RESPONSE TO REVIEWER 2

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

While this study does provide an interesting framework for calculating a (decomposed) risk index that enables comparisons across several administrative units and for the same unit over time, the paper, as it stands right now, seems more like an application of the methodology, without a proper evaluation of the strengths and limitations of the method, its implications for the research domain, or a clear indication of how this paper builds on existing research in the field. This is especially the case for the discussion and conclusion sections, which are too tailored toward the interpretation of the case study, without a proper evaluation of what this new index actually means for research and how it could be adopted beyond the case study. Some interesting questions to address would be: how would this framework perform in regions with limited compliance with building standards? Can we consider this approach applicable in such contexts? In which cases would it be applicable, and in which would it not? For instance, the paper mentions in the introduction that proper planning (and thus understanding risk) is especially relevant in developing countries, but from my understanding, the framework developed in the paper would be much more adequate in more "formal" urban contexts (as in the case study in Spain) than in complex, spontaneous settlements in the "developing world." It may be interesting to address this from a research perspective, as a separate subsection or part of the discussion, to clarify what this research adds and how it generalizes.

We agree that the original version of the manuscript placed excessive emphasis on the case study application, while the broader methodological implications of the proposed framework were not sufficiently discussed. To address this concern, we have substantially expanded the Discussion section by adding a new subsection entitled "6.2 Strengths, limitations and transferability of the proposed framework." In this subsection, we explicitly evaluate the methodological contributions of the framework, discuss its main strengths and limitations, and clarify the contexts in which it is most applicable.

In particular, we now discuss the framework's suitability for regions characterized by formal urban development and reliable socioeconomic datasets, as well as the challenges associated with its application in contexts dominated by informal settlements or limited data availability. We emphasize that the framework should be understood as a flexible methodological structure that can be adapted to different settings, rather than as a universally applicable model.

Now, we have reorganized the Discussion into two subsections to clearly separate the interpretation of the case study results from the methodological implications of the proposed framework. We have also included some modifications taking into account the 'Minor comments'.

"6. Discussion
6.1. Interpretation of landslide risk in the Valencian Community
- - - The original text remains the same - - -

6.2. Strengths, limitations and transferability of the proposed framework

The proposed framework represents a structured and transparent approach for assessing landslide risk over large and heterogeneous regions by decomposing risk into physically based susceptibility (RSI) and socioeconomically driven exposure and vulnerability components (RQI), and by explicitly accounting for their temporal evolution through the mRQI. One of its main strengths lies in its capacity to integrate multi-source datasets with different spatial resolutions and thematic characteristics into a *coherent, dimensionless index, enabling both spatial comparison across administrative units and temporal comparison within the same unit. This feature is particularly relevant for regional-scale analyses, where data heterogeneity and scale mismatches often hinder consistent risk assessment.*

Despite these strengths, the framework also presents limitations that need to be explicitly acknowledged. At the regional scale considered, residential buildings are treated as homogeneous units in terms of construction materials and dwelling unit value, reflecting the level of data aggregation and the lack of spatially detailed building information. This simplification enables consistent comparison across municipalities but may reduce the accuracy of risk estimates at the local scale, particularly in areas with strong intra-urban heterogeneity.

In addition, the exclusion of susceptibility level L5 from the main analysis represents a conservative methodological choice aimed at maximizing regional representativeness, but it may lead to an underrepresentation of extreme-risk conditions at very localized scales.

Its performance strongly depends on the availability and quality of spatially explicit socioeconomic data, as well as on the existence of reliable landslide inventories. Consequently, the framework is most robust in contexts characterized by relatively formalized urban development, established land-use planning instruments, and consistent data collection practices, such as those typically found in European regions. In areas dominated by informal or spontaneous settlements, where building standards are weakly enforced and socioeconomic indicators are poorly documented, some components of the RQI may require alternative proxies or simplified representations. In such cases, the direct transferability of the framework without contextual adaptation may be limited.

