Revision Notes of the Revised Manuscript

Manuscript NO.: Egusphere-2026-160

Title: Integrating multidimensional factors through Bayesian Belief Networks for landslide and debris-flow risk reduction in subtropical zones

Submitted to: Natural Hazards and Earth System Sciences (NHESS)

Letter to editors and reviewers:

Dear editors and reviewers,

Thank you very much for your useful comments, we are now pleased to resubmit the revised version of Egusphere-2026-160 title: "*Integrating multidimensional factors through Bayesian Belief Networks for landslide and debris-flow risk reduction in subtropical zones"*. Based on the comment of reviewer, the authors changed the title to: *"Integrating multidimensional factors through Bayesian Belief Networks for landslide risk reduction in subtropical zones"*.

We would like to thank the reviewers for careful and thorough reading of this manuscript and for your suggestions, which helped us to improve the manuscript. We have carefully considered all the suggested changes and revised the manuscript accordingly.

Please refer to "Detailed response to reviewers' comments" below for studying the changes.

Yours Sincerely,

On behalf of all authors who read and agreed on the revised manuscript.

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Detailed response to reviewers' comments:

-- Reviewer #1 --

Major Comments

1. A major concern relates to discrepancies and confusion in the terminology. Based on widely accepted classification schemes, debris flows are a type of landslide. However, the manuscript differentiates two types of phenomena: landslides and debris flows. What do the Authors refer to when using the term landslides? Besides debris flows, what types of landslides does this manuscript address? I think this choice/description should be included in the Introduction or in another section.

Answer: Thank you so much for your suggestion. The authors agree that the debris flows are a type of landslide. The authors eliminated the content related to debris flows in the revised manuscript.

2. A further significant issue is related to the term risk, which appears to be both overused and, in several instances, misapplied. According to Varnes et al. (1984), landslide risk is the expected number of lives lost, persons injured, damage to properties and disruption of economic activity due to a particular phenomenon (in this case, landslides) for a given area and time period. That said, I have found that Authors often use risk as a synonym for the likelihood of landslides. Notably, this probability represents hazard, which is only one component of risk (as correctly illustrated in Figure 4). I strongly suggest the Authors to carefully revise the terminology as they are presenting a research paper.

Answer: In our study, the authors acknowledge that the terminology has not been used consistently in all sections. In particular, some parts—especially those referring to the probability of landslide occurrence derived from the BBN—may indeed correspond more closely to hazard rather than risk. The authors checked and revised these terms in whole manuscript.

However, as presented in our conceptual framework (Figure 4) and model structure, the proposed BBN explicitly incorporates not only landslide occurrence (hazard) but also exposure components (e.g., population, roads, buildings) and consequence-related variables (risk to life and property). Therefore, the intention of the study is to assess risk in a more comprehensive sense, rather than hazard alone.

To address the reviewer's concern, the authors revised the manuscript carefully to ensure consistent and accurate use of terminology throughout. Specifically:

(i) the term hazard is used when referring strictly to the probability of landslide occurrence;

(ii) the term risk is reserved for outputs that integrate hazard with exposure and consequences (e.g., risk to life and property); and

(iii) the distinction between these concepts is clarified more explicitly in the methodology and discussion sections.

The authors believe that these revisions are improve the conceptual clarity and scientific rigor of the manuscript while remaining fully aligned with established definitions.

3. By reading the paper, I had the impression that this objective has not been fully achieved. For instance, if the study aims to produce a landslide risk analysis, why is the well-established risk equation never mentioned in the text? This omission is particularly "strange" as Figure 4 clearly displays risk as the main objective. Furthermore, it remains unclear whether vulnerability and exposure were actually assessed. How were they assessed? The manuscript lacks a description of this part. Both vulnerability and exposure should be analysed differently depending on the type of element at risk.

Answer: The authors thank the reviewer for this thoughtful and important comment. The authors acknowledge that the description of risk and its components (hazard, exposure, and vulnerability) was not sufficiently clear in the current version of the manuscript, which may have led to the impression that the objective of landslide risk analysis was not fully achieved.

