

Responses to referee #1

The following document provides detailed responses to the various comments, as well as explanations of how we will implement them in a revised version of the manuscript.

This manuscript explores how the length of the observation time window of earthquake catalogues influences probabilistic seismic hazard assessment (PSHA) results, using a 1-Myr physics-based synthetic catalogue for the Eastern Betic Shear Zone (EBSZ). The topic is timely and relevant for slow-deforming fault systems where historical and instrumental records span only a fraction of the seismic cycle. However, several key methodological aspects require clarification and stronger justification, particularly regarding the characterization and validation of the synthetic seismicity and the transparency of fault parameters used in the simulations, detailed below.

We would like to thank the reviewer for highlighting the topic's interest and relevance, and for their suggestions on how to improve the article's methodology and justification.

Fault parameters and slip rates

The manuscript relies heavily on fault-based modelling, yet essential fault parameters are not explicitly reported. It would be important to:

- Provide slip rates for each active fault included in the EBSZ model, rather than only a system-averaged value.
- Summarize key fault parameters (e.g., fault length, segmentation, coupling assumptions) in a table.

this information would be helpful for readers to validate the physical plausibility of the synthetic seismicity and the resulting hazard estimates.

Author's response (AR): We sincerely thank the reviewer for this constructive comment. We fully agree that explicitly reporting the main fault parameters enhances the physical plausibility of the fault-based model.

In response to this suggestion, we have now incorporated a new table in the revised manuscript summarizing the key parameters of the active faults included in the EBSZ model. The table is based on Herrero-Barbero et al., 2021 and provides the slip rates assigned to each individual fault, as well as relevant geometric parameters. For completeness, we also include the original references from which each dataset was obtained.

Table X: Model input parameters for fault sections in the EBSZ obtained from Herrero-Barbero et al., 2021.

Fault name	Fault section name	Rake	Deviation	Slip rate	Deviation	References
Alhama de Murcia Fault (AMF)	Goñar-Lorca		20 0-40	1.1	0.50-1.70	R from stickenslines measured by Martínez-Díaz (1998). SR based on trenches (Ferrater et al., 2017; Ortuño et al., 2012)
	Lorca-Totana		39 19-59	0.9	0.80-1.00	R from 2011 Lorca eq. (Martínez-Díaz, Bejar-Pizarro, et al., 2012) and structural analysis by Alonso-Henar et al. (2020). SR from trenching and morphotectonic analysis (Ferrater et al., 2016; Ferrater et al., 2017)
	Totana-Alhama de Murcia		42 25-58	0.2	0.07-0.32	Data inferred from AMF-4
	Alhama de Murcia-Alcantarilla		42 25-58	0.2	0.07-0.32	SR and R from cross-section restorations (Herrero-Barbero et al., 2020). Min. SR from Silva et al. (2003).
Carboneras Fault (CF)	Southern Carboneras (offshore)		10 0-20	1.2	1.10-1.30	Data from deflected submarine channels in CF-1 (Moreno, 2011) and onshore fluvial channels in CF-2 (Moreno et al., 2015). Max. SR based on GPS data of Echeverría et al. (2015)
	Northern Carboneras (offshore-onshore)		10 0-20	1.2	1.10-1.30	
Palomares Fault (PF)	Southern Palomares-Arteal Faults	-5 (0)	(-25) - 15	0.04	0.01-0.08	Data measured by Booth-Rea et al. (2004), comparing fluvial deposits and paleochannels in PF-1. R in PF-2 is consistent with the moment tensor of a recent M_w 3.6 event (IGN, 2019)
	Northern Palomares (S ^e Almenara)		15 0-35	0.04	0.01-0.08	
	Northern Palomares-Hinojar Faults		15 0-35	0.1	0.04-0.16	R is inferred from PF-2 and SR is based on comparison between PF-3 and LTF-1
Los Tollos Fault (LTF)	Los Tollos Fault		15 0-35	0.16	0.06-0.25	R and SR obtained through trenching by Insua-Arévalo et al. (2015).
Carrascoy Fault (CAF)	SW Carrascoy-Algezares-Casas Nuevas		90 75-90	0.37	0.29-0.45	R and SR estimated from trenches by Martín-Banda et al. (2016). R is referred to the younger reverse branch (see Table S1).
	NE Carrascoy Fault		15 5-25	0.85	0.50-1.20	Data from structural analysis (Martín-Banda, 2020; Sanz de Galdeano et al., 1998; Silva, 1994).
Bajo Segura Fault (BSF)	Hurchillo		90 70-110	0.4	0.29-0.51(0.6)	SR estimations from Alfaro et al. (2012) using stratigraphic markers and assuming pure reverse. Note that GPS data from Borque et al. (2019) show 0.6 ± 0.2 mm/yr of shortening for the entire BSF zone
	Benejúzar		90 70-110	0.27	0.20-0.34	
	Guardamar		90 70-110	0.2	0.15-0.25	
	Bajo Segura Offshore		90 70-110	0.2	0.15-0.25	For R, see seismic profiles from Alfaro et al. (2012) and Perea et al. (2012). SR is inferred from BSF-3

