28 June 2019

Dear Professor Fuchs (Editor, NHESS),

Please find in this document an overview of the revisions made to our manuscript NHESS-2018-363 "Regional Interaction Frameworks to Support Multi-Hazard Approaches to Disaster Risk Reduction (With an Application to Guatemala)" by Gill *et al.*.

We thank you for your directions: "*I received the two reports of the referees as well as your comprehensive answer to their comments. I kindly would like to thank you for the numerous and inclusive explanations of what you plan to revise. In general, the topic presented is of considerable interest to the readers of the target journal, and given your reply I kindly would like to ask you to proceed with the revisions of your manuscript. As indicated by both of the referees, the main focus should be on RCs 1-4 and 18-28 according to your numbering in the Author Comment Supplement. I wish you good success with your work, and I am looking forward to receive a revised version.*"

Our revisions are largely in line with the information we previously prepared and submitted online during the discussion phase in response to the reviewer's comments. Below we include a point by point response, outlining our changes. We have also included a version with all changes tracked, and a clean version of the manuscript with all changes accepted.

Kind regards,

Joel Gill (on behalf of all authors)

Reply to reviewer comments (NHESS_2018-363)

We again thank both Christian Huggel and Kirsten v. Elverfeldt as reviewers for their thoughtful and extensive comments. Both reviewers have highlighted the need for more framing of this manuscript's research and ideas, and an enhanced discussion of why the manuscript might be of interest to others outside of Guatemala. We currently have a second manuscript in review (*International Journal of Disaster Risk Science*) which sets the scene for some of what we have presented in this NHESS submission by assessing the key challenges of constructing and populating regional interaction frameworks—in other words considering the much broader and philosophical implications of going from global to regional multi-hazard frameworks. While we considered the benefits of bringing the two manuscripts together into one submission, we decided that there would be too much information for one submission, and thus divided them into two manuscripts:

- **Manuscript A (IJDRS).** Identifies, characterises, and makes recommendations as to how to address the principal challenges of developing hazard interaction frameworks for use in regional settings.
- **Manuscripts B (NHESS).** Presents an interdisciplinary approach to developing comprehensive, systematic and evidenced regional interaction frameworks to support multi-hazard approaches to disaster risk reduction. We apply this approach in Guatemala, developing regional interaction frameworks for national and sub-national (Southern Highlands) spatial extents.

We now recognise that in splitting them we lost some of the broader framing in Manuscript B (submitted to NHESS), and therefore more framing is needed in the NHESS manuscript to illustrate (i) the current complexities of constructing regional interaction frameworks, and (ii) how the approach we set out in the NHESS manuscript helps to advance this theme.

We believe that our response to reviewers, and the changes we have now made (summarised below), these have helped to address the disconnect between what we have presented in our manuscript to NHESS and the broader multi-hazard literature. We appreciate both reviewers bringing this to our attention and agree with this general sentiment expressed in their reviewer comments. Here is how we have modified our NHESS manuscript:

- ***Section 1: Introduction***. We have restructured the introduction, to better articulate our research questions, as well as framing our work in the context of the complexities of studying hazard interactions. We have highlighted our three main research questions:

    - *For a defined spatial region, how does one construct and populate a synthesis of all relevant potential natural hazard interactions using blended sources of evidence for past case histories and theoretical future possibilities from that region's characteristics? [We develop, confront and discuss an approach for Guatemala that has broader relevance and applicability].*

    - *How do interactions documented in the literature contrast with the knowledge of hazard/civil protection professionals operating in the region?*

    - *What are the implications of our regional interaction frameworks for multi-hazard methodologies to support disaster risk reduction, management and response?*

  We address these by collating and uniting diverse evidence sources, from multiple disciplines, through a visual database (i.e., a matrix) of potential interactions. We demonstrate an approach that is *comprehensive* (includes a broad array of potential hazards), *systematic* (exploring the potential for interactions in Guatemala between each hazard pairing) and *evidenced* (documenting the evidence for the existence of interactions). We have also updated the abstract.

- ***Section 2***: ***Evidence Used to Inform the Regional Framework.*** We have made clearer in this section that we are setting out (i) our data (evidence types) and (ii) the methods used to collect and unite this to address our research questions (now more clearly articulated in **Section 1**). We have made some edits to **Section 2** to make it more streamlined, moving some material to the **Supplementary Material**.

- ***Section 3: Regional Interaction Frameworks (Visualisations).*** We have expanded **Section 3.4** on networks of hazard interactions (or cascades), to include more examples from the evidence collected, and an expanded discussion of the importance of considering such networks.

- ***Section 4: Discussion.*** We have moved the limitations to **Section 2**, and expanded the discussion of how the methods developed in and results of this paper can help to improve both disaster risk reduction practice and advance multi-hazard research. We have characterised the challenges of adding quantitative information to the matrices we present, and outlined potential future research directions to move this forward.

- ***Figures and Tables:*** We have removed Tables 2, 4, 5, 6 and 11 (moving material to the Supplementary Material where necessary), and simplified Table 10. We have removed Figures 1 and 4, and edited Figures 5, 6, and 9 to make them easier to read, removing unnecessary information.

Reviewer 1: Christian Huggel

[RC1] The research on multi-hazards has increased in recent years, recognizing their importance for generating and exacerbating hazards. Several frameworks and approaches have been developed and applied, and this paper nicely considers them here. Multi and cascading hazards are probably of particular relevance to developing countries, such as in Central America and Guatemala. I basically like the approach taken here to draw on diverse sources of information and also include stakeholders of the country. The process is transparently described, yet not in a very clear and coherent way. This brings me to my first main point: the paper, and in particular sections 2 and 3, are quite hard to follow and often somewhat confusing (e.g. the different frameworks and matrices, regional, national, sub-national). As detailed below I think there is potential to shorten and streamline and simplify the text. The methods and results are merged in section 3. The authors may consider separating methods and results in two sections. I'm aware that there may be an issue because the framework, and thus the methods, are somehow representing the results. I recommend to clarify and point the reader more specifically to this issue (whatever the authors chose eventually as an approach to this problem). There is a large number of figures and an excessive number of tables in the paper. I think tables 2, 4, 5, 6 could be removed, and I have some question marks for tables 10 and 11 (see below).

> [AC1] We recognise that both reviewers have noted the need to streamline the paper and simplify the text, and have strived to do this while also adding more information to key sections highlighted by the reviewers. We have moved some material from Sections **2** and **3** to the supplementary material, and removed five tables and two figures.

[RC 2] The other main point, maybe more fundamental, is the following one: I'm wondering what do we finally learn from this study? Although I appreciate and recognize the important efforts made to collect information from a large set of diverse sources and interacting with stakeholders, the result is a relatively simple matrix which I consider to be a bit thin for a journal paper. This point becomes especially acute if you consider that this same matrix and framework was already developed and presented in the previous Gill and Malamud 2016 and 2017 papers. Do the authors think it is justifiable to yet publish another paper which presents basically the same result with (in my opinion) only little additional substance by applying it to Guatemala? The substance may actually be there, i.e. in the many sources studied, but it is currently hardly in the paper. The authors may therefore reconsider how they present what they have researched (cf my comments below). For instance, I hoped to find more quantitative information regarding the physical processes, e.g. how often do such interactions occur? I'm aware that with the approach taken providing quantitative information related to the physical processes may not be so evident but I would like to encourage the authors to think about it.

> [AC2] We believe that this paper builds on the global approaches that we set out in our Gill and Malamud (2014, 2017) papers, and refines/applies these to help characterise potential hazard interactions at national and sub-national spatial scales. While the matrices take the same visual form as the ones in Gill and Malamud (2014), the approach we have used to construct and populate these

matrices are significantly enhanced. We would emphasise that what we are presenting in this paper is not just a matrix output, but also a discussion of a process to go from global to regional scales (interdisciplinary, multi-method approach) that enables the development of comprehensive, systematic and evidenced overviews of potential hazard interactions. We are presenting a suite of visualisations that build on our Gill and Malamud (2014 and 2017) papers with a greater range of hazard types, and matrices that are populated using different evidence. In Gill and Malamud (2014), done at a 'global' and high-level scale, we relied on published literature and case studies, whereas in our NHESS manuscript we have integrated diverse evidence types including interviews, data generating workshops, and interrogation of civil protection bulletins.

We therefore point to the substance of this paper being:

- Development and description of an interdisciplinary, multi-method approach that enables the development of comprehensive, systematic and evidenced overviews of potential hazard interactions at a regional (e.g., national/sub-national) scale. This contrasts with the existing studies of potential interactions, which are generally selective about which hazards they include and do not describe the evidence for including/excluding certain hazards or interactions between hazards.
- Application of this approach in the context of Guatemala to produce a suite of comprehensive and robust frameworks of potential hazard interactions for two spatial scales (national and sub-national), and describes their application to disaster risk reduction (including through initial efforts to embed them into key government agencies in Guatemala). The matrices presented include 21 to 33 hazards (compared to 6 to 11 natural hazards in the surveyed literature examples, which we summarize in **Table 1** of our manuscript).
- Description of an approach for contrasting current individual/collective knowledge with the published regional interaction framework, using Matthews' Correlation Coefficient. The results of this both underpin *why* developing comprehensive and evidenced frameworks of interactions is important (highlighting knowledge gaps), and provides a tool (and we recognize other tools could also be used) to monitor changes in understanding of hazard interactions over time.

