RESPONSE TO REVIEWER 1

We thank the reviewer for the constructive comments and suggestions, which have helped to improve the quality and clarity of the manuscript. Below, we provide a point-by-point response to each comment. In the following pages, text in italics indicates our responses to the reviewer, while changes and modifications made to the manuscript are indicated in quotation marks and in red.

1. Major comments

The manuscript frequently claims that the proposed framework is particularly suitable for large, spatially heterogeneous regions such as the Valencian Community, yet it does not clearly explain why such regions are challenging for landslide risk assessment or how the proposed methodology addresses those challenges. Large and heterogeneous areas are typically characterized by strong geological and geomorphological variability, uneven spatial distribution of landslide inventories, inconsistent resolution of socioeconomic data, and mismatch between geological and administrative boundaries - all of which can undermine comparability and accuracy of regional risk models. The authors should explicitly discuss these challenges and clarify how the RQI, RSI, and mRQI frameworks overcome them, for instance by integrating multi-source datasets, applying normalization to reduce bias among different scales, coupling physical and socioeconomic factors across scales, and using dynamic indicators to capture temporal evolution of risk. Expanding this discussion would convincingly demonstrate the framework's innovation and justify its claimed applicability to spatially dispersed regions.

We thank the reviewer for this insightful comment. In response, we have revised the manuscript to explicitly explain why large, spatially heterogeneous regions pose specific challenges for landslide risk assessment and to clarify how the proposed framework addresses these challenges.

First, we have expanded the methodological section by adding a new subsection (Section 2.3) that explicitly discusses the main sources of heterogeneity affecting regional-scale landslide risk assessment, including geological and geomorphological variability, uneven spatial coverage of landslide inventories, differences in spatial resolution among datasets, and mismatches between physical processes and administrative boundaries. This section clarifies how the proposed framework integrates multi-source datasets within a coherent spatial reference system and applies normalization procedures to ensure comparability across scales.

Second, the description of the study area (Section 3.1) has been revised to better emphasize the spatial, geomorphological, and socio-economic diversity of the Valencian Community, as well as the historical patterns of dispersed and fragmented urban development that complicate exposure and risk assessment at the regional scale.

Finally, the Conclusions (Section 7) have been reinforced to explicitly highlight the suitability of the proposed framework for large and heterogeneous regions, emphasizing the role of dimensionless risk indices and dynamic trend indicators (mRQI, mRSI) in capturing both spatial contrasts and temporal evolution of landslide risk.

These revisions collectively strengthen the methodological justification of the framework and more clearly demonstrate its applicability to large, spatially dispersed regions, as suggested by the reviewer.

To begin with, we have added a new Section 2.3 explicitly addressing these challenges

"*2.3. Considerations on data sources and regional heterogeneity*

Large and spatially heterogeneous territories, such as the Valencian Community, pose significant challenges for landslide risk assessment due to pronounced geological and land-use variability, uneven and incomplete spatial coverage of landslide inventories, and differences in the spatial resolution of available datasets. In addition, the lack of correspondence between physical variables and the administrative units used in socioeconomic datasets can hinder data aggregation and limit the comparability of risk estimates across scales.

To address these limitations, the proposed methodological framework integrates multi-source datasets within a consistent spatial reference system and applies normalization procedures to ensure that indicators derived from different units and spatial resolutions are directly comparable. Landslide susceptibility maps incorporate geological variables, digital elevation models (DEMs), and land-use information, which are combined through weighted coefficients derived from multicriteria evaluation methods. Risk calculation is further supported by the use of residential building economic value as a proxy for exposed wealth.

The methodological design also explicitly addresses regional heterogeneity by linking the risk surface index (RSI, representing the extent of built-up areas under risk) with the risk quality index (RQI, representing risk intensity) within the global risk index (RI). This coupling allows the framework to capture spatial contrasts between mountainous areas prone to landslides and densely built residential zones, ensuring a coherent representation of risk across the entire territory. In addition, the temporal trend indicator of risk quality (mRQI) provides a dynamic measure of changes in exposure and vulnerability, preserving both the magnitude and direction of change through normalization to a –1 to +1 scale.

Although the present implementation focuses on the Valencian Community as a case study, the proposed framework is designed to address challenges inherent to large and heterogeneous regions. Future applications may further refine this approach through the systematic incorporation of additional normalized variables and extended temporal series, enhancing its transferability and robustness in diverse territorial contexts."

