Manuscript title: Seismological analysis of flood dynamics and hydrologically-triggered earthquake swarms associated with storm Alex

Manuscript ID: NHESS-2021-339

Review of the manuscript "Seismological analysis of flood dynamics and hydrologically-triggered earthquake swarms associated with storm Alex " by Chmiel et al. for publication in NHESS.

General comments

The article presents and analyses seismological records at permanent stations related to the storm Alex, which hit the southeastern France in October 2020. This storm was particularly damaging with important flash-flood waves in the rivers, in particular the Vésubie river. The seismological analyses consist of the temporal evolution of the seismic power, the peak frequency and the backazimuths owing to follow the flood propagation. The recordings alos make it possible to detect induced seismicity as three swarms triggered several days after the storm. This paper is of great scientific interest, very well-written and well-illustrated. It uses seismological records in an original way in order to constrain the timing and the propagation of river floods in the area affected by this exceptional weather event. In addition, the detection of induced earthquakes highlights the importance of the rainfall in the seismic activity. The manuscript is acceptable for publication with minor revisions as suggested hereafter.

Our response: We thank the Reviewer for this detailed review, helpful comments, and nice words. Please find below our replies to the Reviewer's comments.

Specific comments

- A threshold at each considered seismic station is used to define the seismic power maxima. It is not clear, and it is not explained, how these thresholds are determined/fixed: from the background noise? From an average of the seismic power over a time window? Please, clarify that point.

Our response: We determine the thresholds manually; they delimit the values in seismic power when the seismic power strongly and rapidly increases. We will add the following sentence (in red) to the manuscript (Lines 91-92):

"Their start and end times are marked in color in Figure 2, and the seismic power thresholds used to define the maxima are shown in Figure B3. We determine the thresholds manually; they delimit the values in seismic power when the seismic power strongly and rapidly increases."

- Again about the seismic power peaks, is the third one specifically defined with the TURF station because it is not very clear on the other two stations?

Our response: In Figure 2C we only mark the third maximum of the seismic power recorded at the TURF station because we cannot identify maxima 1 and 2 at the TURF station. However, we also define the third maximum for the SPIF and the BELV station, and we describe it in Lines 95-100, and Lines 200-205. We will add the following sentence to the manuscript (Lines 91-92):

"The maxima 1 and 2 are not marked in Figure 2C because we cannot identify them at the TURF station."

- Regarding the migration velocity of the earthquakes, are you sure that the velocity is in m/h and not in m/day (line 240)? Commonly, this velocity is considered to be from 10m/d to 100m/d, and Chen et al. (2012) found a velocity at 38m/d. The velocity you determined here, implies a velocity at 500-800 m/d, which is near aseismic slip (according to Chen et al., 2012). Are you considering the migration velocity of the earthquakes inside a swarm, or the migration velocity from one swarm to another? In this last case, I am not absolutely convinced that we can relate the time occurrence of the swarms to a fluid-driven migration. For example, in the central swarm, there are events at around 10 days as in the southern swarm, but also the latest events at more than 60 days (Figure 3).

Our response: Thank you for this comment. Regarding the discussion on swarm migration (Lines 237-244):

We consider the migration velocity from southern swarm to central and northern swarms. The locations are not accurate enough to correctly resolve earthquake migration inside swarms.

In the first version of the manuscript, there was confusion with the units of the migration velocity, which led to an erroneous interpretation. The velocity we estimate (line 240) is well expressed in m/h. The Reviewer is right; our values of 20-30 m/h are much larger than the migration velocity usually reported for fluid diffusion, which is of the order of tens of m/day (e.g., ~38 m/day Chen et al. 2012, ~ 30 m/day Ruhl et al. 2016). On the other hand, our migration velocity is somewhat lower than values usually reported for aseismic slip-driven seismicity, typical of order 100-1000 m/h (e.g., Lohman and McGuire, 2007; Roland and McGuire, 2009; Ruhl et al., 2016; Hatch et al., 2020). However, Chen and Shearer, 2011 and Chen et al., 2012, also attribute migration speeds of orders 10-100 m/h to aseismic slip, which are values compatible with our velocities.

Hence, we rewrite Lines 237-244 and propose an alternative model explaining the northward migration:

"The successive activation of the three swarms could also suggest an alternative mechanism of triggered seismicity. The northward migration of the seismicity is around 20-30 m/h. This velocity is much greater than 1-10 m/day, usually attributed to fluid diffusion-driven seismicity (e.g., Chen et al. 2012, Ruhl et al., 2016). Yet, this velocity is also lower than velocities reported for aseismic slip-driven seismicity (typically 100-1000 m/h, e.g., Lohman and McGuire, 2007; Roland and McGuire, 2009; Ruhl et al., 2016; Hatch et al., 2020). However, Chen and Shearer, 2011 and Chen et al., 2012, also attribute slow earthquake migration of orders 10-100 m/h to aseismic slip, which are values compatible with velocities we found. Hence the northward migration of the seismicity might highlight the horizontal propagation of an aseismic slip along a fault parallel to the valley. The overlying hydrological loading could possibly trigger this aseismic slip, and its northward propagation could drive the successive rupture of seismic asperities corresponding to the three swarms. The interplay between hydromechanical and aseismic slip processes is increasingly recognized as a driver of earthquake swarms (e.g., De Barros et al, 2020; Hatch et al., 2020)."