We recognise that there are additional layers of information that could be helpfully added to what we have currently presented (e.g., how often each interaction occurs). We do not currently have this information in a level of detail that would be helpful to the reviewer or reader, and it was beyond the scope of our initial research remit (which we have set out with more clarity in **Section 1**). For each interaction (not hazard), understanding the frequency-magnitude of occurrence and the range of potential impacts would involve significant work and collation of diverse information that we currently do not have (as noted on page 21 of our original manuscript).

We have highlighted some of the above directions and intent of our work in our introduction, and enhanced the discussion in **Section 4** of quantitative characterisation of hazard interactions, noting current challenges in doing this and how future work could help to enrich this characterisation of potential interactions. We have suggested one approach is using an online wiki-style system where users can click on a cell in the matrix, and upload relevant papers, datasets, or their own assessments of frequency-magnitude to help improve this understanding. We have also emphasized what readers outside of the case-study area of Guatemala might learn from our study.

We note that in **Section 4.2** we have set out a quantitative characterisation of hazard and disaster professionals' individual and collective knowledge of hazard interactions – and outlined the significance of this assessment.

[RC3] Most of, but not all, the interactions are quite obvious and well known, such as storms generating floods and landslides. In fact, most of the paper, including the matrices, focus on two interacting processes but the most interesting aspect I found were the cascading hazards (more than 2 processes involved) but unfortunately they receive only little space. Is it possible to extend this issue, beyond the two case studies (and possibly at the expense of sections 2 and 3 which could be shortened)?

[AC3] (a) The reviewer notes that hazard interactions in **Figures 3** are obvious. We accept that many hazard pairings included in the matrix (e.g., storms triggering floods, earthquakes triggering landslides), and their spatial relevance to Guatemala, are well known. However, we note that this paper is establishing an evidenced framework (expressed as a matrix) of potential interactions. This national scale framework of potential interactions is, we believe, rarely discussed in the current hazard literature, as well as the method for developing a comprehensive and systematic framework. This manuscript has also contrasted the full list of potential interactions in **Figure 3**, with individual and collective knowledge (**Section 4.2**) in the region. The results of this highlight that the spatial relevance of the interactions are not always obvious, and therefore a systematic documentation and visualisation of potential interactions could help. We have made these points clearer in the text. (b) While the matrices focus on how any one single hazard could trigger or increase the probability of another single hazard, it is possible to use these matrices to extract examples of longer cascades. We have made this clearer in the text. We have expanded **Section 3.4** on networks of hazard interactions. We have included an additional extended example, and an expanded discussion of the importance of such networks.

[RC4] Finally, my impression was that some more reflection is needed by the authors. The paper sometimes has more project report character, leaving the reader with a feeling that the authors were short of time. One would like to see more synthesis and less details that are often not particularly relevant. I suggest that the authors take sufficient time to reflect on the objectives and the research questions (both not mentioned in the text) and what can be learned; also how this study contributes to scientific progress. Especially the last point is not evident for me and is not addressed in the paper either. Overall, I'm not sure whether the authors will be able to revise the paper in a round of major revisions in a way that is in my opinion needed, or whether they would rather like to take their time to re submit it at a later stage.

[AC4] We have addressed this comment by reviewing both the introduction and the discussion sections, and improving the way in which we frame the work we have done.

- We have clearly articulated our research questions (see the opening cover letter, pp. 1 to 2, and **AC2**) in the introduction, and in doing so help to frame the subsequent sections.
- We have expanded the discussion section to outline how this manuscript advances both multi-hazard research, and disaster risk reduction practice.

A key step in understanding risk (Sendai Framework Priority for Action 1) is understanding the hazard landscape of a region (i.e., the relevant single hazards, and how they may interact to generate combinations or cascades of interactions). Currently, regional studies of potential hazard interactions are sparse and none of these set out a replicable and scalable method for systematically doing this. In our paper, we describe and apply an approach that is replicable and can be applied at regional, national and sub-national spatial extents.

In the multi-step, method we present through an application to Guatemala, we include 2 to 3 times the number of natural hazards that other regional studies have included, and (rarely done) comprehensively set out the evidence for these interactions being spatially relevant. We integrate evidence from both natural and social science methodologies to construct a visualisation that – when returned to Guatemala – was shown to provoke cross-hazard and cross-institutional dialogue.

We believe this supports the scientific community to help construct more evidenced and detailed profiles of relevant interactions for diverse user groups, and through these profiles identify specific research and innovation gaps, as well as knowledge exchange and collaboration opportunities. We have integrated some of these comments, and expanded on them, in Section 4.

Specific comments:

[RC5] Introduction: I think this section could benefit from more text on the processes. The complexities of interacting hazard processes seem to find little attention.

[AC5] We have added further detail on the complexities of interacting hazard processes to the introduction.

[RC6] Section 3.3.1: this is an example of a section which is quite confusing to read. The six points made towards the end are not really clear and are they needed?

[AC6] We have moved some information into the Supplementary Material to improve the clarity of **Section 3.3.1**.

[RC7] Section 3.4: as mentioned, I found this the most interesting (and probably novel) section but it is not strongly developed. Is a more quantitative analysis possible?

[AC7] We have expanded **Section 3.4** on networks of hazard interactions. We have included an additional extended example from the evidence collected, and an expanded discussion of the importance of such networks. This results in (i) profiling of more examples from Guatemala, and (ii) synthesising key implications for disaster risk reduction from such examples. While we do not have the data to apply such a method to any of the scenarios we present, we can point the reader here to existing methods for quantitatively assessing probabilities of specific hazard cascades (e.g., using event scenario trees, such as done by Neri *et al.* (2008, 2013).

[RC8] Page 17, lines 1-3: another option could be to work with / engage researchers with appropriate level of Spanish language.

[AC8] We acknowledge this is one approach that would work, and included reference to this in the text.

[RC9] Page 17, lines 4-12: a very important point in my experiences working in such sociocultural environments. It applies in particular if risks are considered.

[AC9] We agree, and felt it was helpful to emphasise in the write up given the importance of the natural science community being more aware of such considerations.

[RC10] Page 17, lines 25-28: what are the implications of this points?

[AC10] We asked workshop participants to describe two different types of interaction: (1) one hazard triggering another hazard, and (2) one hazard increasing the probability of another hazard. If confusion between these two types of interaction existed, it is possible that participants may have inadvertently characterised an interaction as one type when they meant the other (i.e., a specific hazard pairing suggested to be a triggering relationship may actually be means to be communicated as an increased probability relationship). We do not believe the results expressed in **Figures 3** and **6** are unduly influenced by this, given the use of multiple evidence sources to construct them. We have changed some wording to clarify this.

[RC11] Discussion section: has interesting and important elements for people working in similar environments. As indicated above, I would like to see more reflection on how this paper advances research on multi-hazards.

[AC11] Our discussion section currently explores how regional interaction frameworks can advance multi-hazard risk reduction. We have focused more on the relationship of our work to practice, rather than research, but can expand the discussion to include more on the latter. We currently explore collective knowledge of hazard interactions in Guatemala, and note that interaction frameworks help to facilitate enhanced cross-institutional dialogue about hazard interactions, their likelihoods and potential impacts. This could help to strengthen collective knowledge of hazard interactions, and the ability of an individual to access this knowledge. We also described the response of hazard and civil protection professionals in Guatemala to our results, and their perspectives on 'next steps'. We also briefly describe in **Section 4** how interaction frameworks can help to improve decision making in key agencies engaged in DRR and civil protection. We have expanded this section to further outline how this work advances multi-hazards research. For example, interaction frameworks can guide future research priorities by determining where there is a lack of evidence and/or understanding of certain interactions. See also **AC2, AC4**, **AC36**.

[RC12] Figure 1: not sure this Figure is needed. Considered that the hazard codes need to be explained which is only done is subsequent figures.

[AC12] We have removed Figure 1, and integrated relevant information into old Figure 2.

[RC13] Figure 5: many place words are not particularly well readable.

[AC13] We have edited the figure to try and make the text larger and clearer.

[RC14] Figure 9: I was wondering whether the color code and the symbols are really used in this figure?

[AC14] We have adjusted the legend in this figure to remove this information.

[RC15] Table 8: I appreciate the level of detail in this table. But it was not clear to me how the hazard sub-types are then used? It is rather just a list which has a value in its own but no further relevance for the paper?

[AC15] The list presented in **Table 8** was developed from the evidence described in **Section 2**, as a classification of hazards relevant to Guatemala, using categories that many stakeholders in the region would understand. We take our classification and use this as the basis for the analysis in **Figures 6** to **8**. We have left **Table 8** in the manuscript, but added a note to **Section 3.2** to outline how this classification is integrated into the rest of the paper.

[RC16] Table 10: I'm not sure how well this table informs us. I found it rather confusing. We see the different bulletin reports which are not necessarily in a logical order (reflecting some issue there) and then the narrative summary. What is really the purpose of this table?

[AC16] The purpose of this table is to demonstrate an approach for identifying relevant, complex cascades that have previously impacted Guatemala. We highlight that while evidence exists for these cascades in a set of civil protection bulletins, they are not outlined in a coherent way but often different strands are included in different bulletins. **Table 10** presents four examples of the cascades that the reviewer highlighted to be particular interesting in **RC3**. We include the bulletin information to connect these examples to the evidence that describes them, but accept that the event description and narrative summary could be combined to make the table more succinct. In **AC3**, we note that we have expanded **Section 3.4** to include a more detailed discussion of cascades. We have also revised the text introducing **Table 10** to better articulate its purpose.