In the Section 3.1 (Study Area), we have modified the last paragraph (lines 330-337) by:

"The Valencian Community is not only extensive but also highly heterogeneous, comprising coastal metropolitan areas, intermediate zones, and mountainous inland regions with distinct geomorphology, land-use patterns, and socio-economic dynamics (Gielen et al., 2018). This diversity poses a major challenge for landslide risk assessment because susceptibility factors, exposure, and vulnerability vary significantly across municipalities. Furthermore, urban development has historically followed a dispersed and discontinuous pattern (Gielen et al., 2018), particularly in coastal and peri-urban areas, which increases the complexity of mapping exposure and evaluating risk. These characteristics require a methodology capable of integrating detailed cadastral data and susceptibility mapping at a fine spatial scale, ensuring comparability across such a fragmented territory.

Although urban development in the region is partially regulated by the Land Use Planning and Landscape Protection Law (LOTPP, 2021), whose article 15 defines the Territorial Strategy of the Valencian Community (ETCV) as the instrument for territorial planning, this framework was introduced relatively late. Its aim is to limit the spread of mass tourism, which expanded throughout Spain after 1970 (Galiana Martín and Barrado Timón, 2006). This trend has been particularly intense in the Valencian coastal zones, reaching its maximum expression along the northern coast of Alicante. As a result, these territories have experienced significant urban expansion (Gielen et al., 2018), often without *adequately considering the impact of natural hazards—further reinforcing the need for a risk assessment approach adapted to large, spatially heterogeneous regions."*

In section 7 (Conclusions), the first paragraph (587-595 lines) has been replaced by:

"The proposed framework demonstrates its suitability for large, spatially heterogeneous regions by addressing two critical issues: territorial diversity and fragmented urbanization. As highlighted by Gielen et al. (2018), the Valencian Community has experienced significant urban sprawl, resulting in scattered residential areas often located in zones with varying hazard levels. By incorporating high-resolution cadastral data and defining dimensionless indices (RI, RSI, RQI) together with trend indicators (mRQI, mRSI), our approach enables consistent evaluation of both the magnitude and quality of risk across municipalities, in contrast to traditional approaches that rely on regional averages and assume territorial homogeneity. Particularly noteworthy is the trend value of the quality index (mRQI), which defines the evolution of high risk in a given local entity and, when increasing, calls for reflection on territorial management practices. In other words, mRQI indicates the adequacy of municipal construction dynamics, highlighting potential progressive occupation of unsuitable land for residential housing in high-risk zones."

As a final point, regarding the normalization of the risk indices, we would like to clarify that RSI and RQI are already defined as dimensionless indicators within the 0–1 range. Following the reviewer's suggestion, we have therefore revised the only indicator that originally lay outside this range, namely the mRQI. This index is now expressed using a consistent, dimensionless normalization.

Accordingly, the mRQI values reported in Table 9 have been normalized to the 0–1 range, improving their interpretability and facilitating direct comparison across municipalities and time periods, without altering the relative trends captured by the index.

Table 9. Quantile values for index thresholds, with mRQI expressed in normalized values.

	Castellón			Valencia			Alicante		
Quantil	**RSI**	**RQI**	**mRQI**	**RSI**	**RQI**	**mRQI**	**RSI**	**RQI**	**mRQI**
Q90	0,91	1,10	0,23	0,65	0,58	0,16	0,68	0,46	0,23
Q60	0,35	0,36	0,00	0,19	0,29	0,00	0,31	0,24	0,02
Q40	0,15	0,21	-0,01	0,10	0,19	-0,02	0,15	0,16	-0,02
Q20	0,06	0,11	-0,15	0,04	0,09	-0,09	0,08	0,08	-0,08

2. Minor comments

1. The methodological innovation of the RQI, RSI, and mRQI indices relative to existing risk assessment frameworks should be stated more clearly. A concise comparison with earlier studies (e.g., Guzzetti et al., 2005; Pereira et al., 2020; Segoni & Caleca, 2021) would help readers understand the conceptual advancement of this work.

[New reference: Guzzetti, F.; Reichenbach, P.; Cardinali, M.; Galli, M.; Ardizzone, F. (2005). Probabilistic landslide hazard assessment at the basin scale. Geomorphology, 72(1-4), 272-299. DOI:10.1016/j.geomorph.2005.06.002.]

We thank the reviewer for this helpful suggestion. Following this comment, we have incorporated the work of Guzzetti et al. (2005) and strengthened the description of the methodological innovation of the proposed indices (RQI, RSI, mRQI, and mRSI) relative to previous landslide risk assessment frameworks.

In the revised manuscript, the introductory paragraph of Section 2.2 ("Risk indices and qualifiers") has been modified to explicitly compare the proposed approach with earlier studies, including Guzzetti et al. (2005), Pereira et al. (2020), and Segoni and Caleca (2021). This comparison highlights the main conceptual advances of our framework, particularly the explicit decomposition of risk components, the use of dimensionless and comparable indices, and the incorporation of a temporal dimension through trend indicators.

