

Initial Response to Reviewer Comments

Title: Hazard Interactions and Interaction Networks (Cascades) within Multi-Hazard Methodologies

[doi:10.5194/esd-2015-94] submitted to *Earth System Dynamics*

We thank **Reviewer #1 (Reik Donner)** and **Reviewer #2 (Warner Marzocchi)** for their positive, insightful and constructive comments on our manuscript, and for waiving their right to anonymity.

In order to support the interactive discussion nature of the review process, we have drafted some initial responses [highlighted grey] to each of their comments, presented in the subsequent pages. We believe the comments made by both reviewers are fair and will improve our overall argument, and thank both Reik Donner and Warner Marzocchi for their time in helping us to create a paper with a clearer argument.

We look forward to any further comments from the reviewers or editor. We would be delighted to then prepare and submit a revised manuscript based on these comments and any further advice from the editor.

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REVIEWER #1 (COMMENTS TO AUTHOR): Reik Donner

General comments: Gill and Malamud discuss a general framework for extending the commonly taken view on hazard assessment by taking interdependences of different types linking various hazards into account. Since such interdependences may significantly affect the susceptibility of regions to hazards of different types, I fully agree with their basic argument that hazard interactions need to be carefully considered for obtaining qualitative and quantitative risk assessments. The discussion presented by the authors is scientifically sound and does not only highlight the insufficiencies of previous approaches, but also proposes possible ways to reaching such realistic assessment. The latter aspect appears to be the main achievement of the present work that goes beyond what has been discussed by the authors in their recent review paper (Gill and Malamud, 2014). At the present stage, this work is purely qualitative, and future studies describing its further extension towards quantitative multi-hazard risk assessments would be most welcome. To this end, this excellent work can be considered as an important milestone on this way. While the manuscript already presents excellent work, I would like to recommend additionally paying specific attention to some minor points listed below to possibly make it even better.

Authors: We are very grateful for this positive, constructive and helpful summary, recognising the value of this contribution to the literature on multi-hazard assessments. We have attempted to address each of the points that you have listed below, and appreciate your thoughtful interaction with our manuscript. We have added some clarifying words at the beginning of each of your comments in [] to give a highlight of what the point is about.

1.[Induced seismicity as an example of anthropogenic processes] Regarding the anthropogenic processes briefly discussed in Section 3.2, I think that another possibly important example of such processes would be induced seismicity, i.e., seismic activity resulting from human activities like construction of large artificial reservoirs or mining/drilling activities. Recent corresponding references on possible cases of induced seismicity include, among others, Kerr and Stone, Science 323, 322, 2009, or Hough and Page, *Bulletin of the Seismological Society of America*, doi: 10.1785/0120150109. I would like to suggest adding some brief comment on such anthropogenic processes.

Authors: We agree that induced seismicity is an important example of anthropogenic processes resulting in the triggering of a natural hazard, in this case seismic activity. Following the helpful suggestion, we will include induced seismicity in a revised version of **Section 3.2**, introducing the following additional papers to the manuscript:

- 5 • Deng, K., Zhou, S., Wang, R., Robinson, R., Zhao, C., & Cheng, W. (2010). Evidence that the 2008 Mw 7.9 Wenchuan earthquake could not have been induced by the Zipingpu Reservoir. *Bulletin of the Seismological Society of America*, **100**(5B), 2805-2814.
- 10 • González, P. J., Tiampo, K. F., Palano, M., Cannavó, F., & Fernández, J. (2012). The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading. *Nature Geoscience*, **5**(11), 821-825.
- Hough, S.E. and Page, M. (2015). A century of induced earthquakes in Oklahoma?. *Bulletin of the Seismological Society of America*, **105**(6), 2863-2870.
- Kerr, R.A. and Stone, R. (2009). A human trigger for the great quake of Sichuan?. *Science*, **323**(5912), 322-322.
- 15 • Klose, C. D. (2008). The 2008 M 7.9 Wenchuan earthquake—Result of local and abnormal mass imbalances?, *Eos Trans. AGU* 89, no. 53, Fall Meet. Suppl., Abstract U21C-08.

We also note that we are currently in the final stages of completing another manuscript exclusively focused on examining the role of anthropogenic processes in the context of natural hazard interactions, which will cover the topic of anthropogenic processes and their influences on natural hazards in much greater detail.