[RC17] Table 11: I'm not convinced that this table and information needs to be part of the paper (and then probably the respective section as well). Please re-consider.

> [AC17] We believe that it is important to make reference to anthropogenic processes in this paper, given their ability to trigger and/or catalyse natural hazards. Many stakeholders emphasised the importance of anthropogenic activity in triggering landslides in Guatemala, for example. Reviewer 2 also noted this to be an interesting section (see **RC35**). We have kept the section short and signpost to other literature. We have moved **Table 11 t**o the supplementary material.

Reviewer 2: Kirsten v. Elverfeldt

[RC18] Summary. The paper deals with the development of regional interaction frameworks for Guatemala by utilizing literature reviews, field observations, interviews, and workshops. With the information thus gathered, a classification scheme of natural hazards is determined. Matrices were used to further determine hazard interactions, with a strong focus on the interaction (triggering or increasing the possibility) of two hazards.

Review summary

1. Does the paper address relevant scientific questions within the scope of NHESS? The paper falls into the subject areas of NHESS. It might fit the scope to understand the behaviour of hazardous natural events.

2. Does the paper present novel concepts, ideas, tools, or data? This remains rather unclear since the authors do not explicitly state the aims, research questions, hypotheses, and novelties of the paper.

3. Are the scientific methods and assumptions valid and clearly outlined? Assumptions are not made explicit. Methods are valid and transparently explained, but explanations would need streamlining and re-structuring.

4. Are the results sufficient to support the interpretations and conclusions? Yes, though the novelty of the results needs to be stressed. I have the feeling that there could be more to the paper than the authors actually delivered. It is difficult to review this paper because the authors leave it to the reader to "read between the lines" and to draw conclusions by herself/himself. In a nutshell, it remains somewhat unclear what we gain by the paper.

5. Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes.

6. Does the title clearly reflect the contents of the paper? Yes.

7. Does the abstract provide a concise and complete summary? Yes. However, in the abstract research questions, hypotheses, aims,: : : are missing (as they are in the text).

8. Is the overall presentation well-structured and clear? No. Needs to be improved.

9. Is the language fluent and precise? Yes.

10. Are the number and quality of references appropriate? Yes.

> [AC18, addressing the comments highlighted in bold above]. The reviewer notes that the manuscript needs some streamlining and restructuring, clearer articulation of assumptions, and added emphasis on the novelty and importance of the results. We have:
>
> - Revised the abstract and introduction (**Section 1**), including making our objectives and research questions clearer, as articulated in the cover letter of this response.

- Revised the introduction (**Section 1**) and discussion sections (**Section 4**) to make it clearer what the novelty of this paper is, and how this advances disaster risk reduction in multi-hazard contexts (see **AC2** and **AC4**).

[RC19] Page 2, Line 3: The authors start very abruptly with the topic of regional interaction frameworks, without really framing their topic. They present the term "regional interaction framework" right at the beginning, whilst the definition of the term only comes one paragraph later.

[AC19] We have expanded the introduction, with more framing of the topic, and its relevance to multi-hazard approaches. We have included a definition of the term *regional interaction framework* immediately after its first use.

[RC20] Page 2, Line 4: It remains unclear in how far your approach is interdisciplinary. Even more so, it remains unclear what "the approach" is that is being applied. I suggest that at least (!) a citation of the previous Gill and Malamud papers on this subject should be given here; it'd be even better to continue (after framing your topic) with briefly explaining what your approach is. In general, the writing style of section 1.1. is rather additive than providing an argument for why the study is relevant or in what context it is to be understood. The aim of the paper remains unclear as well as hypotheses, assumptions, and research questions.

[AC20] In our rewriting of the introduction (see **AC5**, **AC18**, **AC19**), we have set out the approach that we are following and better articulated our research questions.

[RC21] Page 3, Line 13: Is Table 2 necessary? Please consider deleting the table.

[AC21] We have moved this table to the supplementary material.

[RC22] Page 3, Line 20: Here, you distinguish between hazard interactions on the one hand and networks of interactions (cascades) on the other hand, whilst on page 2 you summarized all interrelated effects (including cascades) under the umbrella of the term hazard interactions. Please consider handling this coherently. To me, section 1 is rather overstructured. For example, section 1.3 consists of only three sentences. I'd suggest to re- and de-structure the section, including a better framing of the topic and to be less descriptive and additive, and to put up an argumentation.

[AC22] We have reviewed language and tried to be consistent throughout the. As noted in **AC5** and **AC19** we have expanded the introduction and included more material to frame this discussion. This has resulted in **Section 1** being restructured. Our writing style preference is to retain a 'structure of paper' section at the end of the introduction to guide the reader.

[RC23] Page 4, Line 12: Suggestion to delete Table 4.

[AC23] We have deleted this table, and included the content within the manuscript text.

[RC24] Page 5, Line 30f: I'd also suggest deleting Table 5.

[AC24] We have deleted this table, and included the content within the manuscript text.

[RC25] Page 7, Line 6: Suggestion to delete Table 6

[AC25] We have deleted this table, and included the content within the manuscript text.

[RC26] Page 8, Line 16: Here, and at quite a few instances before and afterwards, you refer to later sections in the paper. This makes reading rather difficult and raises the question whether the paper could be structured more coherently. If you discussed the workshops in section 2.6, why do you discuss their limitations so much later in the paper? As a rule of thumb references to content delivered later in a paper should be avoided.

[RC27] Page 9-10, Lines 15ff: In the paper, comparatively long sections are dedicated to referencing to previous or later content. Suggestion to shorten and re-structure the paper.

[RC28] Page 10, Line 8ff: this explanation of what is required for regional interaction frameworks comes at a rather late stage. Since you mention regional interaction frameworks so often on previous pages, I'd suggest to bring together issues that belong together. This would also decrease the amount of references to previous and later sections in the paper. The paper in its current stage is rather difficult to read and readers might easily lose track of what is the intention of the paper or a section in its own.

> [AC26] [AC27] [AC28] We have reviewed references to previous and future content and tried to reduce this. We think some of this referencing can be helpful, to signpost to the reader that we are building on something that has come previously. We have grouped detail on regional interaction frameworks in Section 2.8

[RC29] Page 10, Line 19: this has been mentioned before (on page 2)

> [AC29] We have rephrased **Section 3.1** so it better builds on what was presented earlier in the manuscript.

[RC30] Page 12, Line 4: In table 8, A-E are named differently from what was proposed in the text.

> [AC30] This is now corrected.

[RC31] Page 12, Line 15: Figure 4: I am not sure that it is useful to have the same figure as in figure 3 repeated only to deliver the information of how many evidence sources were used. I think it is enough to deliver this information via text only (the number of figures and tables is really high for this paper, and not all of them seem to be necessary).

> [AC31] The purpose of **Figure 4** is to rapidly assess where there could be uncertainty, and future research needed. We do not think this would be easy if the information was presented in the text. We tried to add additional information to **Figure 3**, but this reduces the clarity of this key figure. We have moved **Figure 4** to the Supplementary Material, and referred to it in the figure caption of old **Figure 3**.

[RC32] Page 13, Line 14: Figure 5 – again, I'd expect to get this information much earlier, e.g. in section 1.2. In table 9, evidence categories A-E differ again from text

> [AC32] We have moved **Figure 5** to the introduction. A-E are now consistent between **Table 9** and the text.

[RC33] Page 13, Line 24: Figure 6 text is too small, rather impossible to read; is it upside down?

> [AC33] We have increased the text size and reduced the amount of information presented in this figure to increase its clarity.

[RC34] Page 14, Line 18ff: I cannot quite see the difference between example 1 and 4 (Table 10)? It would also be helpful if you explained what you mean by "linear event", "multi-branch event" etc. This again is some example for how you (superficially) describe rather than explain or argue.

> [AC34] We have added further explanation to what we mean by these terms, and enhance the explanations in this section as noted in previous comments (**AC3** and **AC16**). Examples 1 and 4 do

have some similarities, and we have removed one from **Table 10** to help make the discussion more succinct. We will also include a simple, visual summary of each example to illustrate the example.

[RC35] Page 15, Line 13: In table 11, evidences A-E differ from text

[AC35] This is now corrected.

[RC36] Page 16, Line 1: It would be useful if you explained and/or detailed the "useful insights" that are generated. I really do like the way you collate information via different methods (literature, interviews, workshops etc.). But I think your paper stops when it gets most interesting, i.e. hazard cascades/networks and anthropogenic impacts on hazard interactions. Furthermore, since you do not explain what you gain aside from a visualisation and collection of (maybe more or less) known hazard interactions, this important aspect remains far too vague. This might also be because the reader doesn't know your aims, hypotheses, and research questions.

[AC36] We refer to our reply to **AC2** and **AC4**. We would emphasise that what we have gained extends beyond the location-specific visualisation, to a replicable and scalable method that can be applied in other contexts to better understand the hazard landscape. A comprehensive overview of potential hazard interactions allows agencies responsible for hazard monitoring and response to assess if current disaster risk reduction and response strategies, and communication and collaboration mechanisms, can be enhanced to recognise the complexity represented in this paper. We have extended **Section 4** to better articulate the significance of what we have developed and how this can be used (and augmented) to improve disaster risk reduction, along with signposting the relevance of our work in the introduction and other selected places in our manuscript. For example, we have added to **Section 4.4** to describe how interaction frameworks can help to improve decision making in key agencies engaged in DRR and civil protection, such as guiding future research priorities by determining where there is a lack of evidence and/or understanding of certain interactions.