From a broader research perspective, the framework should therefore be understood as a flexible methodological structure rather than a universally applicable model. Its conceptual design allows for adaptation to different territorial and socioeconomic contexts, provided that the indicators used to represent exposure and vulnerability are appropriately redefined. This makes the framework potentially relevant for applications in data-scarce or developing regions, but only after careful consideration of local conditions and data constraints. By explicitly defining its domain of applicability, this study contributes to ongoing efforts in landslide risk research to move beyond static, single-scale assessments toward more transparent, comparable, and temporally dynamic risk representations."

In addition, we have revised the Conclusions section to better highlight the methodological contribution of the study beyond the specific case study.

"7. Conclusions

The proposed framework demonstrates its suitability for large, spatially heterogeneous regions by addressing two critical challenges: 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 contrasting hazard levels. By incorporating high-resolution cadastral data and defining dimensionless indices (RI, RSI, RQI), together with temporal trend indicators (mRQI, mRSI), the framework enables a consistent evaluation of both the magnitude and the quality of landslide risk across municipalities, overcoming the limitations of traditional approaches based on regional averages and assumptions of territorial homogeneity. In particular, the mRQI provides a meaningful indicator of the temporal evolution of risk quality at the local scale, highlighting potential progressive occupation of unsuitable land for residential housing and supporting reflection on municipal land-use practices.

Beyond the specific case study, the main contribution of this work lies in its methodological structure. The use of normalized, dimensionless indices combined with temporal trend analysis allows landslide risk to be decomposed into interpretable components and compared across administrative units and time periods. This approach addresses key challenges in regional-scale risk assessment, such as data *heterogeneity and scale inconsistencies, while remaining conceptually transparent and computationally straightforward, thereby facilitating its transfer to other regions with comparable baseline information.*

Despite these strengths, the framework is most robust in contexts where reliable landslide inventories, cadastral information, and socioeconomic datasets are available, as is typically the case in regions characterized by formal planning systems. In areas dominated by informal settlements or limited data availability, some components of the framework may require adaptation through alternative proxies or simplified indicators. Future research should explore such adaptations, as well as the integration of population-based exposure metrics, in order to further enhance the framework's applicability across diverse geographical and socioeconomic settings.

Forecast-based and scenario-oriented assessments of natural hazards are essential for mitigating their impacts and supporting risk-informed territorial management. While such analyses are increasingly considered by public administrations, they are often implemented only partially or in isolation. Continued refinement of integrated and comparable risk assessment frameworks, such as the one proposed here, is therefore crucial to support more effective planning strategies and to strengthen societal capacity to anticipate and mitigate the consequences of natural hazards."

Additionally, you may want to consider simplifying the mathematical presentation. The methodology is relatively straightforward (which is a positive feature for applicability in other contexts), but the manuscript currently presents several equations that are somewhat repetitive. A more concise set of key equations, with derivations or intermediate steps moved to an appendix/supplementary material, could improve readability.

We thank the reviewer for this helpful suggestion. In the revised manuscript, we have simplified the mathematical presentation by retaining only the key operational equations in the main text, which are sufficient to understand and apply the proposed framework. Repetitive derivations and intermediate algebraic steps have been moved to a new Mathematical Appendix. This appendix explicitly shows how the global Risk Index (RI) can be decomposed into the Risk Surface Index (RSI) and the Risk Quality Index (RQI), and clarifies the assumptions under which further simplifications are possible. This reorganization improves readability while preserving full methodological transparency and reproducibility.

The text of the manuscript between lines 218 and 247 now reads as follows:

"…where RV is obtained through the hazard, exposure, and vulnerability of each affected dwelling unit, and exposure is defined as the constructed residential area in each risk zone (GFA_R) multiplied by the reconstruction cost per unit of surface (DV) (see Eq. (6)). An important feature of this index is the possibility of deriving two highly useful partial indices (see Appendix).