These revisions clarify how the proposed indices build upon and extend existing methodologies, and more clearly position the contribution of this work within the current landslide risk assessment literature.

In this way, the methodological innovation of the proposed indices is now presented in a clearer and more comparative manner. The text replaced the existing paragraph (lines 180 to 188) at the beginning of Section 2.2. is as follows:

"Compared with previous methodologies, the risk indices proposed in this study incorporate several conceptual and technical innovations that enable a more flexible, reproducible, and comparative assessment of landslide risk at regional scale. In this framework, all residential buildings are considered at the Dwelling Unit (DU) level, together with their reconstruction value (DV) and susceptibility level (L_m), allowing for a more detailed quantification of risk and the analysis of its temporal evolution.

Unlike the static probabilistic hazard-focused approach proposed by Guzzetti et al. (2005), which was applied at the basin scale, the indices introduced here explicitly integrate a spatiotemporal perspective, enabling the assessment of risk evolution over an extended historical period (1950–2021).

Pereira et al. (2020) developed a Landslide Risk Index (LRI) at the municipal scale for the entire Portuguese territory by combining susceptibility and exposure factors through fixed empirical weights and applying a normalization procedure to facilitate inter-municipal comparison. While this approach allows spatial comparison, it does not explicitly address the temporal dynamics of risk.

Similarly, Segoni and Caleca (2021) proposed aggregated indicators of landslide risk (ALR and TLR) at the national scale for Italy by combining susceptibility and land consumption data. Their approach focuses on spatial aggregation for a single reference year and does not incorporate temporal trends or building-level economic exposure.

In contrast, the present framework decomposes landslide risk into complementary quantity (RSI) and quality (RQI) components and introduces trend indicators (mRQI, mRSI) that capture the direction and magnitude of temporal change. This design enables consistent spatial and temporal comparison across heterogeneous administrative units and represents a key methodological advancement over existing large-scale landslide risk assessment approaches."

2. The relationships and calculation logic of the indices-particularly the variables Gaj, Faj, LM, and DV-need clearer description. Including a schematic diagram summarizing index derivation, weighting, and normalization would enhance transparency and reproducibility.

We thank the reviewer for pointing out the need to clarify the relationships and calculation logic of the indices. In response, we have revised the manuscript to provide clearer and more explicit definitions of the variables Faj, Gaj, LM, and DV at their first occurrence in the text.

Specifically, the following clarifications have been incorporated:

*• **Faj (adjustment factor)** accounts for the proportion of susceptible area that effectively affects inhabited zones. It is defined as the ratio between the area susceptible to landslides impacting populated areas and the total susceptible area within a given territory. Its value ranges between 0 and 1, and a representative average value of 0.2 was adopted based on the observed relationship between these surfaces.*
*• **Gaj (adjustment factor)** reflects the size or volume of the displaced material associated with the inventoried landslides and also ranges between 0 and 1. In the present case study, this factor was ultimately not applied, as the landslides considered exhibit similar magnitudes and volumes, making additional weighting unnecessary.*
*• **DV (Dwelling Unit Value)** represents the reconstruction cost of residential buildings, expressed in economic units per unit of built surface area (€/m²). The values used in this study were derived from recognized real estate agencies and are directly interpretable, and therefore were not subject to normalization.*
*• **LM (Landslide Magnitude)** expresses the intensity of the landslide in terms of size and impact energy and is commonly used in vulnerability assessments. Given the relatively homogeneous characteristics of shallow landslides in the study area, a single fixed value of LM = 0.6 was assumed on a heuristic scale ranging from 0 to 1, following Silva and Pereira (2014) and Cantarino (2021).*

These revised definitions have been explicitly included in the manuscript at the lines where each variable is first introduced (Lines 147, 152, 163, and 169), improving the transparency and reproducibility of the index calculations.

Line 147 – "The adjustment factor (Faj) accounts for whether the event occurs in an inhabited area, derived from the ratio between the area susceptible to landslides affecting populated areas and the total susceptible area."

Line 152 – "This annual probability (Pa) must be adjusted using the factor Gaj, which reflects the volume of the displaced material in the inventoried landslides."

Line 163 – "In addition, a property valuation can be used to calculate the reconstruction cost of the dwelling, or Dwelling Unit Value (DV), expressed in economic units per unit of surface area, must also be considered."

Line 169 – "Vulnerability is a function of the magnitude or intensity of the landslide (Landslide Magnitude, LM) in energy and size terms. Depends on the resistance capacity of the affected element, which is closely related to building height."