First, regarding the risk concept, the authors agree that the well-established formulation of risk (i.e., Risk = Hazard × Exposure × Vulnerability) should be explicitly stated. In the revised manuscript, the authors incorporated this formulation in the Introduction and Methodology sections to clearly define the conceptual basis of the study and ensure consistency with established frameworks.

Second, the authors would like to clarify that exposure and vulnerability were indeed considered in the BBN model, as illustrated in Figure 4 and implemented in Sections 3.2–3.4 . Specifically, exposure was represented through variables such as buildings, roads, and population presence, while vulnerability was implicitly captured through the characteristics of these elements (e.g., building types, infrastructure conditions) and the presence or absence of protective measures such as embankments. The outputs “risk to life” and “risk to property” were derived from the interaction between landslide hazard and these exposure-related variables.

However, the authors acknowledge that the manuscript does not clearly distinguish and describe how exposure and vulnerability are defined, parameterized, and differentiated across types of elements at risk. In response, the authors revised the manuscript to:

(i) explicitly define hazard, exposure, and vulnerability and their roles in the BBN framework;

(ii) clarify how exposure is quantified for different elements (e.g., roads, buildings, population);

(iii) better explain how vulnerability is represented (e.g., through structural types, protection measures, and sensitivity to damage); and

(iv) emphasize that different categories of exposed elements are treated separately in the model (as reflected in Tables 2 and 3).

The authors believe that these clarifications are significantly improve the transparency and scientific rigor of the manuscript, and more clearly demonstrate that the study does address landslide risk through an integrated framework.

4. The outcomes are also not sufficiently supported. As currently presented, the results may appear somewhat predictable. For example (line 373-374): " the higher the perceived rainfall and property risks, the higher the perceived landslide risk" or (line 387) "that weather conditions are an important factor in risk assessment and mitigation". These statements describe relationships that are largely expected. Expanding the supporting analysis would make their contribution clearer.

Answer: The authors thank the reviewer for this constructive comment. The authors acknowledge that some statements in the Results section may appear intuitive or expected when presented in a general form, which could reduce the perceived novelty of the findings.

However, the main contribution of this study is not the identification of individual factors (e.g., rainfall or exposure), which are indeed well known, but rather the quantitative integration of these factors within a probabilistic BBN framework and the explicit evaluation of their relative influence under different scenarios. For example, the sensitivity analysis provides quantified measures (e.g., variance of beliefs and mutual information) that demonstrate the relative importance of precipitation, property exposure, and other variables, rather than merely stating their influence qualitatively.

To address the reviewer's concern, the authors revised the manuscript to strengthen the interpretation of the results by:

(i) emphasizing the quantitative evidence (e.g., variance values, contribution percentages) supporting each relationship;

(ii) highlighting non-obvious findings, such as the comparatively lower influence of rainfall duration and pre-transported materials despite their common consideration in previous studies; and

(iii) clarifying how the interaction between hazard and exposure variables leads to differentiated risk outcomes for life and property, as demonstrated in Tables 2 and 3.

In addition, the authors revised the cited sentences to avoid overly general phrasing and instead present them in a more analytical and evidence-based manner, directly linked to the model outputs.

The authors believe that these revisions are better demonstrate the added value of the study and make the contribution of the results clearer and more robust.

5. Given the landslide context, I would have expected a cartographic translation of the outcomes displaying the spatial distribution of hazard/risk across the study area. Instead, the results are roughly presented as tables or diagrams. This form limits their interpretability.

Answer: The authors have made scenario-based landslide hazard maps for the Da River basin (Section 3.5, Figure 7) based on BBN network. These maps illustrate the spatial distribution of landslide hazard under different rainfall accumulation scenarios (70–130 mm, 130–240 mm, and >240 mm within 1–3 days), thereby improving the interpretability of the results compared to tables and diagrams alone.