Thus, RI can be expressed as the product of two components: the Risk Surface Index (RSI) and the Risk Quality Index (RQI):

$$RI = RSI \times RQI \tag{13}$$

$$RSI = \frac{GFA_R}{GFA} \tag{14}$$

$$RQI = \frac{RV}{H_H \times Vm \times GFA_R \times DV} \tag{15}$$

The RSI reflects the proportion of built surface under risk relative to the total constructed area. It can approach unity in small LEs with little residential surface almost entirely exposed to landslide *susceptibility. The RQI, on the other hand, indicates whether the risk value approaches its theoretical maximum. Eq. (15) can be further developed and simplified assuming that residential building typologies are similar within a LE, such that vulnerability is constant (V_i = Vm) and DV is uniform (see Appendix).*

Then, using the hazard probability ratio pR4 between susceptibility levels H(L3) and H(L4) defined in the LSM, and considering thar no built-up surface exists in L5, equation (15) becomes:

$$RQI = = \frac{pR4 \times GFA_R L3 + GFA_R L4}{GFA_R} \qquad (16)$$

This simplification of RQI clearly shows that its value depends mainly on the built surface located in high-susceptibility zones ($GFA_R L4$), since pR4 is less than one. Moreover, the RQI value provides insight into whether construction is concentrated in high-susceptibility zones (level L4) and its evolution.

2. Minor comments

- **Line 50:** I am not sure whether "permanently" is the most adequate word here, as it is not possible to ensure such permanence. "This involves a complex process aimed at predicting, reducing, and permanently controlling the factors that trigger such hazards, …"

We agree with the reviewer that the term "permanently" was too strong. The wording has been revised to avoid implying full or irreversible control of natural hazard processes.

"This involves a complex process aimed at predicting, reducing, and controlling the factors that trigger such hazards, …"

- **Lines 63–64:** "Leading to landslides" seems very generic, in the sense of "urban growth leads to landslides." Maybe explain more clearly whether urban growth leads to increased landslide *hazard*, *exposure*, or *risk*. "Weak or absent administrative controls have allowed development in previously overlooked areas, leading to landslides."

That is correct, because the problem is not really the physical landslide process, but rather exposure to it. Therefore, we modify this sentence to the following:

"Weak or absent administrative controls have allowed development in previously overlooked areas, leading to increased exposure to landslide hazard."

- **Equation 2 (and others associated, such as Equation 9):** If it refers to the sum of (H × E × V) for each dwelling unit (DU), then these (H × E × V) terms should be within par entheses in the equation, correct?

We thank the reviewer for pointing this out. We agree that the original notation could be ambiguous. The equation has been revised to explicitly indicate that the summation applies to the product of Hi, Ei and Vi for each unit i or Dwelling Unit, by including parentheses. Then, the Eq 2 will be:

$RV_{LE} = \sum(H_{Dui} \times E_{Dui} \times V_{DUi})$

The same clarification has been applied to related equations (e.g., Eq. 9) for consistency.

- **Lines 176–177:** From my understanding, building resistance was assigned only based on building height, correct? Please explain this limitation. Also, I missed information on how the landslide magnitude was obtained.

We thank the reviewer for this comment. Yes, building resistance was assigned based solely on building height, as this is the only attribute consistently available at the dwelling unit level in the cadastral database. The estimation of landslide magnitude is already described in Section 4.1.3, where LM is defined based on published damage classifications and geomorphological characteristics of the study area. To improve clarity, we have added a brief sentence (Line 446) explicitly stating that a fixed LM value was applied due to the predominance of shallow landslides. In addition, we now explicitly clarify in the methodology that building resistance is derived solely from building height, which represents a data-driven simplification and a known limitation of the approach.

"This fixed LM value was applied consistently across the study area due to the predominance of shallow, small-magnitude landslides".

- **Lines 203–206:** I understand that assuming risk only at L5 would result in excessively high values. But doesn't it introduce inaccuracy to disregard buildings constructed in susceptibility level 5? I haven't taken a look at the map, so there is no way of knowing the representativeness of this class, but I imagine this is an important limitation. Maybe address this choice a bit more, and justify selecting only L4 (and not, for instance, L4+L5 combined).