Validation of the synthetic seismicity

The manuscript states that the synthetic catalogue reproduces the main features of observed seismicity, but quantitative validation is limited. How is the credibility of the RSQSim outcomes validated beyond qualitative agreement? Are synthetic and historical catalogues statistically comparable in terms of rates, magnitude distributions, and moment release? The cumulative seismic moment analysis is useful but should be more clearly integrated into the validation framework rather than presented mainly as a discussion element.

AR: Among the physics-based earthquake simulators used to model the long-term evolution of fault systems during several seismic cycles, RSQSim has proven to be computationally efficient and capable of replicating historical seismicity patterns in complex tectonic environments such as New Zealand, California, Taiwan, and most importantly for our case, Spain (Shaw et al., 2018; Herrero-Barbero et al., 2021; Shaw et al., 2022; Chia-Cheng and Hung-Yu, 2024). Our catalogue as is mentioned in the text is generated by the Herrero-Barbero et al. (2021) model, and details on its validation and use can be found in Herrero-Barbero et al. (2021), Álvarez-Gómez et al. (2023), Herrero-Barbero et al. (2023) and Gómez-Novell et al. (2024). The validation of this model is done using empirical relations of magnitude - rupture dimensions, the magnitude frequency distribution as well as historical and paleoseismological observations. Additionally, a recent work in NZ tested the results of RSQSim simulations into PSHA comparing them with the NZ NSHM 2010, and finding a consistency and good correlation between them (Niroula et al., 2025). The scope of our work is not to validate the RSQSim model (which has been already validated in previous works) but to explore the aleatory uncertainties and variability linked to the observation window into PSHA.

We agree with the reviewer that maybe this explanation on the validation of this kind of model is not made clear in the text. We will add the above explanation to the “Materials and Methods” section.

Maximum magnitude

- The procedure used to calculate M_{max} (average between geological and catalogue-based values) should be explained more clearly and justified.
- The frequent occurrence of $M \geq 7.2-7.4$ events in the synthetic catalogues appears high. How does this compare with the observed catalogue (i.e., how many such events are historically documented)?
- Table 1 suggests that only one adjacent seismogenic area allows $M \geq 7.3$ even considering uncertainty, which appears inconsistent with the synthetic results.

AR: The presence of large $MW > 7.0$ events in our simulated earthquake catalog contrasts with the absence of these large magnitudes in the region's historical catalog. This is likely due to the short observation window in the historical data and the variability in the duration of seismic cycles. This problem is especially significant in low-strain zones, where seismic catalogs record only a small fraction of fault seismic cycles. However, paleoseismological data show evidence observed in the EBSZ that could be related to $MW > 7$ events (Moreno et al., 2016; Martín-Banda, 2020).

Accessibility of key references

Several critical methodological choices (e.g., ZESIS parameters, M_{max} estimation, declustering rules) rely on references written only in Spanish.

- Given that these references underpin essential tables and assumptions, key information should be summarized explicitly in the manuscript for an international audience.
- This is particularly important for Table 1, which contains crucial parameters for the hazard assessment.

AR: We understand the reviewer's concerns regarding the fact that some critical information comes from sources written in Spanish, namely the procedure followed to produce the Spanish National Seismic Hazard Maps (IGN & UPM, 2013) and the ZESIS database (García-Mayordomo et al., 2012c; IGME, 2015; García-Mayordomo, 2015). Thanks to the reviewer's comment, we have also realized that both sources were not properly referenced in the manuscript, as their free online access links were missing. Including these links is certainly the most straightforward way for readers to explore the data further. We also believe that Spanish-language documents can be easily understood through appropriate translation tools. In addition, we have now added a reference (García-Mayordomo et al., 2012c) that includes an English-language summary.

