Horizon 2020
Programme

METIS

Research and Innovation Action (RIA)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 945121

Start date : 2020-09-01 Duration : 48 Months

Seismic source characterizations methodologies and applications

Authors : Dr. Thomas CHARTIER (GEM), Marco Pagani, GEM

METIS - Contract Number: 945121

Project officer: Katerina PTACKOVA

Document title	Seismic source characterizations methodologies and applications
Author(s)	Dr. Thomas CHARTIER, Marco Pagani, GEM
Number of pages	28
Document type	Deliverable
Work Package	WP4
Document number	D4.1
Issued by	GEM
Date of completion	2022-05-02 18:24:23
Dissemination level	Public

Summary

Probabilistic seismic hazard assessment considers the occurrence of earthquakes as Poissonian, each even being independent of the others. As earthquakes do not occur as isolated events but for clusters of foreshocks, mainshock and aftershocks, it is necessary to identify and remove the earthquakes that are other than mainshocks from the catalog before calculating the annual rate of events used for the characterization of the seismic activity of the seismogenic sources of the hazard model. The aim of this study is to find a methodology to obtain a Poissonian declustered catalog while removing as few earthquakes as possible. To do so, we developed a methodology that allows to test the Poissonian nature of a declustered earthquake catalog and find the declustering algorithm that keeps the largest number of events while still performing well on the Poissonian test. Building a hazard model requires to perform statistic on the number of events per units of time and their spatial repartition, therefore, the Poissonian test was developed to reflect these needs. By comparing the inter-event spatio-temporal distances between the events of the tested catalog to the ones from simulated Poissonian catalogs sharing similar properties, we can score the statistical similarities between the tested and the simulated catalogs. We apply this methodology on the catalog for central Italy after being declustered with a range of different published algorithms and an additional algorithm that we propose in this study, and we perform a seismic hazard study for two locations in Central Italy to quantify the impact of the declustering algorithm on the seismic hazard level estimate.

Approval

Date	By
2022-05-03 11:04:10	Dr. Marco PAGANI (GEM)
2022-05-03 11:13:52	Dr. Irmela ZENTNER (EDF)

Research & Innovation Action

NFRP-2019-2020

Methodology for the declustering of earthquake catalogs

Deliverable D4.1

Version N°1

Authors: Thomas Chartier (GEM)

Disclaimer

Document Information

Grant agreement	945121
Project title	Methods And Tools Innovations For Seismic Risk Assessment
Project acronym	METIS
Project coordinator	Dr. Irmela Zentner, EDF
Project duration	1st September 2020 – 31st August 2024 (48 months)
Related work package	WP 4 – Seismic hazard
Related task(s)	Task 4.1 – Source characterisation
Lead organisation	GEM
Contributing partner(s)	
Due date	30/04/2022
Submission date	29/04/2022
Dissemination level	X

History

Version	Submitted by	Reviewed by	Date	Comments
N°1	Thomas Chartier	Marco Pagani	29/04/2022	

Table of Contents

List of figures

List of tables

Abbreviations and Acronyms

Acronym	Description
WP	Work Package
PSHA	Probabilistic Seismic Hazard Assessment
IESD	Inter Event Spatio-temporal Distance

Summary

Probabilistic seismic hazard assessment considers the occurrence of earthquakes as Poissonian, each even being independent of the others. As earthquakes do not occur as isolated events but for clusters of foreshocks, mainshock and aftershocks, it is necessary to identify and remove the earthquakes that are other than mainshocks from the catalog before calculating the annual rate of events used for the characterization of the seismic activity of the seismogenic sources of the hazard model.

The aim of this study is to find a methodology to obtain a Poissonian declustered catalog while removing as few earthquakes as possible. To do so, we developed a methodology that allows to test the Poissonian nature of a declustered earthquake catalog and find the declustering algorithm that keeps the largest number of events while still performing well on the Poissonian test.

Building a hazard model requires to perform statistic on the number of events per units of time and their spatial repartition, therefore, the Poissonian test was developed to reflect these needs. By comparing the inter-event spatio-temporal distances between the events of the tested catalog to the ones from simulated Poissonian catalogs sharing similar properties, we can score the statistical similarities between the tested and the simulated catalogs.

We apply this methodology on the catalog for central Italy after being declustered with a range of different published algorithms and an additional algorithm that we propose in this study, and we perform a seismic hazard study for two locations in Central Italy to quantify the impact of the declustering algorithm on the seismic hazard level estimate.

Keywords

PSHA, declustering, earthquake catalog, Poissonian

1. Introduction

Earthquakes occurrence leads to changes in the stress condition of the region surrounding the rupture (Dieterich, 1994; Console et al., 2006; Felzer and Brodsky, 2006). These changes can induce other earthquakes to occur, creating a sequence of events. The largest earthquake in each sequence is considered as the mainshock while the following earthquakes are tagged as aftershocks and their number decreases as time since the mainshock passes (Omori, 1894); some foreshocks may also occur. Any earthquake catalog is composed of an ensemble of these sequences where the earthquakes are clustered in both space and time.

Probabilistic seismic hazard assessment (PSHA) (Cornell, 1968) has the objective to identify the probability of at least one exceedance of different level of ground motion during an investigation time, very often 50 years. The number of times a reference level of ground motion is exceeded during this time interval is not used. In order to obtain this probability, PSHA requires an estimation of the earthquakes rates in the region of study.

For moderate and low magnitude events the earthquake catalog is used to obtain these rates, simply by dividing the number of observed events by the observation time. However, one common assumption of PSHA is that the earthquake occurrence is Poissonian, in other words considering that the earthquakes are independent, giving to any time an equal probability of occurrence of events. Under this assumption, using for the calculation of the earthquake rates a catalog that includes possible clusters of seismicity can lead to an overestimation of the probability of exceedance of the ground motion or a bias in the definition of the spatial pattern of seismicity.

Fig1 illustrates this point using two catalogs with the same number of earthquakes, one which is Poissonian, one that shows a clustered pattern. The Poissonian catalog leads to more stable values of the probability of exceedance in the study time. Note that this is particularly true for moderate and large values of ground-motion generally characterized by a low probability of exceedance.

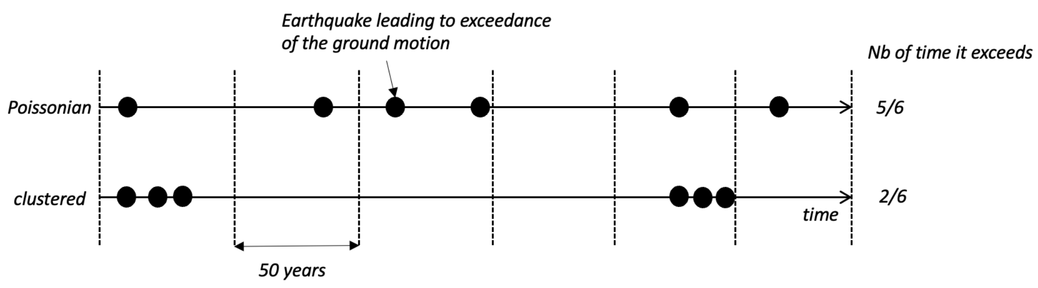

Figure 1: Schematic view of the impact of clustering on the temporal distribution of earthquakes

To correct this overestimation, methods for declustering the catalog have been developed in order to keep only the mainshocks component of seismicity, effectively creating a catalog of events that can be considered Poissonian. For example, the mainshock-windows declustering methods remove all the earthquakes that are within a temporal and a spatial window which both include the mainshock and whose size depend on the earthquake magnitude of the mainshock (Knopoff & Gardner 1972; Gardner & Knopoff 1974; Gruenthal 1985, Uhrhammer, 1986). Other methods calculate the time and distance between each earthquake in the catalog and group the earthquakes into clusters (Reasenberg 1985). In order to make the catalog Poissonian, both methods are effectively creating "holes" in the catalog around each mainshocks. While they are still the most widely used methods for developing seismic hazard models, these methods do not consider the information and knowledge collected during the last 50 years and remain largely untested in many places in the world. Recent studies are proposing new methodologies for declustering, but – to our knowledge – these methods were not yet used in PSHA development (Zaliapin and BenZion, 2020).