- 20 **2. [Define better anthropogenic processes vs. routine hazard events of technology]** In Section 3.3, the authors state that “similarities exist between the routine hazard events of technology and the definition of anthropogenic processes”. Frankly speaking, I do not clearly understand the exact differentiation between both types of hazards from the present discussion. Providing some explicit examples highlighting this difference
25 could be helpful to clarify this point.

- Authors:** We agree with the reviewer that from the current definitions, these two groups (routine events of technology, anthropogenic processes) are difficult to differentiate. In **Section 3.3** we seek to communicate to the reader that there are currently few consistent definitions of technological hazards/disasters, with some
30 definitions incorporating anthropogenic processes and others not doing so. We propose that we revise page 6 of our original manuscript, lines 20–22, to clarify that in this definition of technological hazards, the ‘routine hazard events of technology’ are the same as anthropogenic processes. The explicit example of subsurface mining will be introduced and discussed.

- 35 **3. [Unidirectional vs. bi-directional interaction relationships]** Regarding their discussion of interaction relationships, I have got the impression that the authors consider such relationships as exclusively unidirectional. Or put differently: the present framework is developed and illustrated with the (in my opinion, unnecessary) implicit restriction of unambiguous cause-effect relationships among hazards (as manifested in the terminology of primary versus secondary hazards). In this regard, I was wondering if there exist any
40 examples of bidirectional interactions, either associated with their simultaneous occurrence or relating to feedbacks. I would be keen to learn about the authors’ opinion on this question.

- Authors:** Thank you for highlighting this confusion in our language, as we do not wish to convey exclusively unidirectional interactions. In order to address the suggestions of the reviewer, we will revise the initial
45 paragraph of **Section 4** (page 7), to explicitly state that interactions can be bidirectional, bringing in some of the discussion below and using an example from Nepal (Marston *et al.*, 1996). In our manuscript we have used the term ‘interaction’ as it conveys that the relationship between natural hazards could be bidirectional. For example, we acknowledge that feedback mechanisms can be established, where the triggering of a secondary hazard exacerbates the primary hazard, therefore triggering further episodes of the secondary hazard. The

language of primary and secondary hazard was used in Gill and Malamud (2014) and brought into this manuscript. While recognising that this could imply a unidirectional relationship, we believe that as the same 21 natural hazards are used as both primary and secondary hazards it can also be used to discuss bidirectional relationships (including feedback mechanisms), where a triggered secondary hazard exacerbates the primary hazard. This is visible in the example used in **Figure 4**, showing a storm triggering a flood, which then triggers a landslide, which exacerbates the flooding. Another specific example of such feedback mechanisms, cited in Gill and Malamud (2014), gives an example from Nepal and discusses the undercutting of slopes by river systems causing channel aggradation. This aggradation can trigger greater undercutting, thus developing a positive feedback or cyclic triggering (Marston *et al.*, 1996).

- Marston, R., Kleinman, J., & Miller, M. (1996). Geomorphic and forest cover controls on monsoon flooding, central Nepal Himalaya. *Mountain Research and Development*, 257-264.

4. [Causal relationships] In Section 4.1, the authors describe triggering relationships as “causal” relationships (as opposed to the other two types of interactions among hazards). However, depending on which specific notion of causality is considered, I would argue that the other two types also denote some “causal” (in the sense of directional) relations, yet of different quality than triggering relationships where this relation is “most direct”.

Authors: We agree with the reviewer, that there is a degree of directional ‘causation’ in all of the interaction types in **Section 4**, and will revise the language in **Section 4** to take this into account.

5. [Temporal and spatial scales] The authors emphasize (p.7, l.28) that triggering interactions can occur between a diverse range of hazards and processes. I think that also the issue of scales (both temporal and spatial) is something important to consider when aiming to characterize triggering relationships. It might be interesting to elaborate further on this aspect.