[RC37] Page 16, Line 10: This is another example that re-structuring the paper is necessary. The limitations and uncertainties should be mentioned where you present the respective method; here, you can then focus on the discussion.

[AC37] Many of the limitations we present cut across multiple evidence types, and therefore the limitations are more succinctly described when presented together. We have, however, moved these to end of **Section 2** so that they naturally come after the descriptions of evidence types.

[RC38] Page 16, Line 29: I'm confused by the additional information about translators – have you used them? If not, why? If you did, this should be mentioned earlier.

[AC38] We used a variety of translation methods, and have added a line about this in **Section 2.5** (Stakeholder Engagement: Interviews)

[RC39] Page 17, Line 25ff: Plus, if you use a pre-defined hazard scheme without the option to add other hazards and interactions, participants' knowledge might be missed out.

[AC39] A line was added to the list of limitations.

[RC40] Page 18, Line 22: Table 9 – colour code and symbol code (legend) to be deleted

[AC40] We have removed this information from **Figure 9**.

[RC41] Page 19, Line 17: Why did you set these thresholds and not others? Explanation would be good.

> [AC41] Thresholds of 3 and 5 were selected arbitrarily to demonstrate how this approach could be adjusted to remove those interactions only volunteered by one (or a small number of) professionals, thus acting as a form of quality control. We could have chosen thresholds of 2 or 4, but determined that increments of 1, 3 and 5 would give a spread of results to illustrate the discussion. We do not place great emphasis on the specific threshold in the manuscript, nor try to defend this as being a critical choice. Rather we demonstrate how this approach can help to examine differences between stakeholder perspectives and our national interaction frameworks, and monitor changing understanding and perceptions of natural hazard interactions. We have added a note regarding this to the text.

[RC42] Page 1, Line 11: , and evidenced : : :

[RC43] Page 1, Line 15f: to reduce the number of parentheses, I'd suggest to re-write a part of the sentences as follows: (internationally accessible: 93 peer-review and 76 grey literature sources); (locally accessible civil protection bulletins: 267 bulletins from 11 June 2010 to 15 October 2010)

[RC44] Page 2, Line 3: , and evidenced : : :

[RC45] Page 2, Line 13: Delete "Here, and"

[RC46] Page 2, Line 27: Put "and" in italics (two times)

[RC47] Page 2, Line 29: Consider rephrasing: : : :"that our approach also supports implementation"

[RC48] Page 3, Line 5: , and surface collapses

[RC49] Page 3, Line 7: , and cold spells

[RC50] Page 3, Line 23: for coherence, I'd suggest to change the heading to ": : : regional interaction framework"

[RC51] Page 3, Line 25: evidences [current wording is ok]

[RC52] Page 4, Line 3: , and media reports (please check for "comma + and" throughout the document).

[RC53] Page 4, Line 6: consider rephrasing "an overview of Guatemala's hazard-forming"

[RC54] Page 4, Line 15: include is repetitive in the sentence

[RC55] Page 4, Line 17: verb missing?

[RC56] Page 7, Line 2: helped identifying [Corrected to 'helped to identify']

[RC57] Page 7, Line 7: selected locations [current wording is ok]

[RC58] Page 16, Line 9: Delete "."

[RC59] Page 19, Line 2: "." is missing

> [AC42–59] We have made these corrections, or confirmed that the current wording is correct (RC51 and RC57).

Regional Interaction Frameworks to Support Multi-Hazard Approaches to Disaster Risk Reduction (With an Application to Guatemala)

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Abstract. Here we present an interdisciplinary ~~-~~approach to developing comprehensive, systematic, and evidenced visual syntheses of potential hazard interactions at regional scales (or *regional interaction frameworks*). Frameworks can help to better understand the multi-hazard environment of a specific spatial extent~~to support multi-hazard approaches to disaster risk reduction~~. We set out our approach and apply this ~~approach~~ in Guatemala, developing regional interaction frameworks for national and sub-national (Southern Highlands) spatial extents. The ~~regional interaction~~ frameworks are constructed and populated using five evidence types: (i) ~~publications and reports (~~internationally accessible literature (~~)~~ ~~(~~93 peer-review and 76 grey literature sources); (ii) ~~publications and reports (~~locally accessible civil protection bulletins (~~) (~~267 bulletins from 11 June 2010 to 15 October 2010); (iii) field observations; (iv) stakeholder interviews (19 semi-structured interviews), and ~~a –~~(v) a stakeholder workshop ~~results~~ (16 participants). These five evidence types were synthesised to determine an appropriate natural hazards classification scheme for Guatemala, with 6 natural hazard groups, 19 hazard types, and 37 hazard sub-types. For a national spatial extent in Guatemala, we proceed to construct and populate a regional interaction framework (matrix form), identifying 50 possible interactions between 19 hazard types. For a sub-national spatial extent (Southern Highlands of Guatemala), we construct and populate a regional interaction framework (matrix form), identifying 114 possible interactions between 33 hazard sub-types relevant in the Southern Highlands. We also use this evidence to explore ~~networks of~~ multi-hazard interaction networks and anthropogenic processes that can trigger natural hazards. We present this information through accessible visualisations to improve understanding of multi-hazard interactions in Guatemala. We believe that our regional interaction frameworks approach to multi-hazards is scalable, working at global to local scales with differing resolutions of information. Our approach can also be replicated in other geographical settings~~, –~~. ~~In the discussion section, w~~We ~~with~~ demonstrate how regional interaction frameworks and the discussion of potential scenarios arising from them can help~~ing~~ to enhance cross-institutional dialogue on hazard interactions, ~~and~~ their likelihood, and potential impacts. We ~~also~~ review future research

directions and steps ~~that could help~~ to embed interaction frameworks into agencies contributing to implementation of the Sendai Framework for Disaster Risk Reduction.

1 Introduction

~~1.1 Regional Interaction Frameworks~~

The Sendai Framework for Disaster Risk Reduction (Sendai Framework) is a global plan to reduce disaster losses, adopted by UN member states in 2015. It emphasises the need for multi-hazard approaches (UNDRR, 2015), defined as *"the selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects"* (UNDRR, 2017). A key, but complex, step in understanding risk (Sendai Framework, Priority for Action 1), and the focus of our paper, is ~~therefore~~ understanding the multi-hazard landscape of a region (i.e., the relevant single hazards, and the processes by which they may interrelate to generate combinations or cascades of hazards).

Relationships between hazards include:

- *Compound (or coincident) hazards*, where two or more independent hazards impact the same region in time and/or space (e.g., a heat wave at the same time as an earthquake)
- *Concurrent or consecutive hazards*, where two or more independent hazards occur successively and cause cumulative pressures on a given region (e.g., a hurricane occurring a few days after an earthquake)
- *Triggering interactions*, where one hazard triggers another hazard (e.g., an earthquake triggering a landslide)
- *Increased probability interactions*, where one hazard increases the probability of another hazard occurring (e.g., a wildfire increasing the probability of debris flows given heavy rain),

These relationships can combine to form complex interaction networks. For example, tropical storms can trigger floods and/or landslides; volcanic eruptions can trigger wildfires that subsequently increase the probability of debris flows; and earthquakes can trigger regional subsidence which increases the likelihood of flooding. Many more examples, and extensive case studies, of such interactions feature in the literature (e.g., Tarvainen *et al.*, 2009; Kappes *et al.*, 2010; Gill and Malamud, 2014; Duncan *et al.*, 2016; Tilloy *et al.*, 2019).

Stakeholders involved in implementing the Sendai Framework (e.g., civil protection agencies, hazard-monitoring scientists, urban planners, development practitioners) will therefore all benefit from resources (e.g., tools, review reports) that help to increase understanding of the multi-hazard landscape of a region by systematically identifying and characterising potential hazards and hazard interactions. Building on global approaches for identifying and characterising hazard triggering and increased probability interactions set out in Gill and Malamud (2014, 2016, 2017), here we explore the following research questions:

1. For a defined spatial region, how does one construct and populate a synthesis of potential natural hazard interactions using blended sources of evidence for past case histories and theoretical future possibilities from that region's characteristics? *(Here we focus particularly on triggering and increased probability interactions, but discuss additional hazard relationships in the context of future developments of this work).*
2. How do triggering interactions documented in the literature contrast with the knowledge of hazard/civil protection professionals operating in the region?
3. What are the implications of this work on multi-hazard methodologies to support disaster risk reduction, management and response?

We address these questions ~~This paper~~by collating and uniting diverse evidence sources (e.g., field observations, interviews) from the natural and social sciences, through a visual database (i.e., a matrix) of potential hazard interactions at regional (e.g., national/sub-national) scales. We demonstrate an approach that is comprehensive (*includes a broad array of potential hazards*), systematic (*exploring the potential for interactions in between each hazard pairing*), and evidenced (*documenting the evidence for the existence of interactions*). We label these frameworks '*regional interaction frameworks'* defined to be visualisations that support the identification and characterisation of relevant hazard interactions in a defined region (from 10^2 to 10^6 km^2).