It is worth noting that there is an ongoing discussion in the scientific community around the appropriateness to decluster the catalog (e.g., Gerstenberger et al 2020). Declustering the catalog in order to calculate the earthquake rates might lead to an underestimation of the seismic hazard and risk since aftershocks have been observed to induce damage such as during the Canterbury, New Zealand (Gerstenberger et al., 2014; Gerstenberger et al., 2016), central Italy (Marzocchi et al., 2017), and Kumamoto, Japan (Kamaya et al., 2016). The declustering procedures could also lead to artificial modification of the magnitude frequency distribution (MFD) by removing a larger number of smaller magnitude earthquakes than larger magnitude earthquakes (Mizrahi et al 2021).

In this study, we propose a methodology for leaving as many earthquakes as possible in the declustered catalog while ensuring to the extent possible Poissonian properties. We aim to retain as much earthquakes as possible in the declustered catalog and better constrain the magnitude frequency distribution, but not overestimating the hazard by basing the calculation of the earthquake rates on a catalog that is not Poissonian. For this goal, we introduce a methodology for testing if a declustered earthquake catalog has similar properties as simulated Poissonian catalogs. We obtain this by finding a balance between the Poissonian nature of the catalog and the number of earthquakes remaining after the declustering. We test the proposed methodology using various earthquake declustering approaches.

For each declustered catalog, we analyze the identified clusters and the aftershock productivity is computed in order to be able to inform future PSHA studies that also aim to account for the impact of aftershocks (e.g., Boyd 2012).

2. Methodology: Testing the Poissonian nature of the earthquake catalog

In this section, we present the methodology we developed for testing the Poissonian nature of the catalog. First, we describe the general philosophy then we outline each step of the procedure.

2.1. General philosophy of the methodology

As explained above, the goal of this research is to create a declustering approach that generates a Poissonian catalog while keeping as many earthquakes as possible in the declustered catalog. The proposed approach is geared towards the needs of the source model development in hazard assessment.

Rather than defining a physical limit of the independence of each earthquake to other earthquakes in the catalog, we chose to look at the catalog as a whole and check if the declustered computed has similar properties to synthetic Poissonian catalogs. In other words, we are testing if the temporal and spatial distribution of the seismicity in the declustered catalog share statistical properties similar to the ones of the synthetic catalogs.

2.2. Summary of the testing procedure

The methodology for testing the Poissonian nature of the catalog, includes the following steps:

1. Generate several synthetic Poissonian catalogs. Depending of the size of the catalog to be tested, a different number of synthetic catalogs are generated.
2. Calculate inter-earthquake spatiotemporal distances for both the tested catalog and the synthetic catalogs.
3. For each earthquake of the tested catalog, compare the distribution of spatiotemporal distances with the distributions obtained with the earthquakes from the synthetic catalogs. The more similar are these distributions, the more independent can be considered the tested catalog. This similarity provides a score of independence (or degree to which the tested catalog can be considered Poissonian).
4. Sum the scores of each earthquake from the tested catalog to obtain the score of the catalog as a whole.

2.3. Details of the testing procedure

2.3.1. Generation of the synthetic Poissonian catalog

We assume that in order to be comparable with the tested catalog, the synthetic catalogs must contain the same number of earthquakes as the tested one and cover the same time span. If the tested catalog contains a relatively small number of events (e.g., less than 3000), several synthetic catalogs are generated in order to obtain statistical stability.

In addition, the synthetic catalogs must have a spatial distribution similar to the distribution of the tested catalog. To do so, the tested area is divided into a grid of cells and for each cell, we obtain the probability of having an earthquake as the number of observed earthquakes divided by the total number of earthquakes. In each cell, the spatial distribution of earthquakes is assumed uniform.

2.3.2. Inter-earthquake spatiotemporal distances

The inter-earthquake spatiotemporal distance (IESD) is calculated using the following formula:

$$IESD = ds \times dt \times s_t$$

With ds the spatial distance between the epicenter of events, dt the time in decimal years between earthquakes, and s_t the temporal scaling factor.

Like Zaliapin and Ben Zion (2020), the temporal scaling factors are set by default to 1 for the temporal one but different values can be considered.

2.3.3. Comparison of the distribution of the IESD

For each event in the synthetic catalogs, we compute its IESD from all the other ones and from this list of IESD values, we obtain a histogram (e.g., 50 bins between 0 and ¼ of the maximum distance as the shorter distance are more important to identify the presence of clusters). This distribution is normalized to obtain a probability mass function (Figure 2). Bins with null values are removed from the distribution. This operation is repeated for each earthquake of each synthetic catalog. In the end, each bin is characterized by a set of values (i.e. probabilities, in grey in Figure 1) for which it is possible to compute various statistics (red and purple short lines in Figure 1).

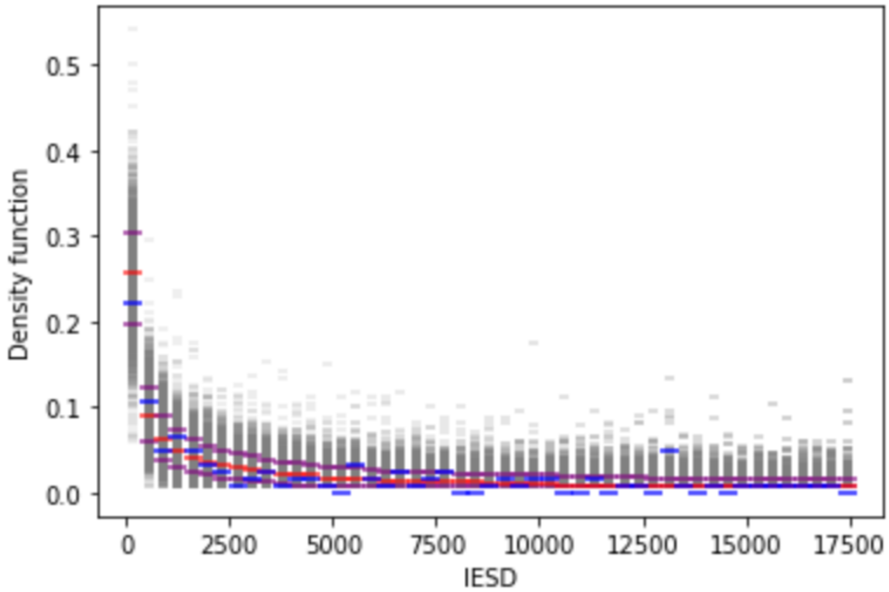

Figure 2 : Comparison of the density functions of the IESD for one event of the tested catalog (in blue) and the density functions from the synthetic catalogs (in grey). In red, the

median value of the IESD density functions in the synthetic catalog, in purple, the 16th and 84th percentiles of the distribution.

Similarly, for the tested catalog we compute the IESD between each earthquake and the other events and the distribution of the IESD following the same binning used for the synthetic catalog (in blue in Figure 2). The distribution is normalized to obtain the mass function *df*.