Authors: We agree with the reviewer that triggering interactions can occur between a diverse range of hazards and processes, but also that the issue of spatial and temporal scales is very important. We will therefore revise **Section 4.1** in our manuscript to include the following discussion of spatial and temporal scales, with examples of volcanic activity and agricultural practice change used to illustrate the importance of considering spatial and temporal scales. We will structure our manuscript to include the following discussion. Spatial and temporal scales are particularly important when going from a global overview of interactions, to a location-specific assessment of interactions. For example, a volcanic eruption could be considered in terms of each individual eruption (occurring over approximately seconds to hours) or a broader period of activity (occurring over approximately months to decades). An anthropogenic process, such as agricultural practice change, could also occur at multiple scales. Agricultural practice change could incorporate both an individual farmer ploughing a new field (at an approximate spatial scale of 0.1–1 km² and temporal scale of days to weeks) and a societal transition from manual to machine-dominated farming (at an approximate spatial scale of 10⁴–10⁷ km² and temporal scale of years to centuries). Both of these examples would result in diverse characterisations of the possible triggering relationships, depending on the scale of interest.

6. [Redundancy between figure captions and text] Throughout Section 4, there is considerable redundancy between figure captions and the main text (e.g., between the last paragraph of Section 4.1 and the caption of Figure 2). I think that this redundancy should be reduced.

Authors: We understand the reviewer’s concern and appreciated that this style of writing adds greater repetition. In the revised manuscript we will carefully examine each figure caption to see if any repetition can be removed in the text, as well as considering advice from the editor. However, we both prefer to use detailed figure captions so that each figure stands alone (particularly for the reader that ‘dips’ in and out of the paper), and can be interpreted easily. These figures are then comprehensively introduced and discussed in the text so

that they are integrated into the discussion within the manuscript. We believe that this makes it easier for the reader to understand and use the figures.

7. **[Probabilistic and/or individual event viewpoints]** In Section 4.2, the authors state that increased probability relationships “change the frequency or extent of the secondary hazard or process”. When considering hazards in some abstract (probabilistic / return period) sense, I agree with this. However, at the level of individual events, a specific primary event would rather change the proximity (and specific characteristics) of the specific next secondary hazard to come affected by the increased probability relationship. From the present paper, it is not always completely clear if the authors wish to consistently take the probabilistic or the individual event viewpoint (not necessarily contradicting each other in general).

Authors: This is a very helpful and thoughtful comment, and we thank the reviewer for using this opportunity to raise it, as it is one that the two authors have discussed also at length. In general, in our discussions, we are considering probabilistic viewpoints, where the probabilistic behaviour of a relationship is often inferred from many individual events. This approach is used to consider in general how one hazard will influence another. We recognise that the approach required when considering a specific case study location may differ to the approach used when discussing populations of interactions in a general and more regional or globally-relevant way. This is a limitation that we have not explicitly brought out in this manuscript, but think that it would be beneficial to do so. We propose adding a paragraph to **Section 2** (*Single vs. Multi-Hazard*), that discusses the challenges of adapting global multi-hazard frameworks for use in regional/local contexts, and also the individual event vs. the probabilistic viewpoint.

8. **[Frequent vs. rare interaction relationships]** In Section 4.3, the authors contrast interaction relationships that “include large numbers of frequently-occurring interactions” and such “that are considered to be less common”. This seems to me a rather arbitrary distinction (i.e., there are no two distinct types, but rather a continuum of cases according to the frequency of interactions). I was wondering if the authors have any objective criteria for associating catalysing and impedance relationships to any of the two aforementioned types.

Authors: We thank the reviewer for noticing our confusing choice of phrasing in **Section 4.3** which we propose to change to (i) clarify our meaning to avoid confusion, (ii) illustrate more fully our agreement that there is a wide spectrum (continuum) between the two end-points of frequent vs. rare, (iii) bring in specific examples. In **Section 4.3** we had aimed to highlight the differential likelihood of different interactions, but agree that this is best illustrated also through examples of different specific interactions, rather than interaction types. We also recognise that choosing two examples relating to triggering relationships is unhelpful, given that the focus of **Section 4.3** is on catalysing and impedance relationships. Within each interaction type we will highlight that there can be found examples of frequently occurring interactions and examples that are less common, with a wide spectrum between these two end points. The associated figure, to which our manuscript comment related (**Figure 3**) does not distinguish between these two end members, it represents possible interactions. We therefore propose changing the text of **Section 4.3** (page 9, lines 16–22), to focus on examples of catalysing/impedance relationships, which we believe also fall on a spectrum between those that occur frequently and those that are less common. For example, vegetation removal or the unloading of slopes through construction has been shown to increase the susceptibility of slopes to landslides in the event of a trigger (e.g., earthquake or heavy rain). We will refer back to the example of road construction catalysing landslides during the 8 October 2005 Kashmir earthquake, cited in **Section 3.2** (Owen *et al.*, 2008). We will also introduce additional supporting literature:

- Brenning, A., Schwinn, M., Ruiz-Páez, A. P., and Muenchow, J.: Landslide susceptibility near highways is increased by 1 order of magnitude in the Andes of southern Ecuador, Loja province, *Nat. Hazards Earth Syst. Sci.*, 15, 45–57, doi:10.5194/nhess-15-45-2015, 2015.

