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Preliminary seismic hazard analysis from wastewater disposal-induced seismicity near the Musreau Lake, Alberta

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Summary

We conduct a preliminary seismic hazard analysis on a cluster of earthquakes associated with wastewater disposal activities east of Musreau Lake, Alberta. For this analysis, we developed a Probabilistic Seismic Hazard model based on Monte-Carlo simulations that account for the non-stationary behaviour of induced seismicity. Under the assumption of a Poisson process, our simulations suggest a 20% probability of an earthquake reaching or exceeding a magnitude of M>4.0 in 1 year if current trends persist. We also find a low probability of 1% for the Peak Ground Acceleration to reach 380 cm/s^2 in a 1-year window. Despite the observed drop-off in event magnitudes by the end of 2020, the seismic hazard potential in the Musrearu Lake region remains non-negligible. It warrants a future study that, for example, could incorporate physics-based models for improved seismic rate forecasting and seismic hazard analysis.

1. Introduction: Musreau Lake seismic cluster

Most of the reported induced seismicity cases in the Western Canada Sedimentary (WCSB) basin have been associated with hydraulic fracturing activities performed to shale oil and gas reservoirs (Atkinson et al., 2016). Contrastly, only a single swarm (Cordell field, Alberta, Schultz et al. 2014) has been directly linked to wastewater disposal, the primary source of induced events and seismic hazards in the United States (e.g., Oklahoma induced seismicity, Ellsworth, 2013). Despite the limited cases overall in Canada, the minuscule fraction of Canadian earthquakes associated with wastewater disposal relative to those attributable to hydraulic-fracturing remains enigmatic and warrants an overall assessment of regional seismic risks.

A new cluster of earthquakes has been detected east of Musreau Lake since January 2018 (Figure 1 (A)). Until January 2021, up to 106 events with M_L>1.3 have been recorded in the area, highlighted by the largest reported event (M_L 3.94) in December 2019. Spatial-temporal analysis has linked these earthquakes to four nearby wastewater disposal wells injecting into the Winterburn Group (Li et al. 2021, this volume). This disposal water is associated with hydrocarbon production in the Montney Formation. Figure 1 (B) shows the total volume injected per month from disposal wells in the study area (orange line) and the monthly number of earthquakes (green bars). Figure 1 (C) shows the correlation between injection volumes and the total number of earthquakes. Finally, to analyze the hazard associated with this event, we conduct a Probabilistic Seismic Hazard Analysis (PSHA) based on the Monte Carlo simulation method while accounting for the non-stationary behaviour of the induced seismicity.

