Responses to Reviewer #2 – June 2026

We thank the anonymous reviewer for their careful reading of the manuscript and their constructive and insightful comments. Below, we address each comment in detail.

RC2–1: The manuscript outlines limitations of catalogue-based PSHA and proposes a framework for handling uncertainties. However, it remains unclear what new scientific insight has been gained. Structuring uncertainty is a useful step, but on its own it does not constitute a substantial scientific contribution unless it leads to: a measurable reduction in uncertainty, or new physical constraints on fault behavior or rupture processes. At present, the manuscript does not convincingly demonstrate either.

The authors should explicitly state what new understanding of seismic hazard in the Southern Apennines emerges from this study. In particular: Does the proposed approach reduce epistemic uncertainty in hazard estimates? Does it provide new constraints on fault interaction, rupture segmentation, or multi-fault behavior? Without such clarification, the contribution remains largely methodological.

Author's response (**AR**): The primary objective of this work is not to reduce epistemic uncertainty, but rather to identify, explore, and structure the main sources of uncertainty affecting fault-based PSHA in the southern Apennines. In this sense, our contribution is to determine which assumptions dominate the uncertainty of the results and which modelling choices have the strongest impact on seismic hazard estimates. Identifying and ranking the most influential sources of uncertainty is, in our view, a fundamental step in probabilistic seismic hazard assessment. The work is grounded in the core of PSHA frameworks, where the goal is not necessarily to eliminate epistemic uncertainty but to explicitly represent alternative scientifically plausible hypotheses and evaluate their consequences.

Aside from this, the scientific contribution of our study is not limited to the methodological implementation of a modelling tool. To our knowledge, this work also represents the first application of a fault-system approach with relaxed segmentation assumptions in the southern Apennines, providing a regional-scale framework to evaluate the influence of alternative rupture hypotheses on seismicity rates and seismic hazard estimates. Within this framework, our analyses show that (i) rupture assumptions strongly control the model outcomes, (ii) some rupture configurations perform better than others when evaluated against independent seismological and geological observations via consistency tests, (iii) background seismicity assumptions have a smaller influence than fault connectivity assumptions, as well as the choice of scaling relationships and *b*-values, and (iv) different subareas exhibit markedly different levels of constraint, highlighting how variations in fault characterization and geological constraints can strongly influence the robustness of fault-based PSHA results.

We believe these outcomes are of interest to researchers working in regions characterized by low-to-moderate seismic activity. Particularly, by identifying the parameters that mostly influence the model outcomes, we can help establishing priority targets for future studies in the region. In the southern Apennines, one of the clearest findings and, therefore, one clear priority target is determining fault rupture behavior and interactions throughout the system.

RC2–2: The authors acknowledge that the model does not explicitly evaluate rupture compatibility. This is an important limitation that requires more careful treatment. In seismic hazard analysis, statistical consistency alone is not sufficient to establish the feasibility of rupture scenarios. Large-magnitude scenarios (e.g., Mw 7.6) must also be evaluated in terms of: known fault geometries, segmentation patterns, mechanical constraints on rupture propagation. The revised manuscript should include a more rigorous discussion of the physical plausibility of the modeled scenarios. Specifically: Are the proposed multi-fault ruptures mechanically feasible given the regional tectonic framework? What are the structural or geodynamic constraints that would support or limit such events? A clearer distinction between statistical compatibility and physical feasibility is essential.

AR: First, we would like to clarify that the objective of this study is not to mechanically validate individual rupture scenarios, but rather to evaluate which levels of rupture complexity are consistent with the available geological and seismological observations and should therefore be considered within a fault-based PSHA framework. In this sense, there is an important distinction between simply generating rupture sets and evaluating which classes of rupture complexity are required to reconcile independent observations in the southern Apennines.

We developed a range of rupture scenarios, including deliberately extreme and exploratory configurations, to investigate how different fault-system rupture scenarios affect the earthquake rates. As such, we did not perform detailed physics-based plausibility analyses to define earthquake rupture scenarios, as this falls outside the scope of this study. By evaluating the consistency of these scenarios with observational data and from a statistical point of view, we can say that we cannot reject the occurrence of large multi-fault ruptures in the southern Apennines. In this sense, our study provides different extreme-case realizations of earthquake rupture occurrences in the region, whose detailed physical plausibility should be investigated in future works.