Regarding the discussion on fluid diffusion process (Lines 234-237):

We included the southern swarm in the discussion about the mechanism of fluid diffusion from surface to depth, since its resumption occurs at the same time as the activation of the central swarm.

"The resumption of activity of the southern swarm at the same time as the activation of the central swarm (6 days after Strom Alex), as well as the activation of the northern swarm (22 days after Storm Alex), are more compatible with surface to depth fluid migration. Yet, as these swarms are at the same depth, this would imply a rather large spatial variation of the hydraulic diffusivity from D=1.4-7.5 m2/s for the southern and central swarms to D=0.4-2m2/s for the northern swarm."

- Any comment on the fact that the "induced" seismicity by the storm is nearly at the same location of the previous background seismicity, especially at depth?

Our response: Indeed, the seismicity following Storm Alex is at the same location as the background seismicity. As shown in Figure 3, this part of the South-western Alps experiences a regular moderate seismic activity. So, we think Storm Alex has promoted ruptures on seismogenic structures that could have failed in the longer term. Hence the storm just played the role of a trigger.

We will add a sentence explaining that (end of section 4.2):

"Finally, the seismicity triggered by Storm Alex is colocated with the previous background seismicity, especially at depth (Figure 3). This area of the South-western Alps experiences regular moderate seismic activity. Therefore, the heavy rainfall has likely promoted ruptures on seismogenic structures that could have failed in the longer term."

- Finally, do you think that such seismic observations can be used to improve the rainfall-runoff simulations?

Our response: Seismic observations can provide the timing and propagation velocity of flood peaks and estimates of the flood's start and end times. This information can provide additional constraints for more accurate rainfall-runoff simulations needed to investigate spatio-temporal flood dynamics further. For example, in this study, we adjusted the flow velocity in the runoff simulation to 5 m/s, which corresponds to the peak velocities retrieved from the seismic observations.

We will add the following sentence into the manuscript at the end of section 4.1:

"In the future works, seismic observations can provide additional constraints for more accurate rainfall-runoff simulations needed to further investigate the spatio-temporal dynamics of flash-floods."

Technical corrections

- line 24: put the citations into (…)

Our response: Thank you for pointing this out, we will correct it.

- line 44: these observations

Our response: Thank you for pointing this out, we will correct it.

- Figure 1A: there is a small typing error in the color scale where 30 is for 300

Our response: Thank you for noticing this error, we will correct the color scale.

- line 77: the sentence begins with a "."

Our response: We will correct it.

- line 78: concerning the "40 rain gauges": Only one is visible in Figure 1A, and then at what distances are they?

Our response: We will add a figure in the Appendix (see below) that shows the position of the regional stream and rain gauges. The rain gauges are located at distances from 2 to 51 km from the SPIF station. The closest rain gauge to the SPIF station is shown in Figure B2. We will add the following sentence to the manuscript in Lines 57-60:

"The ANTILOPE rainfall estimation was produced by Météo-France and constrained by radar data and 40 rain gauges located in the region (Figure 1A). The location of regional rain and stream gauges is shown in Figure B1. The estimation of rainfall maps is highly uncertain in this context due to few rain gauges available, rainfall measurement uncertainties due to observed intensities, limits of the radar observations, and spatial interpolation."

We will also add the following sentence to the caption in Figure B5:

"This is the closest rain gauge to the SPIF station located at the distance of 1.9 km."