Following the reviewer's advice, we have incorporated additional information on the ZESIS zone parameters (Table 1) and on the estimation of M_{max} . We consider that the declustering process is sufficiently described in the text (lines 140–154), where the equations used in the procedure are also detailed.

In the revised version of the manuscript, new text will be included starting at line 163, which will read:

[...] *The seismic parameters of the seismogenic zones adjacent to the EBSZ zone are also required for the model. These data have been adopted from the ZESIS database (Table 1). These parameters were obtained for the ZESIS zones within the framework of the National Seismic Hazard Map project, following a process of declustering and magnitude homogenization of the earthquake catalogue (IGN & UPM, 2013). In that work, different zoning models and procedures for calculating the Gutenberg–Richter parameters were tested and eventually incorporated into the hazard calculations through a logic-tree approach. The maximum magnitude parameter was modelled using a normal probability distribution. The mean maximum magnitude and its standard deviation were derived for each zone based on criteria that balanced the available information on the presence and size of active faults and the magnitude of the largest historical events. Active fault parameters were obtained from the QAFI database (IGME, 2022), which at that time was version 2. Several procedures were evaluated to convert fault-size parameters into moment magnitude using empirical relationships from the literature (IGN & UPM, 2013). Table 1 shows the values referenced for the ZESIS model (IGME, 2015), which we adopt here.*

The caption of Table 1 will now read:

Table 1. Seismic parameters of the seismogenic zones adjacent to the EBSZ zone: β represents the slope of the Gutenberg–Richter relationship; τ (4.0) is the annual rate of earthquakes with magnitude $M_w \geq 4.0$; and MM is the mean maximum magnitude with its standard deviation (σ_{MM}) (after IGN & UPM, 2013; IGME, 2015).

The updated references to the National Seismic Hazard Map and the ZESIS database will now read as follows:

Instituto Geográfico Nacional (IGN) - Universidad Politécnica de Madrid (UPM): Actualización de Mapas de Peligrosidad Sísmica de España 2012. Centro Nacional de Información Geográfica, Madrid, 267 pp., 2013. Free download: <https://www.ign.es/web/libros-digitales/peligrosidad-sismica2012>

Instituto Geológico y Minero de España (IGME): ZESIS: Base de Datos de Zonas Sismogénicas de la Península Ibérica y territorios de influencia para el cálculo de la peligrosidad sísmica en España, 2015. Online Access: <https://info.igme.es/zesis> User's Guide: https://info.igme.es/zesis/docs/Guia-usuario-ZESIS_20150421.pdf

García-Mayordomo, J.: Creación de un modelo de zonas sismogénicas para el cálculo del mapa de peligrosidad sísmica de España. Publicaciones del Instituto Geológico y Minero de España, Serie Riesgos Geológicos/Geotecnia Nº 5, Madrid, 125 pp., 2015. Free download: https://web.igme.es/publicaciones/Home/Publicaciones_Gratuitas

García-Mayordomo, J., Martínez-Díaz, J.J., Capote, R., Martín-Banda, R., Insua-Arévalo, J.M., Álvarez-Gómez, J.A., Perea, H., González, Á., Lafuente, P., Martín-González, F., Pérez-López, R., Rodríguez-Pascua, M.A., Giner-Robles, J., Azañón, J.M., Masana, E., Moreno, X., Benito, B., Rivas, A., Gaspar-Escribano, J.M., Cabañas, L., Vilanova, S., Fonseca, J., Nemser, E. and Baize, S.: Modelo de zonas sismogénicas para el cálculo de la peligrosidad sísmica en España. VII Asamblea Hispano Portuguesa de Geodesia y Geofísica, San Sebastián (Spain), June 23rd to 28th, 2012c, DOI: 10.13140/RG.2.1.4536.5608

Another reference for the QAFI database will be added:

Instituto Geológico y Minero de España (IGME): QAFI: Quaternary Active Faults Database of Iberia, 2022. Online Access: <https://info.igme.es/QAFI>

Interpretation of higher hazard from synthetic catalogues

The manuscript concludes that synthetic catalogues lead to systematically higher hazard than historical or ZESIS-based assessments. This interpretation should be refined. That is, historical catalogues do not necessarily always underestimate hazard; sampling a rare large event from a long-recurrence fault could also lead to overestimation. Alternative explanations should be discussed more explicitly, including catalogue incompleteness, overestimated slip rates or coupling in the synthetic model, and the absence of secondary faults or aseismic deformation.