Furthermore, while SHERIFS does not constitute a physics-based dynamic rupture model and therefore cannot mechanically validate rupture propagation, the explored rupture scenarios are not arbitrarily generated. Their definition is constrained by geological and seismotectonic criteria commonly adopted in fault-based PSHA studies, including fault geometry, segmentation patterns, rupture jump distances, geometrical continuity, kinematic compatibility, seismogenic depth, which we discussed in detail in the section 2.2.2 ("Segmentation rules and rupture scenarios"). We adopted the rupture jump distance as the primary plausibility criterion to define earthquake rupture scenarios. Such distance is one of the primary controls on earthquake rupture propagation and is widely used in PSHA literature and the values we explored are based on earthquake statistics across the world. This means that, despite being exploratory scenarios, they are backed up by observations on earthquakes. In addition, the fault geometries and associated fault parameters used in our study are derived primarily from the DISS database, which represents a community-agreed fault database and has been employed in large-scale and extensively validated hazard models such as ESHM20 (Danciu et al., 2024).

RC2–4: The manuscript attributes the poor performance in SubArea 2 to poorly constrained fault parameters and heterogeneity in available data. While this is a valid observation, it raises concerns regarding the role of this subarea in the overall analysis. If the input data for SubArea 2 are insufficiently constrained, its inclusion in a comparative framework may affect the robustness of the broader conclusions.

The authors should justify the inclusion of SubArea 2 more explicitly. In particular: What is the scientific value of including this subarea despite its limitations? Does it influence the conclusions drawn for better-constrained regions (e.g., SubArea 1)? A sensitivity analysis demonstrating that uncertainties from SubArea 2 do not bias the overall results would significantly strengthen the manuscript.

AR: We do not consider the inclusion of SubArea 2 as a weakness of the modelling framework, but rather as an important result of the analysis itself. The objective of fault-based PSHA is not to operate exclusively in ideal conditions or in regions where geological constraints are equally robust. Excluding SubArea 2 would remove an important part of the regional seismotectonic context and would provide an artificially simplified picture of the capabilities and limitations of the modelling framework.

One clear reason for retaining SubArea 2 is that these faults exist, they are characterized (at least sufficiently to be included in the European model ESHM20) and, as such, they are contributing to the hazard in the zone. Interestingly, neither the current fault model (as represented in DISS) nor the wide range of rupture configurations explored in this study, are able to reproduce the catalogue observations. The post-modelling inconsistency with the catalogue is what led us to suspect that the available geological constraints in this sector may be incomplete or insufficiently constrained (e.g., underestimated slip rates or missing fault information). For this reason, we consider the inclusion of SubArea 2 scientifically valuable. Its behaviour provides insight into where fault characterization remains insufficient and highlights the limitations that poorly constrained geological inputs may impose on fault-based PSHA. In this sense, the poorer performance of SubArea 2 is itself an important result, as it identifies priorities for future geological and seismotectonic investigations.

Importantly, the conclusions drawn for SubArea 1 are not dependent on the performance of SubArea 2. The main findings regarding rupture assumptions, fault connectivity, and model performance remain stable within the better-constrained sector. In this sense, the comparison between the two subareas is itself informative, as it reveals spatial heterogeneity in the quality of the available geological constraints and in the associated epistemic uncertainty.

RC2–5: The addition of figures illustrating buffer sensitivity is a positive step. However, the choice of a 10 km buffer remains primarily based on expert judgment. Given the importance of spatial parameters in fault-based hazard models, a more quantitative justification is needed. The authors should provide a quantitative basis for the selected buffer distance, for example: regional hypocentral location uncertainties, fault dip variability and projection uncertainties, and comparison with independently derived structural constraints. This would improve both the transparency and reproducibility of the methodology.

AR: To provide a quantitative basis for this choice, we analysed the epicentral uncertainty distribution reported in the reference catalogue (CPTI15 v4.0; Rovida et al., 2022). The mean epicentral uncertainty is approximately 5 km, while the 84th percentile of the distribution is around 8 km, approximately corresponding to a one-standard-deviation confidence level. Therefore, a 10 km buffer can be considered a conservative threshold that encompasses the uncertainty associated with the large majority of the macroseismic events that populate the catalogue, particularly moderate-to-large earthquakes. Moreover, the selected value of 10 km is consistent with previous fault-based PSHA applications and SHERIFS-based studies, where similar approaches have been adopted to associate background seismicity with mapped fault systems (e.g., Chartier et al., 2017).