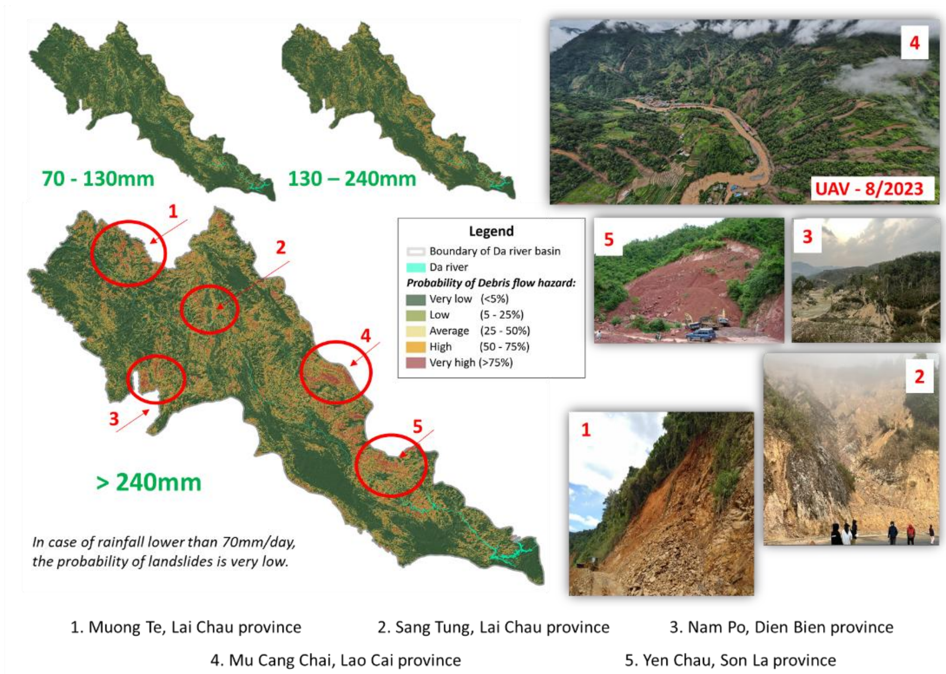

Figure 7. Probability map of landslide occurring in three rainfall scenarios based on BBN model in the Da river basin.

In addition, the revised manuscript includes a discussion (Section 4.2) linking these spatial outputs to practical applications, such as identifying high-priority zones for monitoring and supporting threshold-based early warning and land-use planning. These additions enhance the clarity and applicability of the results, addressing the reviewer's concern regarding their spatial interpretation.

Detail comments:

6. Line 31-32. I would include a definition of landslides instead of describing triggering/predisposing conditions, which are quite heterogeneous. For instance, rotational/translational landslides may occur even on gentle slopes. Moreover, as mentioned above, pay attention to landslides vs debris flows: debris flows are a type of landslide!

Answer: In the revised manuscript, the authors included a concise definition of landslides in the Introduction (second paragraph), rather than focusing only on triggering conditions. the authors also acknowledged the need to better distinguish terminology. The manuscript is revised to clarify that debris flows are a specific type of landslide, and terminology "landslide" is used consistently throughout to avoid confusion.

7. Line 33-38. I think it is good to report data on losses/damage due to landslides. However, I would follow a more logical flow: world data, Asia data, Vietnam data. There is an increasing availability of data and studies on landslide damage worldwide.

Answer: In the revised manuscript, the authors reorganized this section to present information sequentially from global to regional (Asia) and then to the national scale (Vietnam), in order to improve readability and contextual coherence.

8. Line 40. How many landslides? What type of landslides? Do economic losses include damage due to floods?

Answer: The content was revised as follows:

"In Vietnam, records from the Ministry of Natural Disaster Prevention and Search and Rescue indicate that the aftermath of landslides and floods occurring during Typhoon Yagi in 2024 resulted in human and economic losses amounting to 40 trillion VND (approximately US$1.63 billion), with 329 fatalities and over 2,000 people affected. Some provinces recorded more than 1,000 landslide events (such as in Lao Cai and Yen Bai provinces) (Nguyen et al., 2026)".

9. Line 45-118. This part is an example of the confusion in the scientific terminology, as well as the core of the manuscript. What is this work addressing? The Authors leverages the term Risk in the title and throughout the paper; however, the state of the art presented in this paragraph is just describing the framework of landslide susceptibility/hazard. To which, moreover, I would suggest substantial changes and improvements. That said, the literature overview should be refined.

Answer: As done and mentioned in comments 2 and 3, the authors checked and revised the term "hazard" and "risk" in whole manuscript. The authors believe the revised manuscript could make it clearer.