- Devkota, K.C., Regmi, A.D., Pourghasemi, H.R., Yoshida, K., Pradhan, B., Ryu, I.C., Dhital, M.R. and Althuwaynee, O.F., 2013. Landslide susceptibility mapping using certainty factor, index of entropy and logistic regression models in GIS and their comparison at Mugling–Narayanghat road section in Nepal Himalaya. *Natural Hazards*, 65(1), pp.135-165.
- Montgomery, D. R. (1994). Road surface drainage, channel initiation, and slope instability. *Water Resources Research*, 30(6), 1925-1932.

A short discussion of differential likelihoods of triggering interactions will also be added to **Section 4.1** (page 7), using appropriate examples of triggering events with a high, medium and low likelihood, selected from the analysis of *spatial overlap-temporal likelihood* of natural hazard interactions in Gill and Malamud (2014). The revisions to **Sections 4.1** and **4.3** will emphasise the importance of location specific characteristics in determining the likelihood of any interaction or interaction type, when considering applied multi-hazard approaches.

9. [Two vs. four case studies in Section 5] In Section 5, the authors first refer to four case studies, later to two. The first two cases detailed in Section 5.1 are not used any further in the following text, while the other two cases are exclusively discussed in the visualization context. All four examples are clearly relevant in the context of this work, but the way they are introduced and detailed in different parts of the manuscript appears slightly confusing.

Authors: We have made an error in the introduction to **Section 5**, which should read that two examples are discussed in **Section 5.1**, and two different examples are discussed in **Section 5.2**. In **Section 5.1** we introduce two examples of networks of hazard interactions (cascades) to illustrate the wide variation in spatial and temporal extent, frequency of networks of hazard interactions, and impact of such networks. In **Section 5.2** we introduce two different examples to discuss the visualisation of networks of hazard interactions. We had originally included all four in both **Section 5.1** and **5.2**, but felt (i) that there was too much repetition if all four examples were included in both **Section 5.1** and **5.2**, and (ii) if we reduced the examples to just two, the manuscript would not show the same diversity of examples as is achieved with four different examples, spread across the two sections. To address this comment and clarify the way these case studies are introduced and used, we propose adding an additional paragraph at the start of **Section 5** (page 10) which gives a short summary of all four case studies, and explains clearly that we will use two to illustrate variations in the spatial and temporal extent of networks of interactions, and two to consider the visualisation of such networks. We will then rename **Section 5.1** to '*Spatial and Temporal Extent of Networks of hazard Interactions (Cascades)*'. The title of **Section 5.2** will remain unchanged. We believe that these revisions to structure and content will go some way to addressing the concerns of the reviewer.

10. [English] Despite not being a native speaker, I was wondering about a few words and kindly ask the authors to cross-check them:

(i) p.3, l.26: "selected"

(ii) p.9, l.21: "...processes relevant interactions can be..."

(iii) p.10, l.15: "evaluating networks... is important"

(iv) p.15, l.27: The meaning of the term "Earth-systems management" is not fully obvious to me.

Authors: We thank the reviewer for these helpful suggestions, and will cross check each of them when preparing the revised manuscript.

(i) "select" vs. "selected". We agree and will change.

(ii) "Only through the careful assessment of all possible single hazards and *processes can relevant interactions* be identified and assessed." Vs. "Only through the careful assessment of all possible single hazards and *processes relevant interactions can be* identified and assessed." We think the first one is correct, but will revisit when writing the revised manuscript.

(iii) “and finally discuss why we believe evaluating networks of hazard interactions are important” vs. “and finally discuss why we believe evaluating networks of hazard interactions is important”. We agree, this should be singular (is).

(iv) We note that ‘Earth-systems management’ is used in the journal description, and aims and scope, but agree that it would be helpful to add a definition for this term, relating to human actions and decision making that helps to manage aspects of the Earth system.