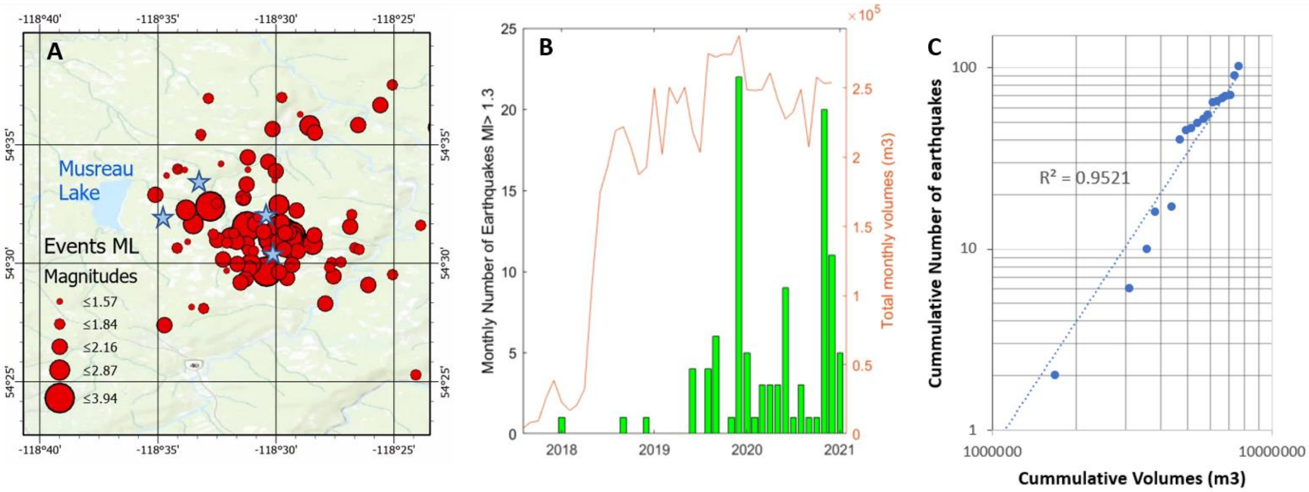

Figure 1. (A) Map view of the events east of Musreau Lake. The blue stars represent the location of the disposal wells. (B) Total volume injected per month from disposal wells in the study area (orange line) and the monthly number of earthquakes M_L>1.3 (green bars). (C) log-log plot of the cumulative number of events as a function of the cumulative injection volume.

2. Theory and methods: non-stationary PSHA

2.1 Probabilistic seismic hazard analysis

PSHA has been largely used for assessing hazard related to natural seismic events. The main output of PSHA is the quantification of possible intense ground shaking at a site in a period of time, represented by a seismic hazard curve that reflects the annual rate of exceedance vs. ground motion intensity. The PSHA methodology can be described in 5 main steps (Baker, 2008):

1. **Define earthquake source areas:** faults and areas that contain the seismic events.
2. **Define the seismic source parameters:** The Gutenberg-Richter (GR) recurrence law states the relationship between the magnitude and the total number of earthquakes in a region, following the relation: $\log(N) = a - bM$, where the b-value indicates the ratio of small and large magnitude events and the a-value is related to the number N_0 of earthquakes with non-negative magnitude, given by: $N_0 = 10^a$.
3. **Identify earthquake distances**: calculation of distances between the site of interest and every single discretized part of the seismic source area. These distances are necessary for the prediction of ground motions based on known/assumed distance, magnitude, and site conditions.
4. **Application of Ground Motion Prediction Equations (GMPEs):** The ground motion prediction equations (GMPEs) predict a probability distribution of ground motion intensity as a function of several variables such as magnitude, distance, site characterization. Each magnitude-distance pair is related to a predicted ground motion intensity. The GMPEs are generally developed using statistical regression on thousand of observed ground motion intensities from several earthquakes (Baker, 2008).
5. **Combine all information to obtain the rate of exceedance plots/ hazard maps:** the total probability theorem is used, and all information is combined to obtain the final hazard curve at a site.

The expressions resulted from the PSHA methodology can be solved analytically. However, the Monte Carlo simulation method for PSHA can easily obtain numerical results and deal efficiently with non-stationary seismicity (Reyes Canales and van der Baan 2019). This method consists of two main steps: (1) generation of synthetic earthquake catalogs and (2) use of GMPEs to generate ground motion catalogs. The main statistical results from PSHA can be obtained from these synthetic catalogs.

2.2. Non-stationary seismicity and time-dependent Gutenberg-Richter parameters

Reyes Canales and van der Baan (2019) derived analytical expressions required in PSHA for non-stationary seismic sources, as well as modifications in the Monte Carlo simulation method to generate non-stationary synthetic earthquake catalogs. To account for non-stationarity, we define time-dependent GR parameters ($a(t)$- and $b(t)$-values). Some of the derived non-stationary expressions include the total expected number of earthquakes $\mathrm{N}(\mathrm{M_{min}} \leq \mathrm{m} \leq \mathrm{M_{max}}; \mathrm{t})$ per time unit in the range $\mathrm{M} = [\mathrm{M_{min}}, \mathrm{M_{max}}]$, which is given by:

$$\mathrm{N}(\mathrm{M_{min}} \leq \mathrm{m} \leq \mathrm{M_{max}}; \mathrm{t}) = 10^{\mathrm{a(t)-b(t)M_{min}}} - 10^{\mathrm{a(t)-b(t)M_{max}}}, \quad (1)$$