10. Figure 1, Figure 2. I think these Figures are not suitable within the Introduction section of a research paper. They would have been appropriate for a review.

Answer: The authors agree with the comment. Figure 1 and 2 were eliminated in the revised manuscript.

11. Section 2.2. This part is the core of the work, but it should be improved. I did not find any definition of warning, for instance, or a clear description of how a Bayesian Belief Network model works.

The following content was added to the section 2.2:

Answer: "A Bayesian Belief Network (BBN) is a graphical model that shows how variables are connected to each other and how they cause each other. Each node has a conditional validation table (CPT) linked to it. This table shows how likely it is that a variable is happen based on its nodes. This model allows for validation inference, which means that changing one variable (like rainfall) could change the performance of other variables (like hazard and risk) through the network. This study employs Bayesian Belief Networks (BBNs) to examine evolving environmental, climatic, and socioeconomic circumstances to establish a land base and subsequently evaluate the risk to the computing network and assets. BBN models are developed through four steps, from determining factors, building a theoretical model, gathering multidimensional data, to the final model. The detail of each step can be explained as follows: …

… The primary objective of the model is to support managers, experts, and decision-makers in anticipating and issuing warnings about potential landslides….”

12. Line 180. This definition may belong to resilience, not to vulnerability. Moreover, how is vulnerability estimated?

Answer: The content was revised as follows:

“Importantly, vulnerability is not included in the model as a separate variable, but is reflected indirectly through the characteristics of the affected objects. (Agboola et al., 2024; Luu et al., 2023). These characteristics include the type of structure, the quality of infrastructure, and the presence of protective measures such as dikes or embankments, thereby determining the level of damage when the same level of danger occurs. Different objects such as roads, houses, or people have different levels of vulnerability, and this is reflected in the model results through the risk to life and the risk to property.

Equally critical are the exposure and resilience dimensions, which reflect population density, existing protective infrastructure, and community preparedness. Resilience is the ability of a system or structure to withstand and recover from the impact of landslides. These elements determine not only the potential scale of damage but also the capacity of vulnerable groups to recover (Alam and Ray-Bennett, 2021; Chen et al., 2024b).”

13. Figure 5. This Figure is not mentioned in the text. What do the Authors mean by thresholds? What does it mean by "landslide hazard higher than 50%"? How are these correlation plots obtained?

Answer: The Figure 5 (now is Figure 3) was mentioned at the beginning of section 2.2 (Step 3).

At the beginning of the step 3, the authors added the following content:

"Landslide warnings are influenced by geological, geomorphological, meteorological, hydrological, land cover and land use, and infrastructure conditions (Figure 3). This Figure refers to the range of input variable values at which the probability of a landslide hazard surpasses 50%. It was run based on the Bayesian Network Model's (BBN) probabilistic response curves. It shows the conditions under which the chance of a landslide is highest. When we say "landslide hazard greater than 50%," it means that the BBN model's posterior probability is greater than 0.5, which means that under certain conditions (like rainfall, slope, or land use), the chance of a landslide is higher than the chance of it not happening. The graphs in the figure are constructed from sensitivity analysis and response analysis of the BBN model, where each curve represents the change in the probability of a landslide with respect to one input variable, while other variables are kept constant or according to their initial distribution. The vertical dashed lines represent ranges of values corresponding to levels of probability of interest (e.g., 50%), thereby defining the influence thresholds of each factor".

14. Line 255. Is the landslide risk (potential economic/social losses) the dependent variable of the model? This part further supports my idea of general confusion within the work.

Answer: The authors thank the reviewer for this important comment.

The authors clarify that the dependent variable in the model is landslide hazard (occurrence probability), not risk. Risk is subsequently derived by combining hazard with exposure-related variables (e.g., people, buildings, infrastructure). The manuscript has been revised to clearly distinguish between hazard prediction and risk assessment, thereby avoiding conceptual ambiguity.

15. Line 263 - 283. The procedures of the landslide risk assessment should be re-written, they are not clear. Moreover, I've never found the risk equation.