In each bin, the value for this earthquake is compared to the value from the distribution of the Poissonian and the centile *c* is calculated, with *c* between 0 if the number of IESD in this bin is lower than all the ones in the synthetic catalogs, 0.5 if the value of the event's density function is equal to the median of the one from the synthetic catalog and 1 if it is higher than all the density functions from the synthetic catalog. Compared with the distance to the mean, this metric has the advantage of taking into account the random variability of the IESD in the synthetic catalogs.

For all bins where the value of the density function *df*, is not zero, a score for the bin is calculated with the following formula:

$$score_{bin} = 1 - \left|\frac{c - 0.5}{0.5}\right|$$

This score, between 0 and 1, is maximal if the distribution of IESD is equal to the central value of the one in the Poissonian synthetic catalogs and minimal if the value is outside of the values of IESD of the Poissonian catalogs.

A strongly clustered catalog will have a lot of similar IESD values and the centiles will be much higher for some of the distance bins than the ones in the synthetic Poissonian catalog. Therefore, the score for most bins will be quite low.

The score for a given earthquake of the tested catalog is the average value of the $score_{bin}$ for all the non-empty bins of the density function *df*.

$$score_{event} = \frac{\sum_{non\ empty\ bins} score_{bin}}{number\ of\ non\ empty\ bins}$$

The score for the whole catalog is the sum of the scores of each earthquake divided by the number of earthquakes in the catalog.

$$score_{catalog} = \frac{\sum_{i=1}^{n} score_i}{n}$$

where n is the number of earthquakes in the catalog. The score of the catalog is therefore between 0 and 1. A catalog with score close to 0 is only constituted of events extremely clustered in both time and space, leading to IESD distribution widely different from the ones of a synthetic Poissonian catalog. A catalog with a score close to 1 is constituted of events with IESD between each other that are extremely close to the ones of a Poissonian catalog. In practice, due to the random variability of the Poissonian process, this is extremely unlikely and the scores are often with a maximum of around 0.5, even for synthetic Poissonian catalogs. A score of 1 would mean that all events in the catalog have the exact same IESD distribution than the median one from the synthetic catalog, something unlikely given the random variability of earthquake catalogs.

3. Example of application of the method in Central Italy

In this section, we present an application of the Poissonian testing methodology to the earthquake catalog of central Italy. We will apply different declustering strategies and test the Poissonian properties of the declustered catalogs.

3.1. Presentation of the earthquake catalog

For this study, we are using the ISC bulletin catalog between 1960 and 2020, for magnitude 3.5 and larger. This catalog is composed of 762 events with most of the events located in the Central Apennine region (Figure 3) and the largest observed event has a maximum magnitude of 6.7 corresponding to the Norcia earthquake of 2016 (Figure 4). Several earthquake sequences can be observed.

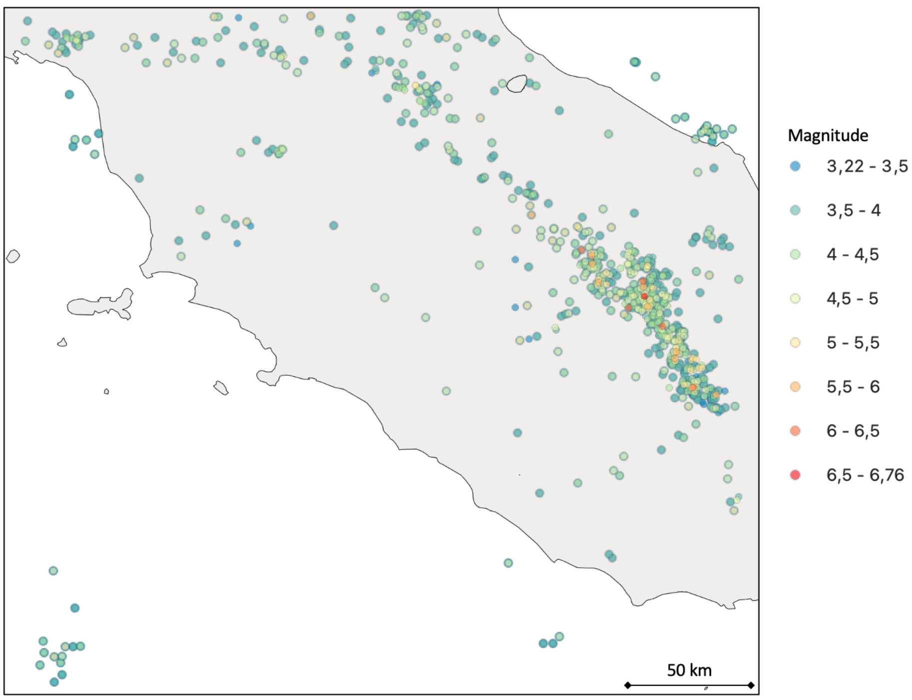

Figure 3 : Earthquake catalog for Central Italy used in this study. The color scale represents the magnitude.

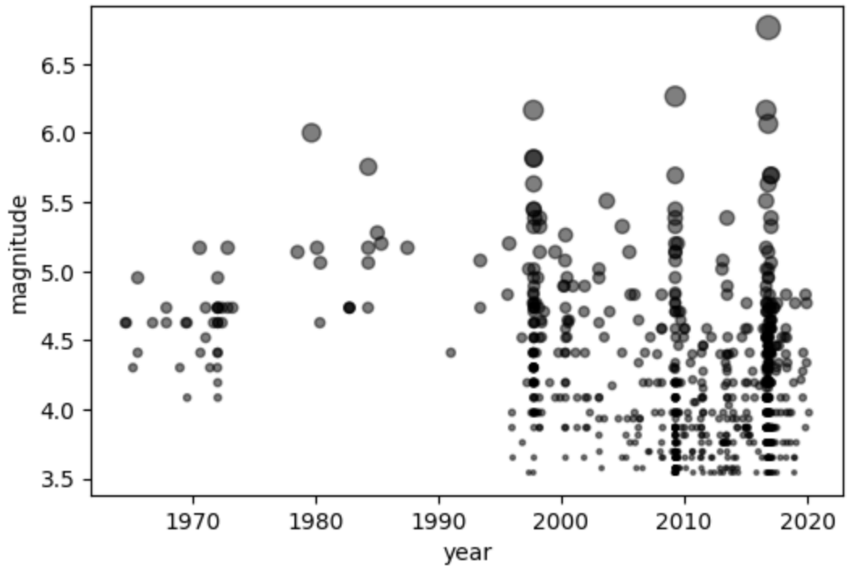

Figure 4: Time distribution of the events in the catalog for Central Italy. The size of the symbols is proportional to the magnitude.

