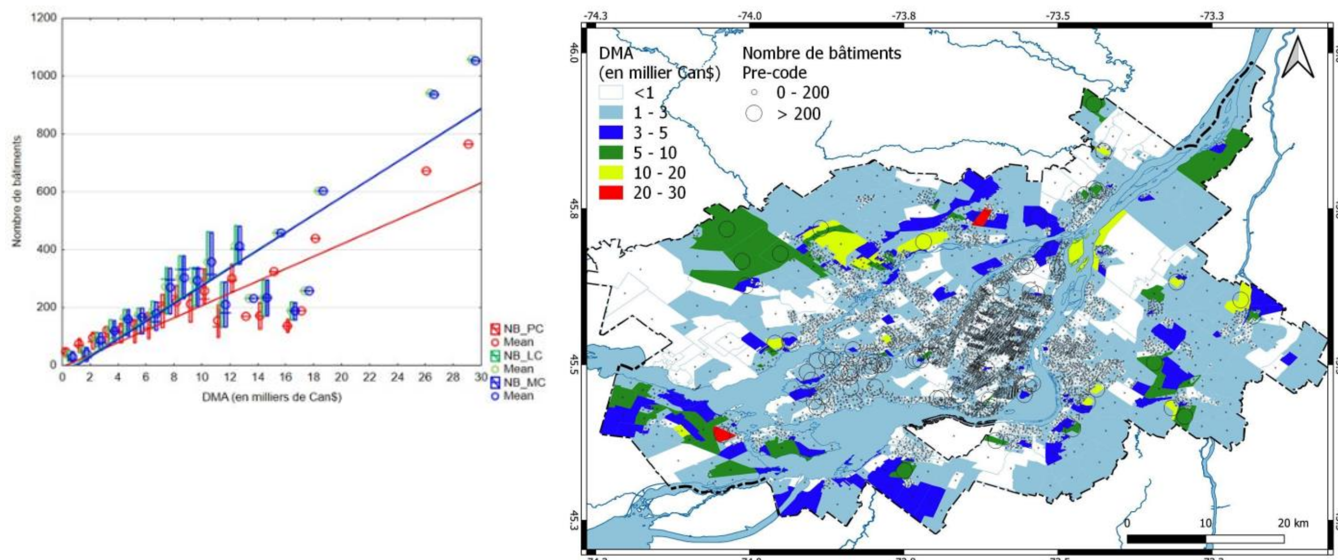
This is intuitive; the higher the value, the higher the replacement or repair cost for a given level of seismic stress, beyond the resistance of the building. The map in Figure 3b locates the DAs where the buildings values are higher than 140 million Can$ with large circles (value corresponding to the last 1% of the DAs). They correlate well with the DAs having AEL values higher than 5,000 Can$ at few exceptions.



(a) *(b)*

Figure 3. Correlation between AEL and total value of buildings in DAs. (a) AEL grouped by steps of 1000 Can$ and total value of the buildings is in kCan$ (b) AEL map and total value of buildings lower and higher than 140 million Can$.

The graph in Figure 4a shows the relationship between the values of AEL grouped by steps of 1,000 Can$ and the number of buildings by code levels of the building. There is a positive relationship between the AEL and the number of buildings. Nevertheless the correlation is stronger, with a lower slope of the linear correlation, for pre-code buildings (red color in Figure 4a) than for low- and moderate code buildings (green and blue colors in Figure 4a). Again, this trend is expected since the seismic resistance of the building is generally lower for old buildings than new ones. The map in Figure 4b locates the DAs where the number of pre-code buildings is higher than 200 with large circles. These correlate well with the DAs having AEL values higher than 5,000 Can$ at few exceptions.



(a) *(b)*

Figure 4. Correlation between AEL and number of buildings by design code level in DAs. (a) AEL grouped by steps of 1000 Can$ and number of buildings grouped by code levels (NB-PC for pre-code; NB-LC for low-code and NB-MC for moderate – code (b) AEL map and number of pre-code building buildings lower or higher than 200.

DISCUSSIONS

This paper investigates the calculation of annualized earthquake loss in the CMM following the FEMA approach and using the Hazus tool. It considers a comprehensive dataset of residential buildings aggregated at the scale of DAs and high resolution V_{s30} mapping to take into account the site condition. The seismic hazard refers to the 2015 model provided by the GSC modified to enhance the grid resolution at 2km. The AEL is estimated around 6.2 million Can$ which corresponds to a value of Can$31.45 per million of building value. At the DAs scale, this estimate is strongly correlated with the number of buildings, the age of the buildings (i.e. the number of buildings with the lowest code level) and the value of the buildings. The AELR is strongly correlated with the level of ground shaking.

FEMA has conducted three AEL studies in USA (1996, 2008 and 2016) that could be used as benchmark for our own analysis. Nevertheless, the comparison is difficult due to differences in building replacement values in counties, grouping several census tracts, with similar hazard values. Counties that have AELR values close to those calculated for the CMM (5.5 million equivalent US$) are Maine (5.7 million), Maryland (5.8 million), Michigan (5.8 million), or Wyoming (4.8 million) according to 2014 data [15]. The AELR value of New York (25.4) or New Jersey (24) and the New York-Northern New Jersey-Long Island metropolitan area (29) is close to the one in CMM (equivalent $25 per million). The AEL per capita value for the CMM is $1.3, which is lower than that calculated for counties in upstate New York ($5-$10) or Wyoming counties ($1-$5) with a similar hazard level.

Annual loss for the return period of 2,475 years contributes the most (37%) in the total AEL (Table 1). The changes in hazard between the 2015 and the new 2020 SHM is relatively important for eastern Canada [16] and increase the loss of 53% for this return period. The AEL estimation should be repeated using the SHM6 accordingly. This analysis will be extended to other populated regions of the St-Lawrence valley with high seismic hazards to provide a comprehensive assessment of residential seismic hazards in Quebec, including the estimates for social and other costs due to earthquakes.

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