We thank the reviewer for raising this point. Indeed, restricting the analysis exclusively to susceptibility level L5 would result in very high-risk values but would also significantly reduce the representativeness of the results at the regional scale, as buildings located in L5 areas are spatially limited and constitute a very small fraction of the total housing stock. Focusing solely on this class would therefore provide a highly localized perspective rather than a comprehensive assessment of landslide risk.

The selection of susceptibility level L4 was motivated by the need to capture the broader range of areas where urban development intersects with potentially unstable slopes, including zones where landslide occurrence is plausible but not systematic. This choice reflects a conservative risk assessment approach, aimed at supporting land-use planning by identifying areas where precautionary measures may be warranted, even at the expense of including some overestimation. Combining L4 and L5 was considered; however, given the limited spatial extent of L5 and its strong overlap with already constrained or non-developable areas, the marginal contribution of L5 to regional-scale risk patterns was found to be low. We have now clarified this methodological choice and its implications as a limitation in the 6.2 Discussion subsection, third paragraph.

- Some limitations could be acknowledged. For instance, the implications of assuming homogeneous buildings for all residential structures (both in terms of Dwelling Unit Value (DUV) and construction materials) and, especially, the assumption that land-use regulations will be properly followed (which may not hold in some urban contexts, particularly where enforcement capacity is limited or informality is widespread).

We agree with the reviewer that these assumptions represent important limitations of the proposed framework. In consequence, the Discussion section (second paragraph of the 6.2 Discussion subsection) has been revised to explicitly acknowledge the assumptions regarding homogeneous building characteristics and compliance with land-use regulations, and to clarify their implications for the accuracy and transferability of the framework.

MATHEMATICAL APPENDIX

An important feature of the RI index (defined in Eq. (8)) is the possibility of deriving two highly useful partial indices. By multiplying and dividing the expressions shown in Eqs. (9) and (10) by the constructed surface in risk zones (GFA_R), we obtain:

$$RI = \frac{GFA_R \times RV}{GFA_R \times \left(H_H \times V_m \times GFA \times DV\right)} \quad \text{(A.1)}$$

Rearranging yields:

$$RI = \frac{GFA_R}{GFA} \times \frac{RV}{H_H \times V_m \times GFA_R \times DV} \quad \text{(A.2)}$$

Thus, RI can be expressed as the product of two components: the *Risk Surface Index (RSI)* and the *Risk Quality Index (RQI)*:

$$RI = RSI \times RQI \quad \text{(A.3)}$$

$$RSI = \frac{GFA_R}{GFA} \quad \text{(A.4)}$$

$$RQI = \frac{RV}{H_H \times Vm \times GFA_R \times DV} \quad \text{(A.5)}$$

On the other hand, Eq. (A.5) can be further developed assuming that residential building typologies are similar within a LE, such that vulnerability is constant ($V_i = Vm$) and DV is uniform. Considering the hazard probability ratios (pR) between susceptibility levels defined in the LSM:

$$pR4 = \frac{H(L3)}{H(L4)} \quad \text{(A.6)}$$

$$pR5 = \frac{H(L4)}{H(L5)} \quad \text{(A.7)}$$

Then, for levels L3, L4, and L5:

$$RQI = \frac{H(L3) \times GFA_R L3 + H(L4) \times GFA_R L4 + H(L5) \times GFA_R L5}{GFA_R H(L4)} = \quad \text{(A.8)}$$

$$= \frac{pR4 \times GFA_R L3 + GFA_R L4 + \frac{1}{pR5} \times GFA_R L5}{GFA_R} =$$

$$= \frac{pR4 \times pR5 \times GFA_R L3 + pR5 \times GFA_R L4 + GFA_R L5}{GFA_R \times pR5}$$

This can be simplified when no built surface exists in L5:

$$RQI = = \frac{pR4 \times GFA_R L3 + GFA_R L4}{GFA_R} \quad \text{(A.9)}$$

This simplification of *RQI* clearly shows that its value depends mainly on the built surface located in high-susceptibility zones (GFA_RL4), since *pR4* is less than one. If the total *GFA* increases in the same proportion as the surface at level L4, the *RQI* value remains constant.