Answer: The content was revised as follows:

"There were two primary steps in the modeling process. The BBN model was first used to figure out the hazard, which is the chance of a landslide happening in certain environmental conditions and with certain triggering effects. Second, this hazard was paired with things like population,

buildings, and infrastructure that could make it worse to figure out how dangerous it was to life and property. In this study, the usual formula is used to define risk as follows: Risk = Hazard × Exposure × Susceptibility. By combining SEM and multivariate regression, the approach enhances both the efficiency and the reliability of the BBN model by incorporating only critical independent variables".

16. What is the spatial resolution of this study? What type of mapping unit is adopted by the Authors?

Answer: *"The spatial resolution of the study is defined by the raster datasets used in the analysis, which were standardized to a resolution of 30x30 m. Accordingly, a grid-based mapping unit (pixel-based approach) was adopted, where each cell represents the smallest spatial unit for analysis and modelling within the BBN framework".*

This information was clarified in the revised manuscript (Step 3, in section 2.2) to improve the transparency of the methodology.

17. Section 3.1. I think the relationships reported in this section are expected. For instance, I think anyone would expect slope, or curvature, to be correlated with SPI, since they are products derived from DEM. Moreover, slope and curvature may be a part of the SPI computation. The same consideration applies to the correlation between DEM and TRI (the Authors forgot to define the acronym). Even in this case, anyone would expect a strong relationship between DEM and roughness.

Answer: The authors agree that some of the relationships identified (e.g., between slope, curvature, SPI, DEM, and TRI) are expected, as these variables are derived from the same DEM and are inherently interrelated.

However, the purpose of this analysis is not to demonstrate novelty in individual correlations, but to quantitatively assess their relative influence and redundancy within the modelling framework (as noted in Comments 3 and 4). Identifying these relationships helps reduce multicollinearity and enables the selection of the most representative variables for integration into the BBN model, thereby improving its robustness and efficiency. Moreover, this approach provides a clearer and more systematic understanding of landslide processes compared to conventional linear analyses, offering added value for both interpretation and methodological development.

Note: TRI is Terrain Ruggedness Index. Its explanation has been added to the step 3 in section 2.2.

18. Figure 7. The reading of this Figure is challenging due to its complexity. Moreover, this Figure gives me the opportunity to raise a few points that are not well presented in the methods. Are the predisposing/triggering factors classified? If yes, what kind of classification scheme/method did the Authors use? In the case of data-binning, I think that the entire work is characterized by a degree of subjectivity, which is not addressed.

Answer: In the revised version, the authors added a more detailed description of the discretization process, the criteria for determining the value ranges, and how to construct the CPT table in Step 3 and 4 in section 2.2 to enhance the transparency and reproducibility of the study. The explanation for Figure 7 has been added in detail in section 3.2 and 4.1.

Additionally, the authors hope that the reviewer can check the Figure 7 (now is Figure 5) again to understand the benefits of the BBN provided:

- All the variables in the BBN model are put into finite states to make it easier to make probabilistic inferences about predisposing and triggering factors. But this procedure is not based on expert opinions; it is based on data, which includes the statistical distribution of the data (such frequency distribution, range of values, and variable characteristics) and the natural characteristics of each factor. Because of this, the categorization ranges show how the data is really structured instead of random selection criteria.

- The BBN model also reduces subjectivity more than other methods do. Once the variables are known, conditional probability tables (CPTs) are used to show how they are related. These tables are made using data and statistical analysis findings (SEM and multivariate regression), not just expert opinion. Using SEM and multivariate regression ahead of time also helped pick out the most important factors. This cut down on duplicate information and made the model more reliable.

- Figure 7 illustrates the states and probability distributions of all the variables in the BBN network. The data defines a range for each value class, and the probabilities that go with them show how much that state affects the risk and hazard of landslides. Consequently, this figure is not a product of subjective classification but a quantitative depiction of probabilistic interactions within the model.

19. Overall, the results and their discussion need to be improved.

Answer: The authors improved whole manuscript (especially the results and discussion) based on your comments. Please check the revised manuscript to see our changes.

20. General comment. The references and literature overview on risk, susceptibility, hazard, vulnerability, and exposure should be improved.

Answer: The references and literature overview in section 1 and 2 were revised. Please check the revised manuscript to see our changes.

Thank you so much!