Currently, regional studies of potential hazard interactions are sparse, and none of these set out a replicable and scalable method for systematically doing this. **Table 1** outlines and characterises seven examples of frameworks for specific named regions or geographical features that include natural hazards and a deliberate attempt to characterise possible hazard interactions. While there is significant variation in the approaches used to construct and populate these frameworks, they helpfully demonstrate the scalability of regional interaction frameworks and issues to be considered when construction regional interaction frameworks. These examples also highlight some of the complexity in understanding potential hazard interactions. For example, while many multi-hazard studies focus only on two or three hazards (Ciurean *et al.*, 2018), the examples in **Table 1** all show regions exposed to a much larger range of hazards (6–11 natural hazards). This results in significant complexity when trying to constrain and characterise the potential relationships between natural hazards, using either qualitative or quantitative tools.

Building on these examples, we present and apply an interdisciplinary methodology in this paper to develop and enhance comprehensive, systematic and evidenced regional interaction frameworks. ~~develops~~ We apply this interdisciplinary approach in the context of Guatemala to produce a suite of comprehensive and robust frameworks of potential hazard interactions for two spatial extents (national and sub-national), and describe their application to multi-hazard disaster risk reduction in Guatemala. We trialled our approach in Guatemala due to (i) the hazardousness of the region, and (ii) logistical feasibility (contacts, language, accessibility). A broad range of natural hazards and anthropogenic processes in Guatemala make it an appropriate country to examine hazard interactions. Guatemala's dynamic geological history and geographical setting give rise to many potential hazards. These include geological (e.g., earthquakes, volcanic activity, landslides, and surface collapses) and hydrometeorological hazards (e.g., tropical cyclones, thunderstorms, hailstorms, tornados, coastal storm surges, floods, drought, heatwaves, and cold spells), as defined by UNISDR (2017). Guatemala ranks high in descriptions of countries exposed to multiple hazards and risks (e.g., Welle *et al.*, 2013; Kreft *et al.*, 2015; Bündnis Entwicklung Hilft/United Nations University, 2017). **Figure 1** shows a map of Guatemala, including key locations and physiographic details.

We believe these to be the first national scale comprehensive characterisation of potential hazard interactions in the published literature, relevant to a wide range of actors involved in disaster risk reduction (DRR). While the regional interaction frameworks developed in this paper specifically support Guatemalan stakeholders, we suggest that our approach is replicable and can support implementation of the Sendai Framework in other settings through improved characterisation of multi-hazard interactions, as we discuss throughout this paper.

comprehensive, systematic and evidenced *regional interaction frameworks* to support multi-hazard approaches to disaster risk reduction (DRR). Here we define regional interaction frameworks to be visualisations that support the identification and characterisation of relevant hazard interactions in a defined region (from 10^2 to 10^6 km^2). Interaction frameworks are a component of a 'multi-hazard' approach, defined by the UN Office for Disaster Risk Reduction (UNISDR) as *"the selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects"* (UNISDR, 2017).

We apply our interdisciplinary approach to two regional spatial extents in Guatemala (national and sub-national), developing what we believe to be the first national scale comprehensive characterisation of potential hazard interactions in the published literature, relevant to a wide range of actors involved in DRR. This approach is scalable and replicable in diverse contexts, as we discuss throughout this paper.

Here we define regional interaction frameworks to be visualisations that support the identification and characterisation of relevant hazard interactions in a defined region (from 10^2 to 10^6 km^2). Interaction frameworks are a component of a 'multi-hazard' approach, defined by the UN Office for Disaster Risk Reduction (UNISDR) as *"the selection of multiple major hazards that the country faces, and the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects"* (UNISDR, 2017).

Here, and throughout this paper, we use 'hazard interactions' to describe these cascades and interrelated effects. Examples include tropical storms triggering floods and/or landslides; volcanic eruptions triggering wildfires that subsequently increase the probability of debris flows occurring; and earthquakes triggering regional subsidence. Many more examples, and extensive case studies, feature in the literature (e.g., Tarvainen *et al.*, 2009; Kappes *et al.*, 2010; Gill and Malamud, 2014; Duncan *et al.*, 2016). The UNISDR Sendai Framework for Disaster Risk Reduction (SFDRR) emphasises the need for multi-hazard approaches (UNISDR, 2015). Stakeholders involved in implementing the SFDRR (e.g., civil protection agencies, hazard-monitoring scientists, urban planners, development practitioners) will therefore all benefit from frameworks that systematically identify and characterise hazard interactions in regional contexts.

There are limited examples of *regional interaction frameworks* in the literature. **Table 1** outlines and characterises seven examples of frameworks for specific named regions or geographical features that include natural hazards and a deliberate attempt to characterise possible hazard interactions. While there is significant variation in the approaches used to construct and populate these frameworks, they helpfully demonstrate the scalability of regional interaction frameworks. The paper is structured as follows: In **Section 2** we outline the methods used to collect five diverse evidence types, characterise this evidence, and describe how we integrate this evidence to construct and populate a regional interaction framework. We combine our description of data collection methods with the characterisation of the data as we it is more helpful for the reader to have this together. In **Section 3** we integrate and use this evidence to characterise hazard interactions and interaction networks (cascades), constructing two regional interaction frameworks for Guatemala (national and sub-national spatial extents). In **Section 4** we discuss future developments of this work and our findings in the context of regional interaction frameworks and multi-hazard assessments for disaster risk reduction. Conclusions are presented in **Section 5**.

Building on these examples, we present and apply a methodology in this paper to develop and enhance *regional interaction frameworks*. We integrate six themes, identified by Gill (2016), of *spatial scale*, *temporal scale*, *likelihood-magnitude relationships*, *selection* and *classification of natural hazards*, *identifying relevant hazard interactions*, *and visualisation style and user communities* to ensure frameworks are comprehensive, systematic and evidenced. While the frameworks developed in this paper specifically support Guatemalan stakeholders, we suggest that our approach supports implementation of the SFDRR in other settings. Our approach is replicable and can help to improve characterisation of hazard interactions.

1.2 Application to Guatemala

We trialled our approach in Guatemala due to (i) the hazardousness of the region, and (ii) logistical feasibility (contacts, language, accessibility). A broad range of natural hazards and anthropogenic processes in Guatemala make it an appropriate country to examine hazard interactions. Guatemala's dynamic geological history and geographical setting give rise to many potential hazards. These include geological (e.g., earthquakes, volcanic activity, landslides and surface collapses) and hydrometeorological hazards (e.g., tropical cyclones, thunderstorms, hailstorms, tornados, coastal storm surges, floods, drought, heatwaves and cold spells), defined by UNISDR (2017). Guatemala ranks high in descriptions of countries exposed to multiple hazards and risks (e.g., Welle *et al.*, 2013; Kreft *et al.*, 2015; Bündnis Entwicklung Hilft/United Nations University, 2017).

Two principal government organisations exist in Guatemala, tasked with supporting DRR. These are CONRED (Coordinadora Nacional para la Reducción de Desastres/National Coordinator for Disaster Reduction) and INSIVUMEH (Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología/National Institute for Seismology, Volcanology, Meteorology and Hydrology). **Table 2** gives an overview of these organisations. Additional organisations engaged in research and practitioner work relating to natural hazards and DRR include universities (e.g., Universidad de San Carlos de Guatemala), private sector consultancies and research institutes (e.g., Private Institute for Climate Change Research), civil society organisations (e.g., Oxfam), and regional and international intergovernmental organisations (e.g., CEPREDENAC, UN OCHA).

1.3 Structure of Paper

In **Section 2** we characterise five diverse evidence types. We integrate and use this evidence in **Section 3** to characterise hazard interactions and networks of interactions (cascades), constructing two regional interaction frameworks for Guatemala (national and sub-national spatial extents). In **Section 4** we discuss our findings in the context of regional interaction frameworks and multi-hazard assessments, with conclusions in **Section 5**.

2 Data and Methods Evidence Used to ConstructInform the Regional Interaction Framework

2.1 Evidence Types and Integration

Developing comprehensive and evidenced regional interaction frameworks requires diverse evidence to improve the systematic identification of relevant hazards and interactions. -In **Table 32**, we group possible evidence types to construct regional interaction frameworks -into (1) publications and other reports, (2) social and other media, (3) field evidence, (4) stakeholder engagement, and (5) miscellaneous. Some overlap exists between these categories, and not all the examples given are relevant in any given location. Of the evidence types in **Table 32**, we used the following:five that can help construct and populate a regional interaction framework for Guatemala (letters **A**–**E** below, and used throughout this paper):

A. *International Literature (publications and reports).* A comprehensive synthesis of literature describing natural hazards in Guatemala and their interactions, including peer-review material, technical reports, databases, and media reports (93 peer-review, 76 grey literature) (**Section 2.2**).

A. *Civil Protection Bulletins (locally accessible publications and reports).* Analysis of government issued, Spanish-language, civil protection information bulletins.

B. (267 bulletins from 11 June 2010 to 15 October 2010) (**Section 2.3**).

C. *Field Observations*. Reconnaissance trips, giving an overview of the hazard landscape of Guatemala (three sites discussed in the text) (**Section 2.4**).

D. *Stakeholder Interviews*. Semi-structured interviews with hazard and civil protection professionals in Guatemala (19 interviews, conducted from 28 February to 14 March 2014) (**Section 2.5**).

E. *Workshop*. A 3-hour workshop with hazard and civil protection professionals in Guatemala (16 participants, 06 March 2014) (**Section 2.6**).