3.2. Different declustering approaches

We apply different published declustering algorithms on the catalog for Central Italy (Figure 5):

- Gardner and Knopoff 1972 with the following windows:
  - Gardner and Knopoff 1974 (GK GK)
  - Uhrhammer 1986 (GK Urh)
  - Gruental 1985 (GK Gruental)
- Reasenberg 1985
- Zaliapin and Ben-Zion 2020

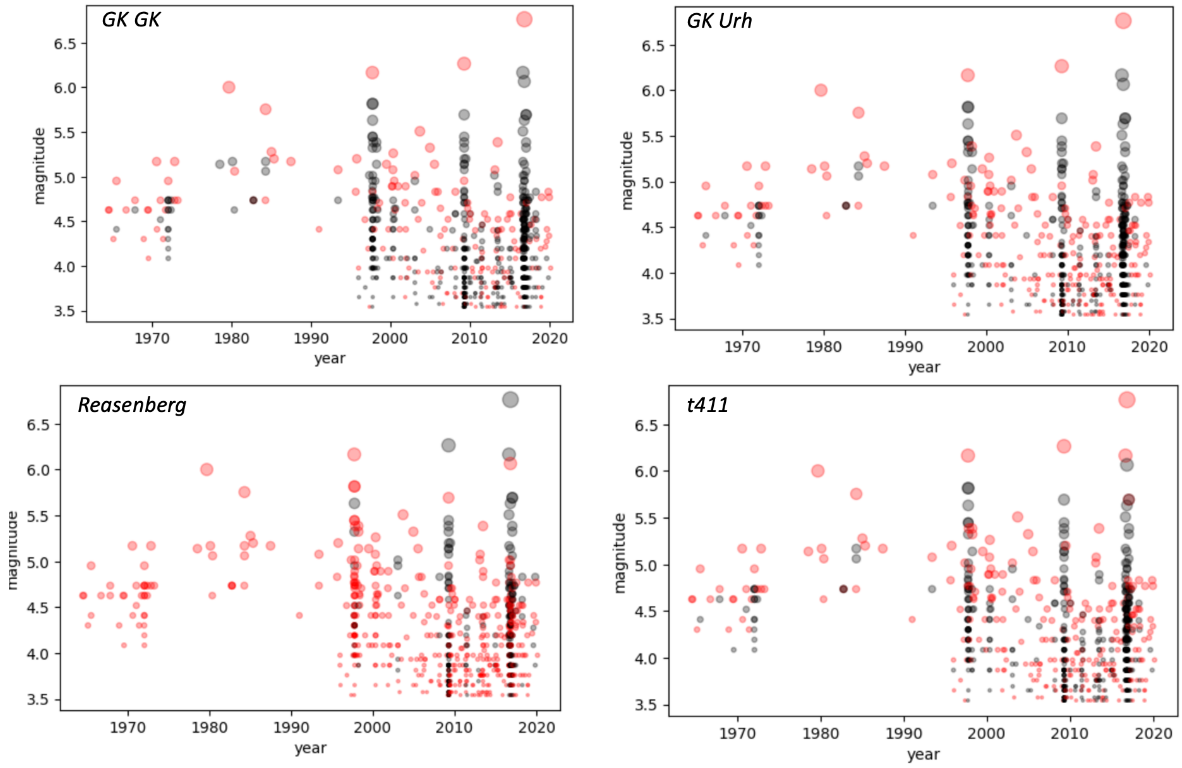

Figure 5: Application of the different declustering approaches to the earthquake catalog. Mainshocks are represented in red (t411 is a declustering method based on IESD).

In addition, we apply a simple declustering methodology based on the same spatiotemporal distance (IESD) used for testing the Poissonian nature of the catalog. The IESD is computed between each event and is this distance is below a given critical distance, the two events are considered to be part of the same cluster. We explore a range of critical distances and as the critical distance increases, the clusters are larger and the number of earthquakes remaining in the declustered catalog is decreasing (Figure 6). This declustering method with further on be referred as t411. In Figure 5, for t411, a critical distance value of 0.002 is used as an example, if the IESD between two earthquakes is less than 0.002, the earthquakes are considered to be part of the same cluster.

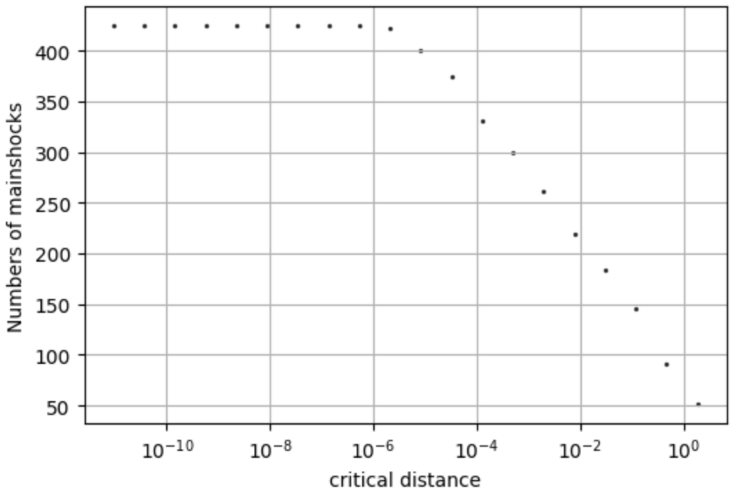

Figure 6 : Scaling of the number of events considered as mainshocks as a function of the critical distance.

3.3. Testing the declustered catalogs

The declustered catalog obtained with the considered declustering approaches are tested using the methodology presented in the methodology section of this report.

First, a set of synthetic catalogs are generated, where each catalog has the same number of events and the same time span as the tested catalog and is reproducing the same spatial pattern of the original catalog (Figure 7).

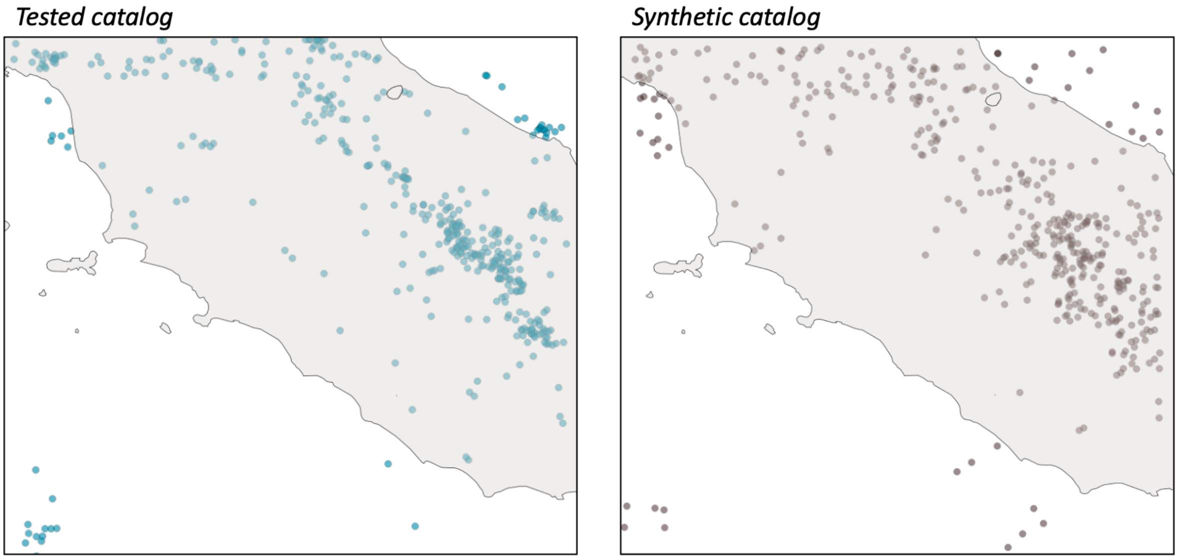

Figure 7 : Example of a declustered catalog and the corresponding synthetic catalog used for the test.

In Figure 8, we note that the tested catalog still contains some cluster events, creating steps in the cumulative distribution with time, while the Poissonian synthetic catalogs do not show major steps in their distribution. However, the synthetic catalogs show some random variation of the annual earthquake rate relative to the average rate.