The values of these indices did not need to be weighted as they are directly applicable. Furthermore, their very definition includes a normalised variation, excluding DV. However, DV is a recognised value that is easy to interpret and, in our opinion, does not require normalisation.

Regarding the suggestion to include a schematic diagram, we agree that such visual tools can be useful. However, given the relatively straightforward formulation of the indices and the number of variables involved, we consider that adding a diagram would substantially increase the length and complexity of the methodological section without providing proportional additional clarity. We therefore have opted to improve the textual explanations while keeping the methodology concise and readable.

3. The study would benefit from a brief uncertainty or sensitivity analysis to evaluate how variations in data inputs (e.g., susceptibility classification or economic valuation) affect risk index results. Even a qualitative discussion would strengthen confidence in the robustness of the findings.

We appreciate the reviewer's suggestion. The susceptibility maps used in this study were produced in previous official assessments, and the economic valuation of dwellings was obtained from external specialised organisations. The extreme input values and their implications are described in the manuscript.

With regard to sensitivity, the risk indices show consistent behaviour when applied to nearly 300 municipalities with appreciable risk levels. The use of percentile-based classification also contributes to standardising the results and reducing the influence of outliers. Moreover, the provincial analyses illustrate how different initial conditions and data ranges affect the final risk values, without revealing disproportionate variations or unstable intervals.

4. Although the dataset spans more than seven decades, temporal changes in landslide risk are not well illustrated. Incorporating a time-series trend, decade-based comparison, or discussion of major shifts in risk drivers would make the "spatiotemporal" aspect of the study more convincing.

We appreciate the reviewer's comment. The temporal variation is captured through the mRQI and mRSI indices, which quantify changes in landslide risk during the 1981–2021 period. This interval corresponds to the decades in which construction activity intensified in the region. As shown in Table 9, at least 10% of the municipalities (P90) exhibit a marked upward trend in risk levels.

We have incorporated a brief paragraph in the manuscript to clarify these temporal patterns and reinforce the spatiotemporal interpretation of the results, replacing the paragraph between lines 483 and 485:

"Table 9 presents the percentiles used to define the lower limits of the index levels. The province of Castellón shows higher quantile thresholds for the state variables, which appears to indicate a greater risk situation due to its mountainous orography and the predominance of small settlements. This confirms the interpretation noted in Table 1.

Moreover, the temporal indices reveal that at least 10% of the municipalities (P90) show a notable upward trend in risk during 1981–2021. Castellón and Alicante both display similarly elevated values, although driven by different factors: Castellón's increase is mainly attributable to its inherently more susceptible geomorphological conditions, while in Alicante the rise relates to tourism-driven development and growing construction pressure in areas exposed to slope instability."

5. The discussion of socioeconomic influences such as tourism and urban expansion remains qualitative. Integrating basic quantitative indicators-such as land - use change, population growth, or infrastructure density - would provide stronger empirical support for the interpretation.

We appreciate the reviewer's insightful observation. Socioeconomic drivers such as tourism pressure and urban expansion indeed contribute to increased landslide risk. These influences are incorporated indirectly in our analysis through the economic valuation of dwellings (DV), which reflects local demand dynamics and the upward pressure exerted by tourism-intensive or rapidly developing areas. As a result, variations in DV partly account for underlying socioeconomic dynamics without introducing additional independent indicators.

Explicitly quantifying these drivers using variables such as land-use change, population growth or infrastructure density would certainly strengthen the socioeconomic interpretation; however, integrating such datasets would require a broader methodological framework and constitutes a substantial extension of the current study. As indicated in the 'Major comments' section, this represents a natural direction for future work, where socioeconomic indicators could be incorporated systematically into the risk model.

6. The manuscript would benefit from editorial refinement. Ensure consistent terminology throughout (e.g., unify "risk zone," "susceptibility zone," and "management class"), verify incomplete references, and standardize equation formatting and figure captions for clarity and professionalism.

We thank the reviewer for this observation. A thorough editorial revision of the manuscript has been performed. Terminology has been standardised throughout the text; specifically, the expressions 'susceptibility zones' have been replaced by 'risk zones' in lines 496, 525, 530 and 534, and the term 'risk zone' is now used consistently across the manuscript.

The expression 'management class' was not employed in this study; however, the term 'management classification', which is used in the manuscript, accurately reflects the categories defined in our methodology.

All equations have been reformatted using MathType to ensure consistency, the reference list has been checked and cross-verified through Mendeley, and all figures have been reviewed and standardised using Grapher to improve clarity and presentation quality.