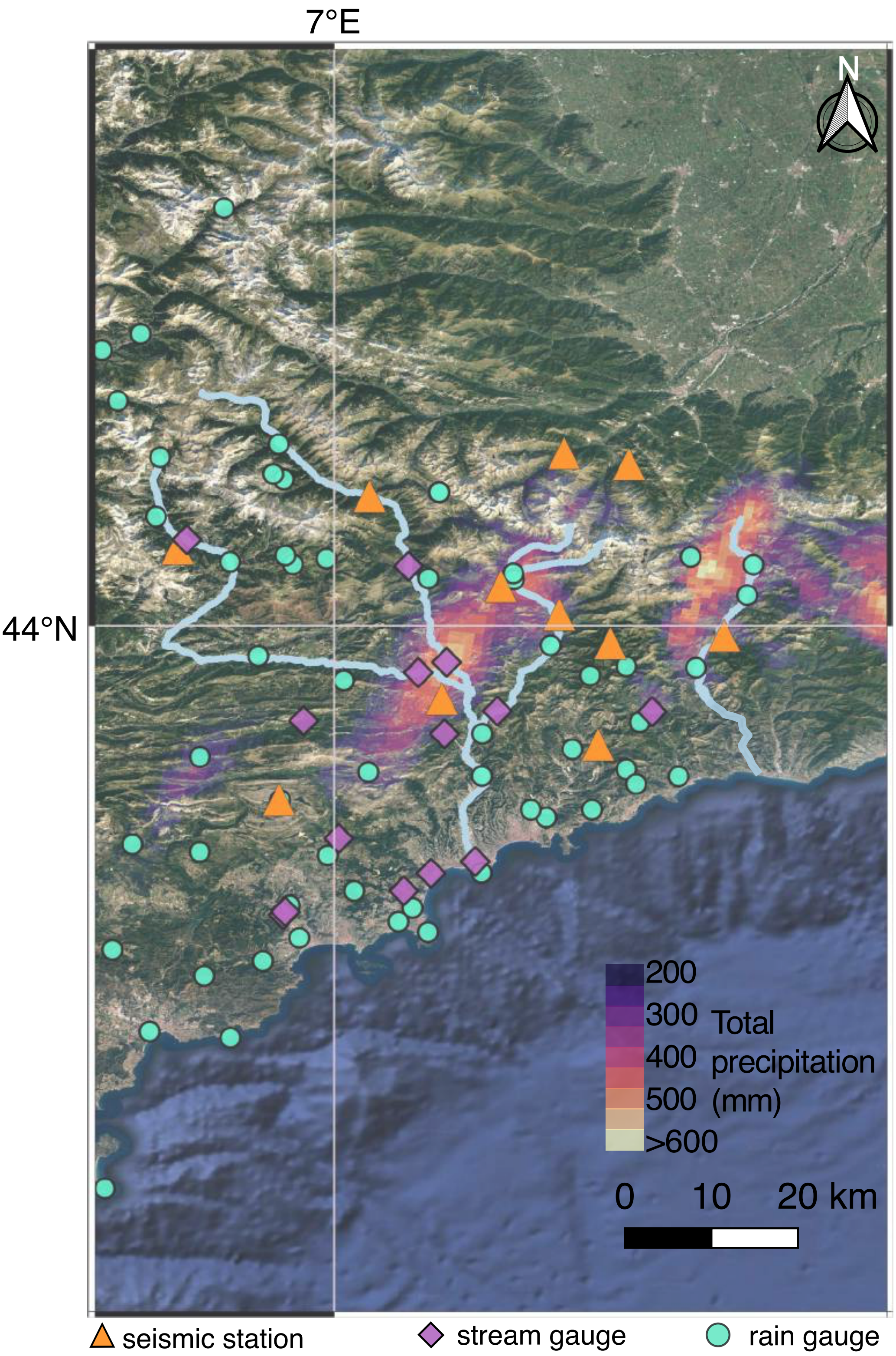

Figure B1: The location of rain and stream gauges and seismic stations in southeastern France.

- Please indicate more precisely that Figures B5 and B6 are for SPIF station.

Our response: We will add "SPIF" to panels A, B, and D in Figure B5 and to panels A and B in Figure B6. We will also add "SPIF" to panels A, B, and D in Figure B5. We will also add *"SPIF station seismic data analysis and meteorological data"* to the caption of Figure B5 and *"Backazimuth analysis at station SPIF"* to the caption of Figure B6.

References:

Chen, X., and Shearer, P. M. (2011), Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, J. Geophys. Res., 116, B09309, doi:10.1029/2011JB008263.

De Barros, L., Cappa, F., Deschamps, A., & Dublanchet, P. (2020). Imbricated Aseismic Slip and Fluid Diffusion Drive a Seismic Swarm in the Corinth Gulf, Greece. Geophysical Research Letters, 47, https://doi.org/10.1029/2020GL087142

Hatch, R. L., Abercrombie, R. E., Ruhl, C. J., & Smith, K. D. (2020). Evidence of aseismic and fluid-driven processes in a small complex seismic swarm near Virginia City, Nevada. Geophysical Research Letters, 47, e2019GL085477, https://doi.org/10.1029/2019GL085477

Lohman, R. B., and McGuire, J. J. (2007), Earthquake swarms driven by aseismic creep in the Salton Trough, California, J. Geophys. Res., 112, B04405, https://doi.org/10.1029/2006JB004596.

Roland, E., and McGuire, J. J. (2009), Earthquake swarms on transform faults, Geophysical Journal International, Volume 178, Issue 3, Pages 1677–1690, https://doi.org/10.1111/j.1365-246X.2009.04214.x

Ruhl, C. J., Abercrombie, R. E., Smith, K. D., and Zaliapin, I. (2016), Complex spatiotemporal evolution of the 2008 Mw 4.9 Mogul earthquake swarm (Reno, Nevada): Interplay of fluid and faulting, J. Geophys. Res. Solid Earth, 121, 8196– 8216, https://doi.org/10.1002/2016JB01339, .