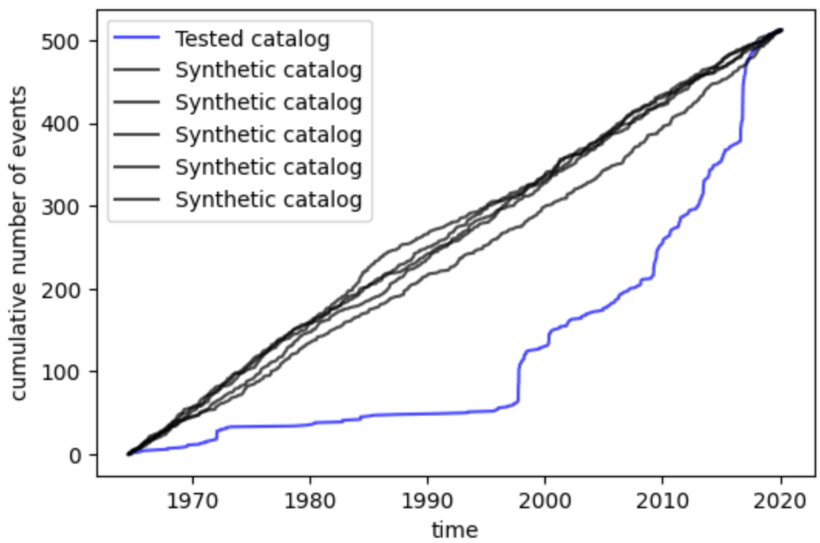

Figure 8 : Temporal distribution of events in the tested catalog and the synthetic catalogs.

For the application of the t411 methodology, we explore a range of critical distances and test the Poissonian nature of each of the declustered catalogs obtained. In Figure 6, we showed that the number of events remaining in the catalog decreases as the critical distance increases. As the number of events decreases, only events that are more isolated from the other are left in the catalog, therefore, the Poissonian test result value increases (Figure 9). For the rest of this study, we will use the critical distance of 0.002, as it leaves a large number of earthquakes in the catalog (261) while having a good Poissonian test score of 0.39.

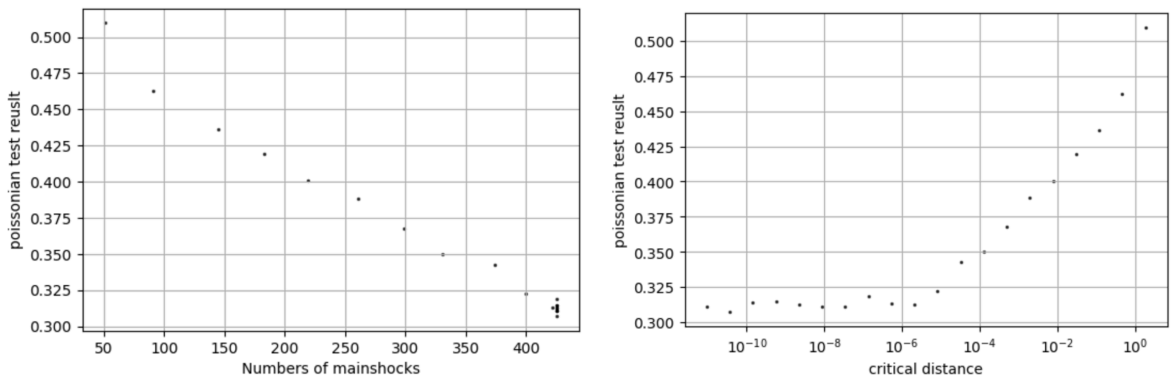

Figure 9 : On the left, result of the Poissonian test as a function of the number of earthquakes left in the declustered catalog. On the right, we show the dependence of the Poissonian test from the critical distance used for the declustering.

3.4. Results

Following the methodology presented in this study, the IESD distribution of the tested catalog is compared to the distribution obtained from the synthetic catalogs. The scores are presented in Table 1 and Figure 10.

Table 1 Result of the Poissonian test for each declustering approach

Declustering	GK GK	GK Gruental	GK Uhr	Reasenberg	Zaliapin	t411
Poissonian test score	0.38	0.39	0.37	0.29	0.38	0.39
Number of events	187	159	259	513	250	261

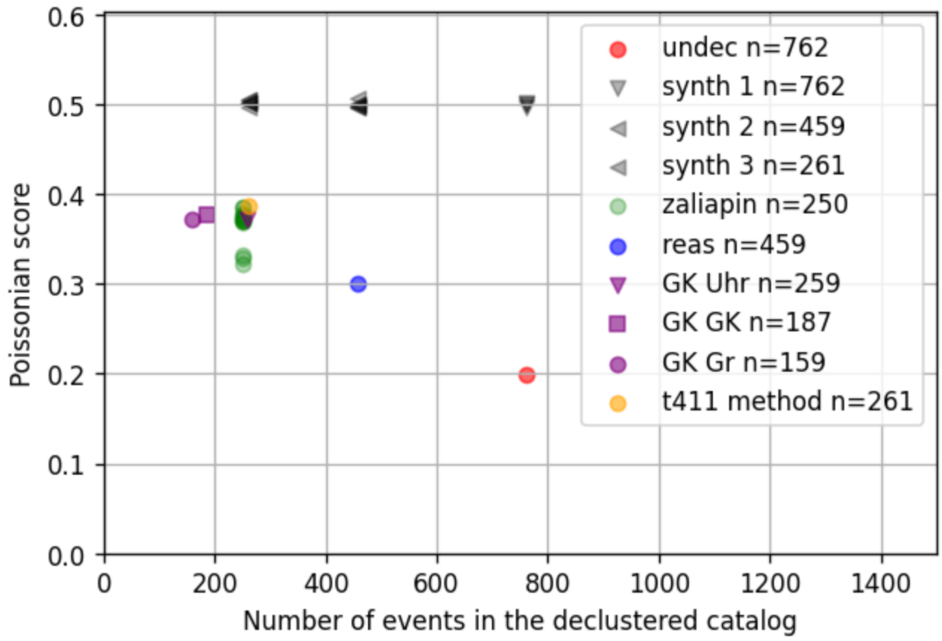

Figure 10 : Results of the Poissonian test for each declustering approach as well as for the undeclustered catalog and two sets of synthetic catalogs with different number of events.

In addition to the different declustered catalogs, the Poissonian test is also applied to the full catalog and on a range of synthetic catalogs of different sizes. As expected, the full undeclustered catalog performs poorly with the overall score of 0.2. In comparison, the synthetic catalogs have the highest possible scores of around 0.5, with some small variability due to the randomness of the generation process.

The Reasenberg approach leaves a too many earthquakes in the declustered catalog (459) and therefore it shows a low score for the Poissonian test (0.3). The Zaliapin and Ben Zion (2020), Gardner and Knopoff with the Gruental windows and the t411 approaches keep a similar number of earthquake and perform better on the Poissonian test (around 3.8, 3.9). Gardner and Knopoff using the other windows perform similarly on the test but keep fewer events in the catalog.