AR: We understand the reviewer's concern that calculating hazard from a historical catalogue does not necessarily lead to higher hazard results, and we fully agree. In the paper, we state that this is what we observe in our particular case study, and that a major reason for it is the fact that, because we are sampling 1-kyr-long sub-catalogues in a slow-moving fault region with long seismic cycles, there is a significant chance of extracting catalogues that capture larger magnitudes ($M > 5.5$) and higher activity rates than those present in the available historical catalogue. As a consequence, using synthetic seismicity catalogues yields higher hazard values compared to the historical one.

Of course, we do not claim that this result can be straightforwardly extrapolated to every slow-moving fault region worldwide. As the reviewer points out, in some areas the historical record may indeed include a large event (e.g., central Australia), which could lead to somewhat overestimated hazard results.

To clarify this point, in the revised version of the manuscript we are adding a new figure (Figure X) comparing the cumulative rates of the synthetic and historical catalogues.

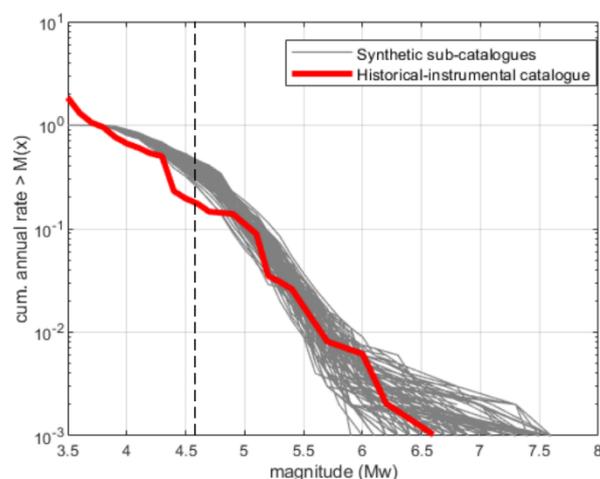


Figure X. Frequency magnitude distribution for the 100 synthetic catalogues (grey lines) and the historical-instrumental catalogue (red line). The dashed line represents the magnitude of completeness for the full length of synthetic catalogues according to Herrero-Barbero et

al., 2021. The magnitude of completeness for the historical-instrumental catalogue is M_w 3.5 (IGN-UPM, 2013).

Additionally, we will modify line 38 at the beginning of Section 6 (Conclusions), which will now read:

When the source model characterization relies entirely on the historical earthquake catalogue, the incompleteness of the data becomes a major limitation, as fault seismic cycles are usually longer.

Finally, following the reviewer's suggestions, the last line of the paper (line 355) will now read:

To better understand the models and their impact on seismic hazard, further investigations should focus on issues such as fault segmentation, structural development, frictional properties, and degree of coupling (aseismic deformation and secondary faulting).

Epistemic uncertainty

The manuscript states that epistemic uncertainties are common to all synthetic sub-catalogues, but fixing epistemic uncertainty does not eliminate it. The authors should clarify how epistemic uncertainties related to fault geometry, slip rates, coupling, and GMPE selection are treated, and how they differ from variability associated with the observation time window.

AR: As our work specifically addresses the variability associated with the observation time window, we have deemed it necessary not to address other epistemic uncertainties. Some of those mentioned by the reviewer are discussed in the work of Herrero-Barbero et al. (2021), from which we used the synthetic seismic catalogue. Similarly, discussing the impact of GMPEs on the results is a topic that is beyond the scope of this work, for which there is extensive literature and various approaches for their integration into PSHA.

The first paragraph of the discussion can be a little confusing regarding this matter and will be reworded:

The main objective of this work is to examine the variability between subcatalogs with analogous characteristics derived from a single synthetic catalog. This approach ensures that the epistemic uncertainties associated with their generation are common to all subcatalogs, making the differences observed in their comparison independent of those uncertainties. Since our study focuses specifically on the variability introduced by the observation time window, we have deliberately decided not to address other sources of epistemic uncertainty. These uncertainties have been previously explored in Herrero-Barbero et al. (2021), from which the synthetic seismic catalog used here originates.

Thus, I suggest this manuscript can be published after a major revision.