REVIEWER #2 (COMMENTS TO AUTHOR): Warner Marzocchi

General Comments: The paper discusses the importance of modeling the interactions among different hazards, natural and not, to obtain a more realistic risk assessment. The paper is well written (maybe with some unnecessary repetitions), and the topic of great interest. My general opinion is positive but I think that the paper misses to take into account some key issues for a proper multi-hazard assessment.... To sum, I am positive about this paper because it reiterates the importance of the interaction among different hazards in a multi-risk perspective. This is certainly commendable. However, I think that the authors should make an effort to address the points raised [below].

Authors: We are very grateful for this positive, constructive and helpful summary, and appreciate the thoughtful comments you have made below to help us improve the manuscript. We have attempted to address each of your key issues below and will welcome further dialogue. We have added some clarifying words at the beginning of each of your comments in [] to give a highlight of what the point is about.

Major Point 1. [Forecasting time windows] The first issue, and probably the most important, is that the authors do not discuss the forecasting time windows for hazard assessment. The importance of this topic for multi-hazard and multi-risk assessment has been already discussed in Marzocchi *et al.* (2012; W. Marzocchi, A. Garcia-Aristizabal, P. Gasparini, M.L. Mastellone, A. Di Ruocco, 2012. *Basic principles of multi-risk assessment: a case study in Italy. Natural Hazards*, 62, 551-573), and it will be summarized here.

The ‘hazard’ is essentially the probability of a threatening event in one specific time-space window. The (forecasting) time window is of critical importance and it is usually related to the specific use of the hazard assessment in terms of risk reduction. For instance, a long-term hazard assessment (e.g., a forecasting time window of 50 years) is usually adopted for land use planning, like to define the building code for the earthquakes threat. On the other hand, the management of rapidly evolving emergencies usually requires short-term assessments (e.g., days to weeks). Considering long- or short-term hazard provides completely different scenarios for hazard interactions. For example, let us consider the landslide hazard. We can calculate the probabilities of landslides occurrence for the next decades just simply looking at the historical catalog. The fact that most of landslides are caused by earthquakes is not relevant in the long-term hazard because this is true also for the landslides occurred in the past and reported in the historical catalog (assuming that the long-term earthquake rate is not changing with time). So, the interaction between earthquakes and landslides could be irrelevant for the long-term hazard assessment. Of course, if we are considering the short-term hazard assessment (as I guess the authors are doing), the fact that a large earthquake (like the Gorkha event) has just occurred modifies significantly the probability of landslides in the next few months (due to the occurrence of aftershocks). So, the interaction between hazards has to be considered specifying clearly the forecasting time window. Marzocchi *et al.* (2012) explore in detail this point showing a probabilistic framework to explain when hazard interactions are relevant or not (see section 3.2).

Authors: We thank the reviewer for raising the very interesting and relevant point of forecasting time windows. We will add the subject of forecasting windows in **Section 2** as an important consideration to our manuscript, including reference to the referee’s manuscript, along with two others.

- Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M.L., Di Ruocco, A. (2012). Basic principles of multi-risk assessment: a case study in Italy. *Natural Hazards*, 62, 551-573.
- Kappes, M. S., Keiler, M., von Elverfeldt, K., & Glade, T. (2012). Challenges of analyzing multi-hazard risk: a review. *Natural Hazards*, 64(2), 1925-1958.
- Selva, J. (2013). Long-term multi-risk assessment: statistical treatment of interaction among risks. *Natural hazards*, 67(2), 701-722.

We will revise our manuscript to add a paragraph to **Section 2** that describes our general, globally-relevant approach (generalising across forecasting time windows that are short- and long-term, discussed below), but that acknowledges the importance of establishing clear boundary conditions when developing location specific multi-hazard risk/multi-risk assessments.