The main purpose of the sensitivity analysis presented in this study is precisely to evaluate the influence of the background-seismicity treatment on the model outcomes. The results show that varying the buffer distance (5–10–15 km) produces only minor changes in the resulting MFDs and that the choice of a 10 km buffer produces the best fit to the observed data. More importantly, the results remain very similar across the tested buffer distances and differ only slightly from those obtained when background seismicity is not considered at all. For example, El Kadri et al. (2025) chose not to explicitly include background seismicity, reaching a conclusion that is remarkably similar to that obtained in this study.

For this reason, given the limited sensitivity of the results to the tested buffer distances and the comparatively smaller influence of background-seismicity assumptions on the final model, we believe that the selected 10 km buffer represents a reasonable and robust choice within the explored range of uncertainty. Additional analyses based on alternative criteria would likely refine the justification of the selected value but would not materially affect the conclusions of the study.

Other comments from the reviewer: In its current form, the study appears to focus primarily on structuring epistemic uncertainties within a modeling framework, rather than reducing or constraining these uncertainties through physical or tectonic insight. As a result, the manuscript reads more as a methodological application (or software-oriented validation exercise) than as a contribution that significantly advances our understanding of seismic hazard in the Southern Apennines. However, in its current form, it does not yet provide a clear and demonstrable advance in seismic hazard understanding.

AR: We agree that a major component of this work consists of identifying, structuring, and exploring epistemic uncertainties within a fault-based PSHA framework. However, we think our work goes beyond a purely methodological or software-oriented exercise. Understanding which assumptions dominate the uncertainty, which modelling choices exert the strongest influence on the results, and which aspects of the fault system require further investigation constitutes an important scientific contribution, particularly in regions where fault-based seismic hazard models have not previously been developed.

The primary objective of the study is not to determine how faults in the southern Apennines physically rupture, nor to reduce epistemic uncertainty. Rather, it is to construct the first fault-system model for this region and to systematically explore the principal sources of uncertainty that should be considered in a future fault-based PSHA framework. Such an approximation is the core of current PSHA applications, where models represent not only the best available science in a region (method- and data-wise), but also all the conceivable uncertainties in such datasets and modelling assumptions. This objective is fully consistent with the philosophy and intended scope of SHERIFS applications, which are designed to evaluate alternative rupture hypotheses and their implications for seismic hazard rather than to mechanically validate rupture processes.

Within this framework, the study provides several seismotectonic insights. Our results indicate that single-fault assumptions are systematically less consistent with observations when compared to more complex rupture models, that rupture complexity exerts a strong control on seismicity rates and hazard estimates. Importantly, the observed importance of rupture complexity is consistent with evidence provided by the 1980 Irpinia earthquake, suggesting that similar behaviour cannot be neglected in long-term earthquake rupture forecasts for the Southern Apennines.

The study also highlights the strong influence of geological data quality on model robustness, as demonstrated by the contrasting behaviour of the investigated subareas. In this sense, the work not only explores uncertainty but also identifies which sources of uncertainty are most influential and where future efforts in fault characterization should be prioritized.

References:

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Response to Editor – June 2026

Comment from the editor: […] strengthen the discussion regarding the regional seismic hazard significance of your findings.

AR: Our work represents, to our knowledge, the first application of a fault-system approach with relaxed segmentation assumptions in the southern Apennines, and its primary objective is to identify, explore, and structure the main sources of uncertainty affecting fault-based PSHA in the southern Apennines. In this sense, our contribution is to determine which sources of uncertainty dominate the results and which modelling choices have the strongest impact on seismic hazard estimates. The results provide new insights into the role of rupture complexity in the southern Apennines fault system. In particular, our analyses show that (i) rupture assumptions strongly control the model outcomes, (ii) some rupture configurations are more consistent than others when evaluated against independent seismological and geological observations, (iii) background seismicity assumptions have a smaller influence than fault connectivity assumptions, as well as the choice of scaling relationships and b-values, and (iv) different subareas exhibit markedly different overall consistency with data, highlighting the critical role of fault-model assumptions and geological data constraints for fault-based PSHA.

Following the suggestions provided by the editor and the reviewer, we have strengthened the discussion of the regional seismic hazard significance of our findings throughout the manuscript. In particular, we expanded the introduction to include the suggested references, revised Sect. 4.1 and 4.2 to better discuss the implications of rupture complexity and fault characterization and geological constraints for seismic hazard assessment in the southern Apennines, and clarified the scientific contribution and regional seismic-hazard significance of our results in the Conclusions.