3.5. Impact on the seismic hazard levels

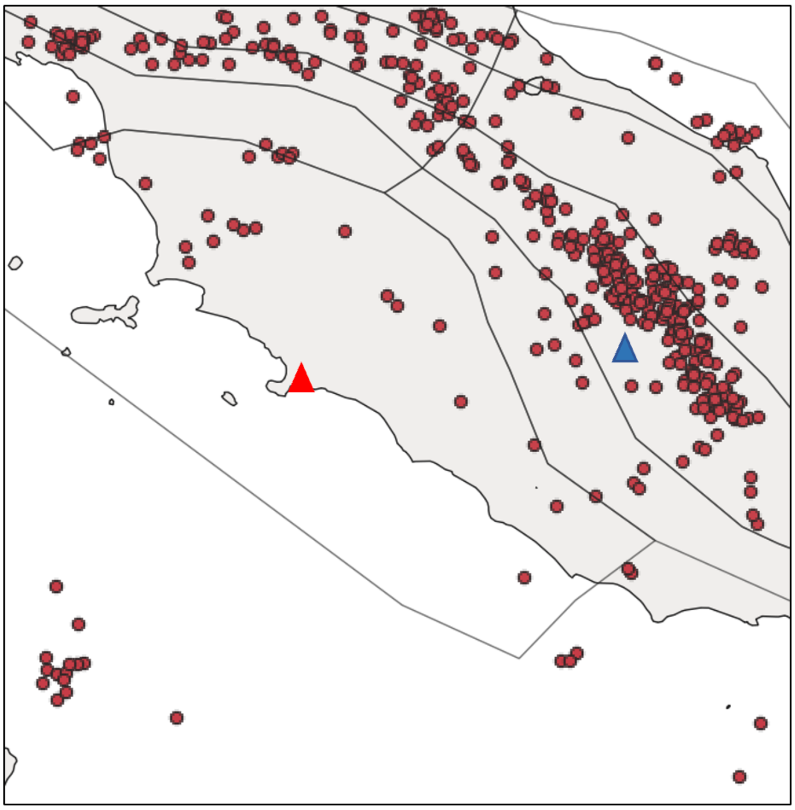

Figure 11 : Simplified hazard model for Central Italy based on the area source of ESHM20. The declustered catalog used is in red, the site 1 is represented by the red triangle and site 2 is represented by the blue triangle.

In order to observe the impact on the seismic hazard, we developed a hazard model using each one of the declustered catalog. This model is using the geometry of area sources included in the European Seismic Hazard Model 2020 (ESHM20 see https://gitlab.seismo.ethz.ch/efehr/eshm20), the GMPE developed by Ameri et al. (2017) is used and the earthquake rates are calculated using a maximum likelihood approach on the declustered earthquake catalogs. The hazard is calculated at two theoretical sites. Site 1 (in red in Figure 11) located in a relatively stable area of Italy, and site 2 (in blue in Figure 11) is in a more active area, in the Apennines.

The impact of the declustering approach in the hazard results is greater for the site located in an active region, closer to many earthquake clusters, than for the site in the stable region where the declustering removes only few earthquakes.

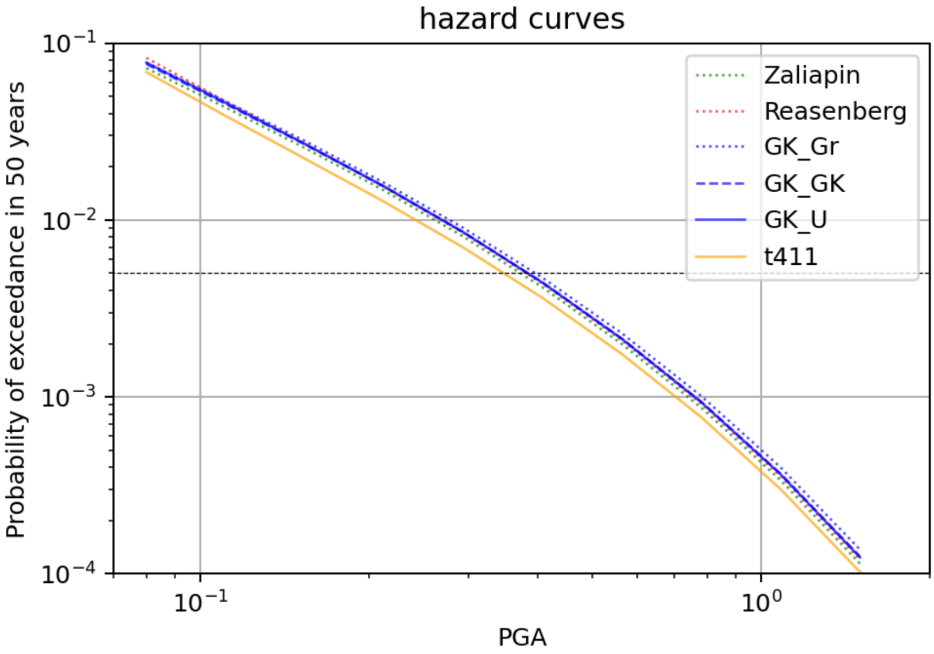

Figure 12 : Hazard curves for Site 1 for each declustering approach.

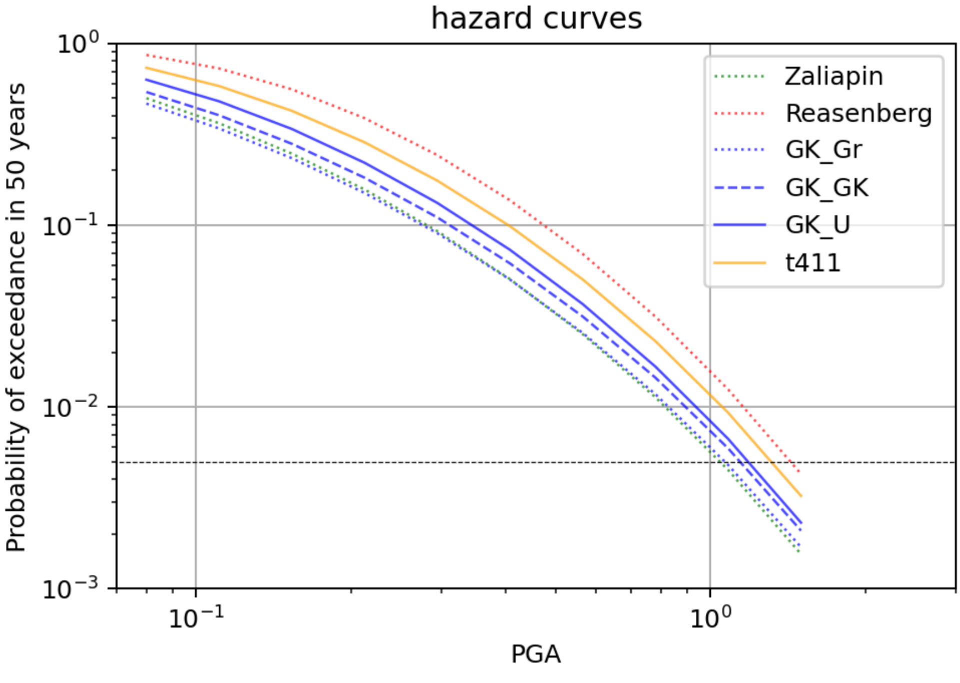

Figure 13 : Hazard curves for Site 1 for each declustering approach.

The results of the Poissonian testing can be used to select and weight the different declustered to be explored in a logic tree. Given the values presented in Table 1, Zaliapin, GK using the Gruenthal windows and t411 approaches would be ones with the highest weights in a logic tree.

4. Additional examples

4.1. The Izmit Duzce Sequence

We test different declustering methodologies using the 1999 North Anatolian Fault (Turkey) earthquake sequence. The ISC-GEM catalog from 1998 to 2012 in the Izmit region is used (Figure 14).

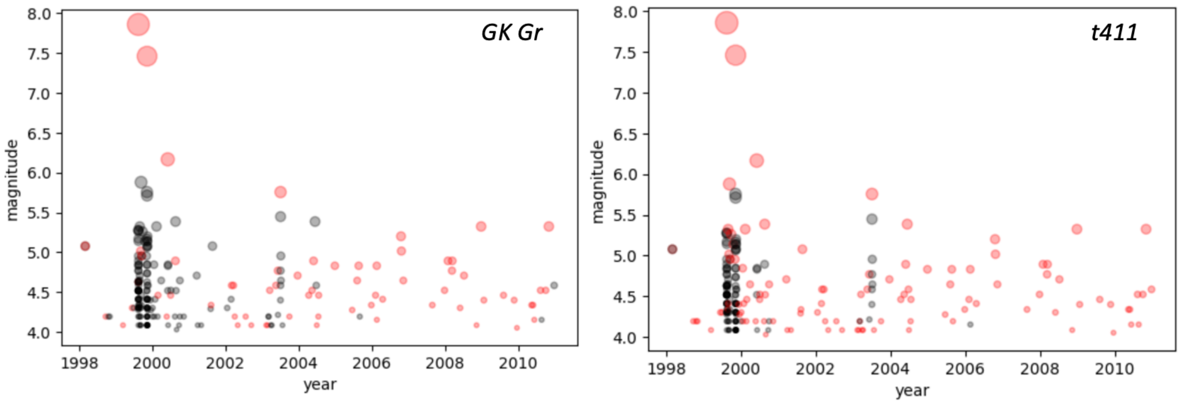

Figure 14 : Application of the declustering methods to the catalog. Mainshocks are in red.