We agree that the forecasting time window is important and that this will differ depending on the use of a particular multi-hazard risk assessment (MHRA)/multi-risk assessment (MRA) [N.B., please see our response below to Major Comment 2, regarding use of MHRA vs. MRA]. We agree with Marzocchi *et al.* (2012) that prior to developing a MHRA/MRA the space-time assessment window should be clearly stated, and will be determined based on the requirements of the users of the MHRA/MRA. We will state this more clearly in our revision. We clarify here that in the context of this manuscript we are not focusing on a specific application of a MRA or a specific forecasting time window, rather we are generalising across different forecasting time windows in order to describe what *may* occur. With reference to whether or not interactions are relevant, from the perspective we have taken in explaining interactions, we believe that the interactions between certain hazards are relevant for long-term hazard assessments. Marzocchi *et al.* (2012), for example, notes that tsunami databases already include the possibility that a tsunami is caused by an earthquake. Therefore, our understanding of your argument is that the interaction ‘earthquake → tsunami’ is irrelevant in the long-term hazard assessment of tsunamis (i.e., a tsunami database already takes into account the preceding earthquake). We do not dispute that the database of tsunamis already takes into account the tsunami triggers, and note that it is an important point. However, even in this long-term forecasting time window it is important to acknowledge this interaction (even if only that the interaction can occur) to ensure clear and coherent communication on the spatial/temporal association of tsunamis with earthquakes, to all stakeholders. We do not dispute the importance that you are stating, and illustrated in Marzocchi *et al.* (2012), but believe in the context of our argument of potential hazard interactions, both long-term and short-term forecasting are included (i.e., we are not considering ‘just’ short-term time windows).

If you would like to correspond further on this issue, either through the discussion journal platform, or via e-mail, we would be happy to do this.

Major Point 2. [Hazard vs. risk] The second issue is that the authors seem to confuse the hazard with the risk. Hazard is an essential component of risk assessment, but it is not the risk. So, I think that introducing vulnerability interactions in the multi-hazard assessment is not proper (like they did in their figure 1). Again, Marzocchi *et al.* (2012) addressed this distinction in their Figure 2. I emphasize that this distinction is not only semantic. In a multi-hazard/risk perspective, it is important to mention that hazards cannot be (usually) compared, while the risks can. In fact, hazards are usually represented by curves that represent the exceedance probability of some quantity of interest, like ash fall thickness, ground shaking acceleration, etc. So it is not clear to me how we can compare them meaningfully and say when a hazard is higher than another one. On the other hand, the associated risks can be easily compared.

Authors: We agree with the reviewer that there is a substantive difference between hazard and risk, and do not wish to convey in our manuscript that these are interchangeable. We propose revising the figure caption for **Figure 1** and associated text in **Section 2** (pages 3–4) to make our meaning clearer, and remove any confusion about where we are referring to hazard and where we are referring to risk. Our **Figure 1** (from Gill

and Malamud, 2014) originally related to the transition from multi-layer single hazard risk assessments and multi-hazard risk assessments. Our reading of the multi-hazard literature suggested that it was common to use the term ‘multi-hazard risk’, although we also acknowledge that multi-risk is a valid alternative.

- 5 **Major Point 3. [Triggered vs. increased probability]** The final issue is about the distinction between “triggered” and “increase probability” made by the authors. This distinction is not clear to me. It seems that the authors assume that triggering is a deterministic link between hazards. In my view the concept of triggering and of increase probability are identical, at least this is true in seismic and volcanic hazard. We can talk of deterministic causal relationship only retrospectively (when you have already observed that one event triggered another one). But when we see the problem in a prospective way, the occurrence of an event **may** increase the probability to trigger another event, but very rarely we can be sure about this triggering. Of course the authors can mean something different, but I think that this distinction has to be clarified.

15 **Authors:** This is a thoughtful and stimulating comment, and we appreciate the reviewer’s contribution. We propose, following the below outline of ideas, adding a discussion in **Section 4** of our manuscript, where we outline our reasons for distinguishing triggered and increased probability as two different groups, while also acknowledging these two terms (triggering, increase probability) are end members. We will also highlight that we are not ‘only’ discussing deterministic links, and that randomness (stochasticity) is certainly a key element. We believe the manuscript will benefit from a stronger explanation.

20 We propose two themes where one can differentiate between one event *triggering* another event, and one event *increasing the probability* of another event.