For the latter two (D and E), principal government organisations tasked with informing disaster risk reduction and response activities in Guatemala are CONRED (Coordinadora Nacional para la Reducción de Desastres/National Coordinator for Disaster Reduction) and INSIVUMEH (Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología/National Institute for Seismology, Volcanology, Meteorology and Hydrology). Additional organisations include universities (e.g., Universidad de San Carlos de Guatemala), private sector consultancies and research institutes (e.g., Private Institute for Climate Change Research), civil society organisations (e.g., Oxfam), and regional and international intergovernmental organisations (e.g., CEPREDENAC, UN OCHA).

- ~~*Publications and reports (internationally accessible)* (**Section 2.2**). A comprehensive synthesis of literature describing natural hazards in Guatemala and their interactions. This included peer-review material, technical reports, databases and media reports.~~

- ~~*Publications and reports (locally accessible)* (**Section 2.3**). Analysis of government issued, Spanish-language, civil protection information bulletins.~~

- ~~*Field observations* (**Section 2.4**). Reconnaissance trips, giving an overview of the Guatemala's hazard-forming environment (defined in Liu *et al.*, 2016).~~

- ~~*Stakeholder engagement* (**Sections 2.5** and **2.6**). 19 semi-structured interviews and a 3-hour workshop with hazard and civil protection professionals in Guatemala.~~

Other evidence types (e.g., historical records, community knowledge) are included in peer-review and grey literature publications we examined~~.~~, or may be particularly pertinent in other geographical locations. The use of multiple evidence types (vs. a reliance on one evidence type) facilitates a more comprehensive characterisation of hazards and hazard interactions. For each evidence type considered, we do not use all possible examples, methods, and sources; rather we use examples of key case studies from regions of interest. Collecting and interpreting this evidence requires engagement with a range of organisations engaged in research and practitioner work relating to natural hazards, disaster risk reduction, and disaster response. Through **Sections 2.2** to **2.6** we characterise our data (evidence types) and the methods used to collect and unite this to address our research questions. ~~For each evidence type considered, we do not use all possible examples, methods and sources; rather we use examples of key case studies from regions of interest.~~ We outline limitations associated with this evidence and the methods used to collect it in **Section 2.7**. In ~~**Table 4**~~**Section 2.8**, we summarise how we integrate evidence types to develop our regional interaction frameworks in **Section 3**.

2.2 Publications and Reports (Internationally Accessible)

Internationally accessible publications and reports includes both peer-review and grey literature, ~~including~~ such as journal articles, edited volumes, Masters and PhD theses, textbooks, technical reports, databases, and NGO disaster situation reports. ~~These~~ This compilation of literature all reports on hazard events in specific geographic regions, providing evidence of hazard interactions. For example, Rose *et al.* (2004) present a set of papers on natural hazards in El Salvador (edited volume), and ReliefWeb (2018) present a situation report on the impact of Tropical Storm Nate in Central America (disaster situation report). We identified multiple publication and report types with information about Guatemala. We prioritised literature giving a broad overview of natural hazards, synthesising multiple texts, or characterising hazard interactions. It is beyond the scope of this study to examine publications on every aspect of hazards in Guatemala, or to review all publications on any one aspect of a hazard.

We primarily accessed literature using large web-databases (Google Scholar, Web of Science) for peer-reviewed articles and general online searches for other grey literature (e.g., media reports). We used Boolean search methods, including both ‘Guatemala’ and keywords associated with a preliminary list of 21 natural hazards (from Gill and Malamud, 2014). For example, ‘earthquake’, ‘aftershock’, ‘seismic’, ‘tremor’, and ‘liquefaction’ were searched for alongside ‘Guatemala’ and ‘Central America’ to identify relevant material. We evaluated results to determine their relevance and identify other keywords. We also identified specialist books, such as an edited volume on the geology of Central America (Bundschuh and Alvarado, 2007).

We examined literature in a systematic manner, collating references, maps and figures for 17 (of the 21) natural hazards: earthquake, tsunami, volcanic eruption, landslide, flood, drought, regional subsidence, ground collapse, soil (local) subsidence, ground heave, storm, tornado, hailstorm, lightning, extreme temperature (heat), extreme temperature (cold), and wildfire. Snow avalanches and snowstorms have limited spatial relevance in Guatemala, and geomagnetic storms and impact events have little country-specific (vs generically relevant) information. For each hazard considered, we cross-referenced diverse literature to characterise it at a level of detail appropriate to this study, including information on spatial and temporal distribution, triggering relationships, and impacts. We identified and used as evidence 169 sources, with 93 (55%) of these being peer-review, and 76 (45%) of these being grey literature. ~~We use this evidence in **Section 3** to help develop a regionally appropriate hazard classification and synthesise relevant interactions.~~

2.3 Publications and Reports (Locally Accessible)

Another evidence type to inform the development of regional interaction frameworks is locally accessible reports, such as government or NGO bulletins, newspapers, and emergency call out records. Civil protection information bulletins and newspapers can both give a focused overview of natural hazard occurrences (e.g., Guzzetti *et al.* 1994; Trimble, 2008; Raška *et al.* 2014; Taylor *et al.*, 2015), providing information on hazard interactions or noting triggering relationships.

In Guatemala, we use Spanish-language civil protection information bulletins from the *Coordinadora Nacional para la Reducción de Desastres* (CONRED, National Coordinator for Disaster Reduction). Bulletins are issued when there is a threat to lives, livelihoods, and infrastructure, and include information on hazards, their spatial and temporal extent, and their impacts, including triggering other hazard~~s triggering~~. Natural hazards occurring in remote regions or having a very low impact (e.g., very small landslides) are unlikely to be included in bulletins, and therefore bulletins do not provide a complete record of events. CONRED may issue multiple bulletins per day, depending on the evolution of, for example, a weather system or a disaster event. Bulletins are distributed to a mailing list of personnel, with some on their website (CONRED, 2018b) and ReliefWeb (2016). At the time of writing, CONRED bulletins are not systematically archived online. We therefore classify these bulletins as locally accessible.

CONRED made available to the authors (electronic format) 267 accessible information bulletins published over a 127-day period between the 11 June 2010 and 15 October 2010. Based on their numbering, we believe CONRED published 413 bulletins during this 127-day period. Additional information that characterises these bulletins is included in **Supplementary Material (Table S1)**. We searched the 267 accessible bulletins for keywords, placing these into context by looking at the surrounding sentences. Taylor *et al.* (2015) used this approach to enrich the UK national landslide database by examining newspaper archives.

We selected and used the following six keyword verbs connecting two hazard types and suggesting an interaction between them (with an abbreviated Spanish verb base in parentheses): *to trigger* (*desenca*), *to provoke (provoc), to generate (genera), to cause (caus), to produce (produ)*, and *to catalyse* (*catal*). We performed a keyword Boolean search in Spanish using the abbreviated form of the verb base to ensure the return of multiple derivatives of the verb. To check if there were other verbs of interest, we then searched for the following hazard keywords in Spanish form (both singular and plural): *seismic, earthquake, volcano, eruption, landslide, flood, collapse, sinkhole, hurricane, storm, tsunami, drought, tornado, wind, rain.* We also searched for references to three active volcanoes (*Pacaya*, *Santiaguito*, and *Fuego*) in Guatemala. From these hazard keywords and three volcanoes, we looked for any further interaction verbs that might be included near these words and identified no additional keyword verbs using these. The number of keyword search results for each of the six keyword abbreviated verb bases connecting two hazard types are: *to trigger* (*desenca, 0 results*), *to provoke (provoc, 26 results), to generate (genera, 58 results), to cause (caus, 22 results), to produce (produ, 37 results)*, and *to* *catalyse (catál, 0 results).*

~~In **Table 5**, we show a~~In total,~~ summary of keywords used~~ ~~and~~ there were ~~a total of~~ 143 results ~~over~~ from 95 bulletins, prior to us processing them based on their relevance to the theme of hazard interactions. These results included some bulletins with more than one result.

By examining the context, we determined that 39 of the 143 results (from 36 different bulletins, on 28 unique days) described unique events where interactions occurred between natural hazards. These results are presented in the **Supplementary Material** (**Table S2**). ~~In **Section 3.4**, we outline and characterise examples of networks of interactions extracted from these bulletins.~~ The results in this section, although based on an incomplete dataset, demonstrate examples of the types of interactions that could occur. Further research could use a larger sample of bulletins to better characterise interactions in Guatemala, or an event database such as EM-DAT (CRED, 2018). This would be necessary if the frequency of different types of events was a consideration, with a four-month period being too short to analyse this.

2.4 Field Observations

Field observations can also help to understand the relevance and dynamics of hazards and hazard interactions. For example, Havenith *et al.* (2003) describe field evidence of earthquake-triggered landslides in the Northern Tien Shan Mountains of Kyrgyzstan. Approaches include reconnaissance visits to improve contextual understanding of the region, detailed geological, geomorphological or hazard mapping, and the application of technologies such as rain gauges, drones, and thermal imaging infrared cameras.