Where the $b(t)$-value and $a(t)$-values are the time-dependent GR parameters. $\mathrm{M_{min}}$ and $\mathrm{M_{max}}$ are the minimum and maximum magnitude, respectively. Also, by assuming non-stationary Poisson distribution, the number n of events in a certain time interval is given by:

$$P[N = n; t_a, t_b] = \frac{{m_\lambda}^n(t_a,t_b)(t_b - t_a)^n e^{-m_\lambda(t_a,t_b)(t_b - t_a)}}{n!}, \quad (2)$$

where $m_\lambda(t_a; t_b)$ is the mean of the time-varying rate of occurrence $\lambda\,(t)$ in the interval $t = [t_a, t_b]$.

3. PSHA implementation and results

We implement the PSHA methodology to this induced seismic cluster. First, we calculate the GR parameters using the Alberta Geological Survey earthquake catalog (AGS, 2021), which contains events from January 2018 – January 2021. We performed Maximum Likelihood Methods (MLM, Aki, 1965; Wiemer and Wyss 1997) to estimate the GR parameters (See figure 2 (A)). To estimate the Magnitude of completeness of the catalog (Mc), we performed Maximum Curvature Methods (Wiemer and Wyss 1997). For the error estimation, we use the methodology described by Shi and Bold (1982). Figures 2 (B) and (C) show the temporal evolution of the $a(t)$- and $b(t)$-values, using a screening time window of 1-year length. MLM is also performed in the estimation of GR parameters using the screening time window. Note that the $b(t)$-values in early 2020 are relatively low, close to 0.8, implying higher seismic hazard. In contrast, by the end of the same year, the $b(t)$-values have increased to 1.2, leading to a decrease of the seismic hazard. This feature agrees with the apparent reduction of events larger than M>3 by the end of 2020.
Once the GR parameters have been estimated, we follow the methodology described by Reyes Canales and van der Baan (2019) to generate synthetic earthquake catalogs and develop a seismic hazard analysis for non-stationary sources. We define a seismic source area that covers all events east of Musreau Lake. For simplicity, we do not include sources of natural or induced seismicity outside of the study region. We simulate 10,000 realizations of 1 year each to generate the synthetic

earthquake catalog. The locations of the earthquakes are randomly distributed in the seismic source area. From these realizations, we can obtain useful statistics like the probability $P[N=n;t_a,t_b]$ of n occurrences larger than magnitude M>4 in 1 year (Figure 3 (A)). These probabilities can be calculated analytically as well (See eq. 2). There is a 20% of probabilities to reach an earthquake M>4 in 1 year period from these results. However, this probability increases to 38% when greater hazard scenarios are considered.
To generate the ground motion catalogs, we use the GMPEs described by Atkinson (2015), designed for small-to-moderate events at short hypocentral distances. Once the ground motion catalogs are calculated, we generate a seismic hazard curve for a central location in the seismic source defined for the Musreau Lake seismicity (Figure 3 (B)). Using a 1% in 1-year level, which is equivalent to a rate of exceedance of 0.01, we obtain Peak Ground Accelerations (PGA) of 380 cm/s^2 from this seismic curve. As a reference, PGA values between 220 and 400 cm/s^2 range from moderate to moderate/heavy local potential damage (Worden et al., 2012).