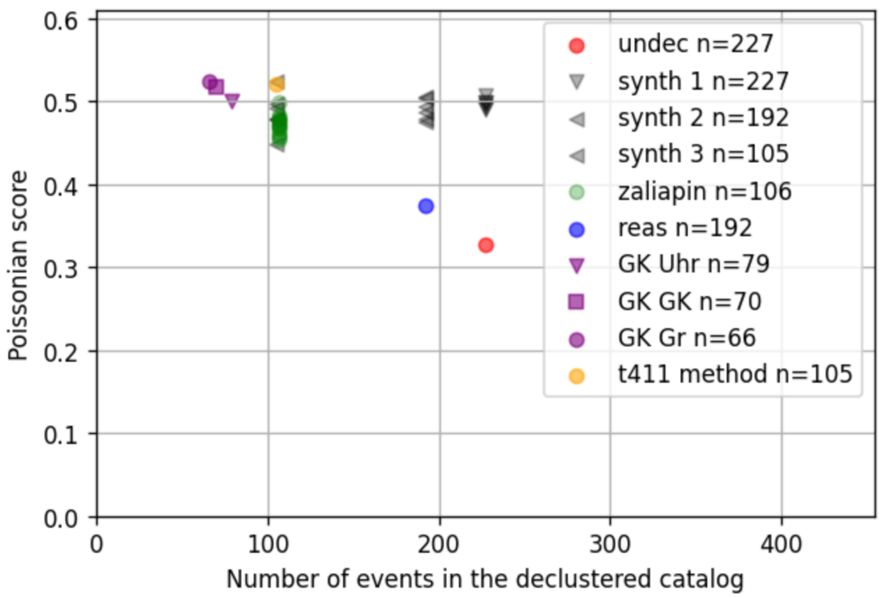

Figure 15 : Poissonian test result and number of events for each declustered catalog.

Interestingly, for this earthquake sequence most of the declustering approaches (but Reasenberg) lead to a very good score, equivalent to the score of the synthetic catalogs.

4.2. The Christchurch Sequence

Different declustering approaches are applied to the 2010 Christchurch (NZ) earthquake sequence, using the ISC-GEM catalog (Figure 16).

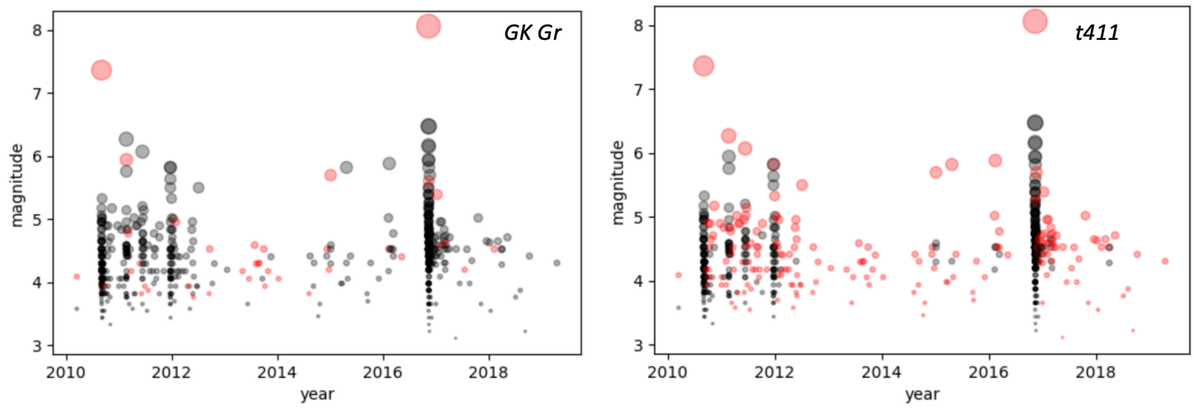

Figure 16: Declustering applied to the Christchurch sequence

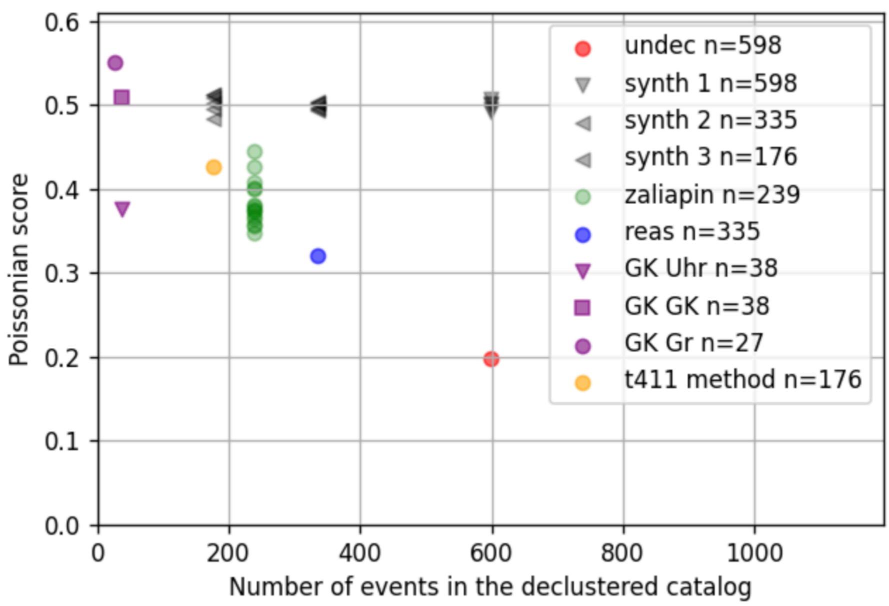

Figure 17 : Poissonian test result and number of events for each declustered catalog.

For this earthquake sequence, the different declustering algorithms perform quite differently, with the Gardner and Knoppof windowing approach leaving few earthquakes in the declustered catalog than the other approaches but performing very well on the test for two of the windows used.

5. Conclusion

In this study, we have developed an approach to test the Poissonian nature of a declustered earthquake catalog. This allows to find the declustering method that keeps the largest number of events in a catalog of events that can be considered to a high degree independent. This is the best compromise available when we preparing seismicity information used for the computation of the magnitude frequency distribution of the seismogenic sources of the seismic hazard model. This methodology relies on the statistical comparison of the declustered catalog with a set of synthetic Poissonian catalogs. Inter-earthquake spatiotemporal distances are computed and the distribution of the distance values in the tested catalog is compared to analogous distributions obtained from synthetic Poissonian catalogs. The closer the distributions are, the higher the is score measuring the level of a catalog of being Poissonian.

The proposed methodology is tested using a catalog for central Italy and, compared against several published declustering methodology. The performance of each declustering method computed using the proposed methodology allows to propose a weighting for these methodologies in a logic tree. The impact of the declustering methodology on the variability of hazard results is evaluated for two sites in Italy. Our results show a larger impact for the one located in the most seismically active region.