In Guatemala, from January to March in 2014 (9 weeks total), we visited regions in the Southern Highlands of Guatemala (identified in **Figure 1**) affected by multiple natural hazards and anthropogenic activity. We aimed to familiarise ourselves with the features of key locations and hazards in Guatemala, but did not gather primary field data (e.g., community interviews). We enhanced our ~~:~~

~~U~~understanding of Guatemala's multi-hazard environment, observing the spatial and temporal scales at which hazards and anthropogenic processes act. This helped to enrich interviews with expert participants (described in

~~*Interviews with expert participants* (~~**Section 2.5**), ~~collecting richer data because of a clearer~~ understanding ~~of~~ examples, local places names, and descriptors used by participants to characterise and evidence natural hazard interactions in Guatemala. ~~Visits helped identify local place names and descriptors for sites affected by hazards.~~

We conducted multiple field visits alongside INSIVUMEH, with support from the University of Bristol, and one field visit with CONRED. This helped to develop constructive relationships, establishing the mutual trust and respect required for subsequent data-rich interviews (Kitchin and Tate, 2000). Examples of principal field locations and relevant interactions are (a) Lake Atitlán (e.g., tropical storms triggering landslides, landslides triggering flooding, landslides triggering lake tsunamis), (b) Volcán de Fuego (e.g., lahars triggering floods), (c) Volcán de Santiaguito (lahars triggering flooding) We completed one field visit with CONRED. In **Table 6**, we use personal observations and information from both peer-review and grey literature to describe select locations. We include information on interactions and/or networks of interactions. We return to these examples when illustrating networks of hazard interactions in Guatemala (**Section 3.4**).

In **Table 6**, we use personal observations and information from both peer-review and grey literature to describe select locations. We include information on interactions and/or networks of interactions. We return to these examples when illustrating networks of hazard interactions in Guatemala (**Section 3.4**).

2.5 Stakeholder Engagement: Interviews

Interviews provide additional evidence to construct and populate regional interaction frameworks. Participants often come from diverse backgrounds, with differing understanding of natural hazards and geographic regions. Participants with relevant evidence can include both 'experts' (e.g., hazard and disaster professionals) and local people who might be impacted by hazards (e.g., farmers, local government, communities). Selecting participants based on their experience and relevance to a research question (purposeful sampling), can result in data-rich interviews (MacDougall and Fudge, 2001; Longhurst, 2003; Suri, 2011; Palinkas *et al.,* 2015). Semi-structured interviews provide one means by which to have this dialogue, focused around questions on hazards and hazard interactions. This style gives enhanced freedom to explore areas of interest and pursue emerging lines of enquiry (Qu and Dumay, 2011).

Prior to travelling to Guatemala in 2014, we obtained ethics approval from King's College London for research with human participants. At the start of each interview we explained the purpose of our work and sought informed, prior consent to use data generated. All participants gave permission for us to use their data and identify their institution unless this would identify the individual. We interviewed 21 hazard and civil protection professionals in Guatemala, during 19 interviews. **Supplementary Material (Table S3)** characterises the interview participants. Participants came from academia, the private sector, INSIVUMEH, and CONRED. We selected interview participants from diverse professional backgrounds in terms of hazard speciality (e.g., earthquakes, landslides, floods) and engagement in the disaster cycle (e.g., early warning, mitigation, recovery). We identified contacts before travelling to Guatemala through their online profiles and professional engagement in other projects, and through introductions once in Guatemala.

We ensured that participants were comfortable to reduce possible power relations between the interviewer and participant (Kitchin and Tate, 2000; DiCicco-Bloom and Crabtree, 2006; Qu and Dumay, 2011). Interviews ranged from 30−120 minutes, following a semi-structured approach (Longhurst, 2003; Qu and Dumay, 2011). Interviews included opportunities for participants to talk about (i) their background and training, (ii) their consideration and use of information on hazard interactions, (iii) examples of existing multi-~~networks of~~ hazard interaction networks, and (iv) hazard interaction visualisations. All interviews aimed to cover these key themes, however there were differences in the order that they were introduced, and the specific questions asked. Interviews were conducted in Spanish (with a translator), in Spanish (without a translator), and in English, depending on the context.

Supplementary Material (**Table S4**) presents key statements relating to natural hazards, interactions, and anthropogenic processes, extracted from these 19 semi-structured interviews. Multiple participants highlighted specific interaction examples. These include ones noted in internationally accessible publications (e.g., lahars from Santiaguito triggering flooding, Harris *et al.*, 2006), and interactions not described in other evidence types (e.g., Pacific coastal flooding due to simultaneous high tides and river sedimentation). ~~We use participants' comments as evidence when constructing regional interaction frameworks for Guatemala (**Section 3**), helping to develop a natural hazards classification and identify relevant hazard interactions.~~

2.6 Stakeholder Engagement: Workshop

Another form of stakeholder engagement are workshops designed to generate data through activities and focused discussion. We organised a 3-hour workshop in Guatemala involving 16 civil protection professionals at CONRED. Participants included senior and junior staff working in diverse departments. **Supplementary Material** (**Table S3**) characterises participants, with all giving permission for us to use their data in an anonymised form. ~~Workshop limitations are discussed in **Section 4.1**.~~

During our workshop, participants independently completed two tasks.

Task 1. *Network Linkage Diagram for 21 Hazards (16 participants)*. Participants used this to record triggering relationships that they believed to be relevant to Guatemala. We did not expect any participant to map out all relevant interactions.

Task 2. *7 × 11 Hazard Interaction Matrix (15 participants)*. Participants completed a blank hazard interaction matrix, with seven primary hazards on the vertical axis and eleven secondary hazards on the horizontal axis. Results are outlined in **Section 2.6.2**.

We therefore collected two sets of visual records that document participants' perceptions of relevant hazard interactions in Guatemala. We include ~~an example of each diagram in **Figure 1**, with~~ all completed diagrams ~~included~~ in the **Supplementary Material** (**Figures S1** and **S2**). Completed network linkage and interaction matrix diagrams vary in the number and range of interactions proposed to be relevant in Guatemala. The number of interactions proposed by any one participant using the hazard linkage diagram, for example, ranged from 8 to 35, with a mean of 18 and a median (50^{th} percentile) of 15.

Using all 16 completed network linkage diagrams (Task 1), we can represent the combined knowledge of the workshop participants, and use this as evidence when constructing regional interaction frameworks for Guatemala. In **Figure 2**, we overlay evidence from 16 completed network linkage diagrams on a blank interaction framework, showing the number of participants (out of 16) proposing each triggering relationship. Of a total possible 441 (21×21) interactions, there are 86 different interactions proposed in **Figure 2** as being relevant in Guatemala (by 1–16 participants), equivalent to 20% of the 441 possible interactions. Consequently, 355 interactions (80% of the 441 possible interactions) were determined by all 16 participants as not relevant in Guatemala. Some of the proposed interactions may not be relevant (false positives), and others not proposed by participants may be relevant (false negatives) in Guatemala. We present more detailed statistics resulting from this workshop, and analysis of the hazard interaction matrices, in the **Supplementary Material**.

These results highlight different opinions on which hazard interactions are relevant in Guatemala. There is strong consensus on the occurrence of some interactions, but weak consensus on others. We use this data in **Section 3** as additional evidence of possible hazard interactions in Guatemala. The workshop results demonstrate the need for communication across hazard disciplines, and the value of comprehensive, systematic and evidenced frameworks to enhance understanding of relevant interactions.

2.7 Limitations Associated with Methods and Data Collection

Evidence types **A**–**E**, characterised in **Section 2**, are each associated with limitations and uncertainties:

i. *Information Accuracy*. Based on our working with blended sources of grey-literature evidence we found that it can sometimes be difficult to verify information sources, including media articles and textbooks, civil protection bulletins, and personal perspectives offered through interviews and workshops. Where possible, we evaluated authenticity by cross-referencing grey and older literature with peer-review and recent literature. Including grey-literature, however, broadens the scope of reviews and provides comprehensive access to available published evidence (Mahood *et al.*, 2014).

ii. *Bias Towards High-Impact Events*. Civil protection bulletins, like newspaper articles, focus on events that affect the things humans value (Carrara *et al.*, 2003), and thus exclude events with a low societal impact. In contrast to newspaper records, bulletins are less likely to focus on novel events (Moeller, 2006) and it is reasonable to expect a higher level of specialist understanding compared to newspaper journalists (Ibsen and Brunsden, 1996).

iii. *Information Omission.* Our semi-structured approach to interviews may make it difficult to focus on important issues (Kitchin and Tate, 2000), increasing the likelihood of missing pertinent topics.

iv. *Language Barriers.* The evidence in **Section 2** required working across language barriers. Civil protection bulletins required translation from English to Spanish (when selecting keywords) and Spanish to English (when analysing keyword search results). We did not translate all text in the 677 pages of the bulletins, but rather searched for keywords within the text, and examined their context. Working in a non-native language may have resulted in missing interactions and/or misunderstanding context. Interviews and the workshop were conducted in a non-native language (either for us or the interviewee) making it harder to ensure consistency and minimise the omission of information (Squires, 2009). The use of translators may also result in challenges (Temple, 2002; Temple and Young, 2004). For example, translators can change the meaning of questions, directly or indirectly contribute to answers, or change interview dynamics. Careful selection of translators can minimise the impact of these limitations, as can working with researchers with an appropriate level of Spanish language.

v. *Cultural Barriers and Positionality.* Interviews and the workshop involved working across cultures. Our position in social and cultural structures influences our perspective of the world, and the way that this then influences the conduct and interpretation of stakeholder engagement (e.g., Merriam *et al.*, 2001; Sultana, 2007; Fisher, 2015). Race, nationality, age, gender, social and economic status influence our positionality (Madge, 1993), as do prior experiences pertinent to this research. The interviewer, translator and interviewees may have different perspectives, value systems, customs and social behaviours. Relationships between these groups can be complex and dynamic, with similarities and differences (Merriam *et al.*, 2001). Recognising cultural differences and similarities has implications on how to manage interview contexts to ensure that they are fruitful (Schneider and Barsoux, 2002).