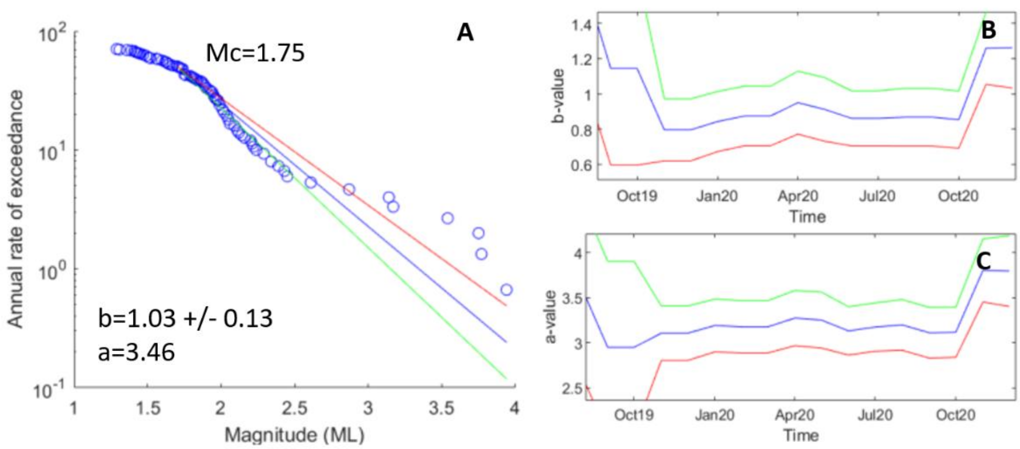

Figure 2. (A) Magnitude-frequency distribution for the Musreau Lake earthquake cluster. (B) and (C) show the temporal evolution of the GR parameters using a screening time window of 1 year in the catalog. The blue line shows the GR estimated parameters using MLM. The upper (red) and lower (green) curves show the repective uncertainties of the GR parameters.

4. Conclusions

The cluster east of Musreau Lake is the second case of wastewater disposal-induced seismicity recorded in Alberta. Despite the scarcity of wastewater disposal-induced seismicity cases in the WCSB, it is crucial to identify and study these cases as they can lead to considerable seismic hazard. For the Musreau Lake case, we provide a preliminary seismic hazard assessment by considering the non-stationary behaviour of the induced seismicity. The seismicity has shown a reduction of event magnitudes by the end of 2020, particularly events larger than M>3; however, the hazard is still non-negligible. Assuming that the observed seismic parameters will remain constant for 1 year, our findings suggest a 20% probability for an earthquake to reach a magnitude of M>4 if trends continue. However, this probability increases to 38% when greater hazard scenarios are considered. In terms of expected ground motions, there is a low (1%) probability in 1 year for the PGA to reach 380 cm/s^2, a value in the range of moderate to moderate/heavy potential damage. These preliminary findings necessitate further examinations of seismic hazard forecasting, which can be based on models such as the Seismogenic Index (Shapiro et al., 2010) and the Hydromechanical Nucleation Approach (Norbeck and Rubinstein, 2018). We also recommend improving the seismic monitoring in this area since a complete earthquake catalog is paramount for robust seismic hazard assessments.