6.6 Supplementary materials

Python notebooks with the examples presented in this report will be available on the GEM cloud. (https://cloud.openquake.org/s/gnHBsRapSpQoKxj/)

7. References

Ameri, G., Drouet, S., Traversa, P. et al. Toward an empirical ground motion prediction equation for France: accounting for regional differences in the source stress parameter. Bull Earthquake Eng 15, 4681–4717 (2017). https://doi.org/10.1007/s10518-017-0171-1

Boyd O. S.; Including Foreshocks and Aftershocks in Time-Independent Probabilistic Seismic-Hazard Analyses. *Bulletin of the Seismological Society of America* 2012;; 102 (3): 909–917. doi: https://doi.org/10.1785/0120110008

Console, Rodolfo, Maura Murru, and Flaminia Catalli. "Physical and stochastic models of earthquake clustering." Tectonophysics 417.1-2 (2006): 141-153.

Cornell C A; Engineering seismic risk analysis. *Bulletin of the Seismological Society of America* 1968;; 58 (5): 1583–1606. doi: https://doi.org/10.1785/BSSA0580051583

Dieterich, James. "A constitutive law for rate of earthquake production and its application to earthquake clustering." Journal of Geophysical Research: Solid Earth 99.B2 (1994): 2601-2618

Felzer, Karen R., and Emily E. Brodsky. "Decay of aftershock density with distance indicates triggering by dynamic stress." Nature 441.7094 (2006): 735-738

Gardner, J. K., and Leon Knopoff. "Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?." Bulletin of the seismological society of America 64.5 (1974): 1363-1367.

Gerstenberger M, McVerry G, Rhoades D, Stirling M. Seismic Hazard Modeling for the Recovery of Christchurch. Earthquake Spectra. 2014 ; 30(1):17-29. doi:10.1193/021913EQS037M

Gerstenberger M, David A. Rhoades, Graeme H. McVerry; A Hybrid Time-Dependent Probabilistic Seismic-Hazard Model for Canterbury, New Zealand. *Seismological Research Letters* 2016 ;; 87 (6): 1311–1318. doi: https://doi.org/10.1785/0220160084

Gerstenberger, M. C., Marzocchi, W., Allen, T., Pagani, M., Adams, J., Danciu, L., et al (2020). Probabilistic seismic hazard analysis at regional and national scales: State of the art and future challenges. Reviews of Geophysics, 58, e2019RG000653. https://doi.org/10.1029/2019RG000653

Grünthal, Gottfried. "The up-dated earthquake catalogue for the German Democratic Republic and adjacent areas-statistical data characteristics and conclusions for hazard assessment." 3rd International Symposium on the Analysis of Seismicity and on Seismic Risk (Prague 1985). 1985

Kamaya, Noriko, Kiyoshi Takeda, and Tetsuo Hashimoto. "New Japanese guidelines for the information of the prospect of seismic activity after large earthquakes and their applications." Journal of Disaster Research 12.6 (2017): 1109-1116.

Knopoff, L., and J. K. Gardner. "Higher seismic activity during local night on the raw worldwide earthquake catalogue." Geophysical Journal International 28.3 (1972): 311-313.

Marzocchi, Warner, Matteo Taroni, and Giuseppe Falcone. "Earthquake forecasting during the complex Amatrice-Norcia seismic sequence." Science Advances 3.9 (2017): e1701239.

Mizrahi L, Shyam Nandan, Stefan Wiemer; The Effect of Declustering on the Size Distribution of Mainshocks. *Seismological Research Letters* 2021;; 92 (4): 2333–2342. doi: https://doi.org/10.1785/0220200231

Ōmori, Fusakichi. On the after-shocks of earthquakes. Vol. 7. The University, 1894.

Reasenberg, Paul. "Second-order moment of central California seismicity, 1969–1982." Journal of Geophysical Research: Solid Earth 90.B7 (1985): 5479-5495.

Uhrhammer, R. A. "Characteristics of northern and central California seismicity." Earthquake Notes 57.1 (1986): 21.

Zaliapin, I., & Ben-Zion, Y. (2020). Earthquake declustering using the nearest-neighbor approach in space-time-magnitude domain. Journal of Geophysical Research: Solid Earth, 125, e2018JB017120. https://doi.org/10.1029/2018JB017120

8. Reviewers' comments

In March 2022, the developments made in this task were presented to two external reviewers, David Marsan and Matt Gerstenberger.

8.1. Comments made by David Marsan

8.1.1. General notes:

- Magnitude should be included in the declustering strategy in order to properly capture the size of the clusters. Additional work is needed in this direction, at the minimum as a test.
- While discussing if the time sequences should look Poissonian or not, Thomas argued that the test of the Poissonian nature of a catalog needs to be tested in the space and time dimension together, but the time sequence doesn't need to be Poissonian if events are far away spatially. So the time sequence needs to be Poissonian locally, but not regionally. David on the other side argued that the time sequence should have Poissonian probabilities as well. In other words, the time sequences should be Poissonian both locally and regionally. More work is needed to better investigate these aspects.
- As for the comment on the Poisson nature of a process: if the events are not independent at small spatial scale, then they are not at any other, larger scale. On the contrary, if they are independent at a given spatial scale L, say, 100 km, then there is no reason to believe they can be dependent at scale > 100km (theoretically speaking this is not true, but why would earthquakes be independent at small scale and then become correlated at larger scale?).

8.1.2. More specific comments

- The developed methodology is similar to the HDB scan presented in Campelo et al 2013.
- The number of aftershocks far away from the mainshock is too large. A second look is needed to see if we observe a $1/r^2$ relationship.
- David offered to share the code for his declustering strategy and for the ETAS-based declustering so they can be use to test the sensibility of the Poissonian test.
- Explain the implantation of the space-time distance between the events in the catalog.
- Plot the time series for the declustered catalog in Italy, both locally and for the whole region
- Use the Kolmogrov Smirnov test to test if the inter-event time is Poissonian.

8.2. Comments made by Matt Gerstenberger

8.2.1. General notes

- Clarify better the context of why using a Poissonian catalog is important in seismic hazard assessment and, in particular, the tradeoff we address between level of Poissoniariety and number of mainshocks left in the catalog.
- Explain better the goal of this study in the framework of the ongoing discussion within the scientific community on using declustered catalogs or not.
- More examples should be included to showcase the sensitivity of the Poissonian test proposed. Some test cases were suggested, including the Canterbury earthquake sequence in New Zealand.

8.2.2. More specific comments

- Add a test on the sensitivity of the proposed Poissonian test to the size of the grid used for the generation of the synthetic catalog. This test needs to be done using several testing regions.
- Testing if the completeness of the catalog has an impact on the result of the declustering would be helpful to understand the limits of the methodology.
- Discuss about the opportunity of adding the declustering as a branch set in the logic tree Reference to the discussions that occurred in the context of the new Italian national model.
- Explain the implantation of the space-time distance between the events in the catalog.

8.3. Evolutions due to the comments of the advisors

Following the comments of the advisors, several tests and modifications were made to the methodology presented in this study.

Tests were performed on the generation of the synthetic catalog used for testing, by changing the grid size used for the generation of the events. It was found that the result of the test is not very sensitive to the grid size until the grid becomes very fine, of the order ot the size of an earthquake cluster.
We also tested the methodology on different earthquakes sequences suggested by the advisors, such as the Canterbury (NZ) sequence of 2010.

The advisors comments helped us to better clarify how the methodology works and to better explain the different steps that are carried on in this approach.

Figure 18: Example of a figure

(To add hyperlink: Click on References tab and add caption – then choose Figure)