- 25 • *Theme 1. Direct vs. indirect sequence of physical processes between the primary and secondary hazard.* Although we recognize there can be a continuum between ‘triggered’ and ‘increased probability’ relationships in terms of meaning, we believe that one can roughly (and at a certain level, intuitively) differentiate between these relationships by considering direct vs. indirect sequences of interacting physical processes between the primary and secondary hazards. For an example of a (roughly) direct sequence, the addition of water to geological material on a hillslope can directly trigger landslides (heavy rain → landslides). In contrast, an example (roughly) of an indirect sequence, is a forest fire removing vegetation which in turn reduces the shear strength of the slope and is thus much more prone to landsliding in the future if there is an earthquake or heavy rain (forest fire → reduced slope strength → [with external trigger of an earthquake] landslides). In this example, some of the population of landslides may occur during a rain or earthquake event that would not have occurred if the forest fire had not occurred. Another example of an indirect sequence is the impact of ground subsidence on flooding. Subsidence in itself may not trigger a flood, however it could make flooding more likely to occur in the event of a river spilling over its banks, a storm surge or a tsunami.
- 35 • *Theme 2. Temporal sequences.* We believe it is also possible to differentiate between triggering and increased probability relationships by considering the timing of the sequence of events. Take the following time sequence (arbitrary units and lengths of time for the windows):

Time Window 1 [Primary Hazard Window] **Time Window 2A** **Time Window 2B**

45 Using this time sequence, both forward looking (i.e., during **Time Window 1** which occurs before the primary hazard) and retrospective approaches (i.e., during **Time Window 2A** and **2B** which occurs after the primary hazard, and includes the secondary hazard) can help differentiate between triggering and increased probability relationships. As an illustrative example, we will take an earthquake as the primary hazard, and a triggered landslide population event as the secondary hazard:

- 50 • **While in Time 1 what will happen in Time 2A and 2B [forward looking]?** Prior to an earthquake [primary hazard] occurring [**Time 1**], it can be stated that given an earthquake, landslides [secondary hazard] may occur in the time period after the earthquake (e.g., minutes

to days) [**Time 2A**]. Furthermore, while in **Time 1**, we can state that more landslides may occur much later after an earthquake event (months to years) [**Time 2B**] due to reduced shear strength of the slope (similar to an indirect sequence of physical processes given in Theme 1 above). A different response is likely to be needed at an operational level for these two timings.

- **While in the interface between Time 2A and 2B, what has occurred in Time 1 and 2A [retrospective] and Time 2B [forward looking]?** Immediately after an earthquake [*primary hazard*] has occurred, we can identify any landslides [*secondary hazard*] that were triggered by the earthquake. We can also look forward to **Time 2B**, and state that there is now an increased probability of landslides due to the decreased shear strength of the slopes in the region.

- **While at end of Time 2B, look back at Time 1, 2A and 2B [retrospective].** At the end of **Time 2B**, we look back retrospectively to assess what landslides have been triggered directly by the earthquake (done through triggered landslide event inventories) and those landslides that have resulted from decreased shear strength (more difficult to quantify in actual practice).

When generalising across these three time windows, it is perhaps helpful therefore to recognise that an earthquake [*primary hazard*] can both trigger and increase the likelihood of landslides [*secondary hazard*] occurring in [**Time 2A and 2B**].

Therefore, while we agree that there are similarities between these two interactions types in that they both represent a change in probability of a secondary hazard (e.g., landslide) given a primary hazard (e.g., earthquake), we would suggest that they can be characterised by two end-member types (with a continuum between them):

- i. *Triggering*: A probability associated with a threshold being reached or passed.
- ii. *Increased Probability*: A probability associated with a change in environmental parameters so as to move towards, but not reach a particular threshold.

We would suggest that for the purposes of operational hazard management, it is beneficial to consider both (i) and (ii) above, distinguishing between the two interaction types. For any given window of time after a primary hazard, agencies such as civil protection professionals may want to know what the likelihood is of landslides occurring (being *triggered*), but also whether there is a change in the likelihood of landslides beyond this window of time (*increased probability*). Again, if you would like to correspond further on this issue, either through the discussion journal platform, or via e-mail, we would be happy to do this.

Optional Point 1. As a final suggestion, I would like to see a little bit more emphasis on the probabilistic and quantitative nature of hazard assessment. This is just a suggestion and it is not mandatory, but I do think that quantitative assessment of the hazard (and of the consequent risk) is the only possible strategy to plan rational risk reduction actions.

Authors: We agree with this reviewer (and the first reviewer) that there is an important role for quantitative hazard assessment methods. In our revised manuscript will provide a more substantive discussion of quantitative hazard assessment, notably in **Section 2** (Single vs. Multi-Hazard).