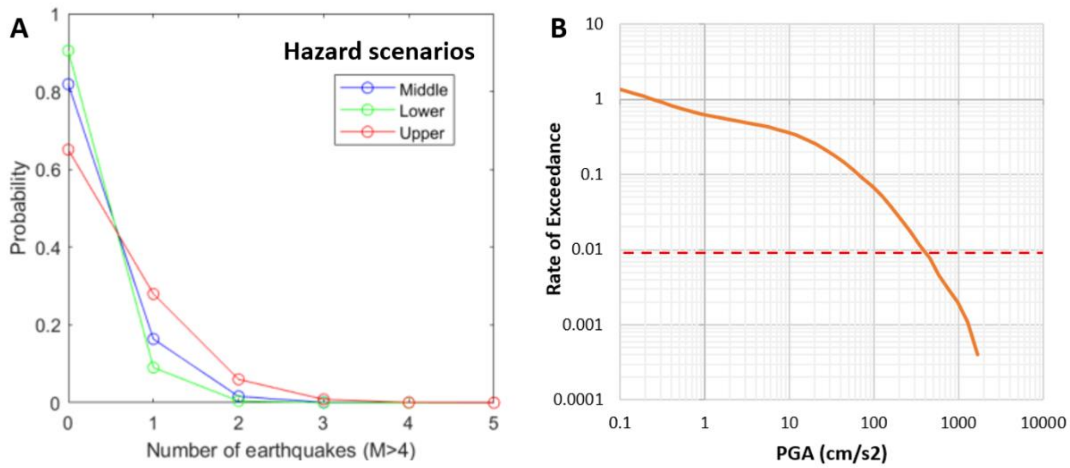

Figure 3. (A) Probability $P[N = n; t_a, t_b]$ of n occurrences larger than magnitudes M>4 in 1 year. The blue line shows the probabilities obtained from GR parameters estimated using MLM. The red and green curves show the probabilities based on the uncertainty of the GR parameter estimation. (B) Annual seismic hazard curve for the Musreau Lake seismicity.

References

Aki, K., 1965, Maximum likelihood estimate of b in the formula logN= a-bM and its confidence limits: Bull. Earthq. Res. Inst, 43, 237-239.

Alberta Geological Survey, 2021, Alberta Earthquake Dashboard. URL: https://ags.aer.ca/data-maps-models/interactive-maps-and-apps/ae. [January 2021]

Atkinson,G., Eaton, D., Ghofrani, H., Walker, D., Cheadle, B., Schultz, R., Shcherbakov, R., Tiampo, K., Gu, J., Harrington, R., Liu, Y., van der Baan, M., Kao, H. 2016. Hydraulic fracturing drives induced seismicity in the western Canada sedimentary basin: Seismological Research Letters, 87, 3, 631-647.

Atkinson, G. (2015). Ground-motion prediction equation for small- to-moderate events at short hypocentral distances, with application to induced-seismicity hazards. Bull. of the Seism. Soc. of America, 105, 981–992.

Baker, W., 2008, An introduction to probabilistic seismic hazard analysis (PSHA). Version 1.3, doi: https://web.stanford.edu/˜bakerjw/ Publications/Baker_(2008)_Intro_to_PSHA_v1_3.pdf

Ellsworth, W. L. (2013). Injection-induced earthquakes. Science, 341, 6142.

Li, T, Gu, Y. J., Wang, J., Wang, R., Yusifbayov, J., Reyes Canales, M., Shipman, T., 2021, Recent earthquakes induced by wastewater disposal near Musreau Lake, Alberta. Geoconvention 2021, Calgary, Canalda.

Norbeck, J.H., Rubinstein, J.L., 2018. Hydromechanical earthquake nucleation model forecast onset, peak, and falling rates of induced seismicity in Oklahoma and Kansas: Geophysical Research letters, 45, 2963-2975.

Reyes Canales M. and Van der Baan M. (2019) Including non-stationary magnitude-frequency distributions in probabilistic seismic hazard analysis. Pure and Applied Geophysics, 176(6), 2299-2319.

Schultz, R., V. Stern, and Y. Gu, 2014, An investigation of induced seismicity near de Cordel Field, west central Alberta and its relation to nearby disposal well: Journal of Geophysical Research: Solid Earth, 119, 3410-3423.

Shi, Y., & Bolt, B. A. (1982). The standard error of the magnitude- frequency b-value. Bulletin of the Seismological Society of America, 72, 1677–1687

Shapiro, S., Dinske, C., Langenbruch, C. 2010. Seismogenic Index and Magnitude probability of earthquakes induced during reservoir fluid stimulations: the leading edge, 29, 936-940.

Wiemer, S., and Wyss, M. 1997, Mapping the frequency-magnitude distribution in asperities: an improved technique to calculate recurrence times?: Journal of Geophysical Research, 102, 15115-15128.

Worden, C.B., M.C. Gerstenberger, D.A. Rhoades, D.J. and Wald (2012). Probabilistic relationships between ground-motion parameters and Modified Mercalli intensity in California Bull. Seism. Soc. Am. 102(1), 204-221.