vi. *Participant Selection.* Hosts at CONRED and INSIVUMEH generally selected interview and workshop participants. We desired participants from a diversity of professional backgrounds and levels of seniority, and this was generally respected. While participant selection was not in our control, the purposeful sampling used was an appropriate approach (MacDougall and Fudge, 2001; Longhurst, 2003; Suri, 2011; Palinkas *et al.*, 2015).

vii. *Power Dynamics.* Age, gender, educational level, ethnicity and socio-economic status can influence an interview or workshop process and the results (e.g., Valentine, 1997; Edwards, 1998; Kitchin and Tate, 2000; Qu and Dumay, 2011). Genuine rapport, respect, trust, and an understanding of cultural differences can reduce the impact of power dynamics (Kitchin and Tate, 2000; DiCicco-Bloom and Crabtree, 2006).

viii. *Peer Influence.* During the workshop, a controlled environment was encouraged during the completion of tasks. It was, however, difficult to prevent those sitting next to each other from seeing other contributions and speaking about what they were including.

ix. *Hazards and Interaction Classifications.* Gill and Malamud (2016) discussed difficulties in distinguishing between triggering and increased probability interaction types. Workshop participants may have found this distinction between two different interaction types confusing, inadvertently characterised an interaction as one type when they meant the other. Participants may have a different understanding of what any of the interaction or hazard types includes, and the use of a pre-defined hazard scheme in workshops may restrict discussion of other hazards not included in this scheme.

These examples are likely to have resulted in some uncertainty within the evidence used, and therefore within the interaction frameworks produced using this evidence. Some sources of uncertainty can be mitigated, and appropriate actions were taken to do so, including the following~~.~~:

- ~~For example, a~~A reflexive and respectful approach ~~can reduce~~reduced language barriers, cultural barriers and power dynamics on the results of stakeholder engagement.~~,~~
- ~~and a~~A critical approach to literature analysis ~~can~~ determined where inaccuracies may exist in grey or historical literature.
- Integrating multiple evidence types ~~also~~helped ~~helps~~ to reduce the impact of uncertainties on regional interaction frameworks.
- We ~~can~~ cross-~~ed~~referenced personal perspectives expressed in interviews, for example, with peer-review literature to explore accuracy.
- We used g~~G~~lobal interaction frameworks ~~also~~to serve as useful databases of what could occur, helping to evaluate the scope of possible interactions before ascertaining their relevance in Guatemala.

We suggest, therefore, that the regional interaction frameworks presented in the remainder of this paper are robust assessments of potential triggering and increased probability interactions in Guatemala. It is possible, however, that relevant hazard interactions and anthropogenic processes, or the likelihood or spatial distribution of these, will vary over time.

2.8~~7~~ ~~Summary~~ Integration of Evidence Types ~~Used~~ to Construct and Populate ~~Inform Our~~Interaction Frameworks

~~**Sections 2.2** to **2.6** describe five evidence types (letters **A**–**E** below, and used throughout the remainder of this paper) that can help construct and populate a regional interaction framework for Guatemala:~~

~~**B.** Publications and reports (internationally accessible) (93 peer-review, 76 grey literature) (**Section 2.2**).~~

~~**C.** Publications and reports (locally accessible civil protection bulletins) (267 bulletins from 11 June 2010 to 15 October 2010) (**Section 2.3**).~~

~~**D.** Field observations (four sites discussed in the text) (**Section 2.4**).~~

~~**E.** Interviews (19 interviews, conducted from 28 February to 14 March 2014) (**Section 2.5**).~~

~~**F.** Workshops (16 participants, 06 March 2014) (**Section 2.6**).~~

~~Other evidence (e.g., social media, instrumental records, and others noted in **Table 3**) may be pertinent in other~~

geographical locations. The use of multiple evidence types (vs. a reliance on one evidence type) facilitates a more comprehensive characterisation of hazards and hazard interactions.The construction of comprehensive and systematic regional interaction frameworks requires three components for a region of interest, each bringing together diverse strands of evidence, and unifying them within a formal structure, supported by expert knowledge (Neri *et al.*, 2008):

i. **Information on relevant single hazards and appropriate ways to classify these**, using the evidence in **Sections 2.2** to **2.6,** and the classification of 21 natural hazards in Gill and Malamud (2014).

ii. **Information on relevant hazard interactions to populate the interaction framework** (i.e., identifying how single hazards interact with each other), using the evidence in **Sections 2.2** to **2.6**, and the matrix of globally possible interactions in Gill and Malamud, 2014.

iii. **An appropriate visualisation framework to represent hazard interactions.** We adapt existing visualisation frameworks (Gill and Malamud, 2014, 2016, 2017), and ensure these are appropriate to Guatemala.

We can then use this framework and evidence presented in **Section 2** to identify potential multi-hazard interaction networks, and explore how anthropogenic processes can trigger natural hazards or catalyse hazard interactions (Gill and Malamud, 2017).

3 Regional Interaction Frameworks (Visualisations)

We now proceed to develop our comprehensive, systematic and evidenced *regional interaction framework* for Guatemala. In **Section 3.1**, we discuss the construction and population of regional interaction frameworks. In **Section 3.2**, we present a revised hazards classification scheme for Guatemala. In **Section 3.3**, we use this scheme and additional evidence to populate two regional interaction frameworks, a 21×21 hazard interaction matrix completed for a national spatial extent (Guatemala), and a 33×33 hazard interaction matrix completed for a sub-national spatial extent (Southern Highlands of Guatemala). In **Section 3.4**, we use these frameworks and evidence from **Section 2** to illustrate and discuss two multi-hazard interaction networksnetworks of hazard interactions (cascades). In **Section 3.5**, we consider anthropogenic processes triggering hazards and catalysing interactions in Guatemala.

3.1 Guiding the Construction and Population of Regional Interaction Frameworks

The construction of comprehensive and systematic regional interaction frameworks requires three components for a region of interest, each bringing together diverse strands of evidence, and unifying them within a formal structure, supported by expert knowledge (Neri *et al.*, 2008):

i. **Information on relevant single hazards and appropriate ways to classify these**. Here we identify single

~~hazards through diverse evidence types, including literature, field observations, semi-structured interviews, and workshops.~~

ii. ~~**Information on relevant hazard interactions to populate the interaction framework** (i.e., identifying how single hazards interact with each other). We identify interactions using the same diverse evidence types, supplemented by literature on global and regional interaction frameworks.~~

iii. ~~**An appropriate visualisation framework to represent hazard interactions.** We adapt existing visualisation frameworks (Gill and Malamud, 2016), and ensure these are appropriate to Guatemala.~~

~~Gill (2016) identified six themes for consideration when developing regional interaction frameworks: (i) spatial scale, (ii) temporal scale, (iii) likelihood-magnitude relationships, (iv) selection and classification of natural hazards, (v) identification of hazard interactions, and (vi) user requirements and visual style. We revisit these themes in~~ In **Table 3~~7~~**, we explore in the context of Guatemala six themes set out by Gill (2016) to guide the generation of regional interaction frameworks~~ for Guatemala.~~: *spatial scale*, *temporal scale*, *likelihood-magnitude relationships*, *selection and classification of natural hazards*, *identifying relevant hazard interactions*, and *visualisation style and user communities*. We integrate perspectives from hazard and civil protection professionals in Guatemala (from semi-structured interviews and the workshop, see **Sections 2.5** and **2.6)**. Professional organisations have an understanding of local culture, language and knowledge, and have the mandate to adapt interaction frameworks into suitable forms for other stakeholders (e.g., policy makers and communities).

3.2 Relevant Natural Hazards and Hazards Classification

Gill and Malamud (2014) propose a broad classification of 21 natural hazards, in six hazard groups (geophysical, hydrological, shallow Earth, atmospheric, biophysical, space). This, or an alternative, comprehensive classification can be adapted to develop a regionally specific classification, using available evidence. We use this approach to propose a detailed, location-specific classification of natural hazard types in Guatemala, building on evidence in **Section 2**. We begin by identifying which of the 21 natural hazards listed in Gill and Malamud (2014) are relevant in Guatemala, and sub-divide selected hazards where evidence supports an expanded classification. We present our evidenced classification scheme in **Table 4~~8~~**, including six hazard groups, 19 hazard types, and 37 hazard sub-types. We also include an indication of the evidence supporting this classification, using identifying letters **A**–**E** introduced in **Section 2.7**, and specific referenced publications and reports where appropriate. The 37 detailed natural hazard sub-types in **Table 4~~8~~** helps to improve the detail by which we can characterise ~~hazard~~ interactions in regional interaction frameworks (e.g., see ~~.~~**Section 3.3**).

Our classification is one way of grouping relevant natural hazards, with alternative classifications possible. Other natural hazard types may exist in Guatemala that have been missed from our classification, including those occurring less frequently or having a lesser impact than those we consider. We reduce the likelihood of missing key hazards by reviewing multiple evidence types to ensure a comprehensive and evidenced classification. We include 26 to 32 more hazard sub-types than existing regional interaction frameworks (e.g., Tarvainen *et al.*, 2006; Kappes *et al.*, 2010; Liu *et al.*, 2016). In addition to the 37 natural hazard sub-types in **Table ~~8~~4**, we could also consider how a changing climate influences natural hazards (see McGuire and Maslin, 2012, for a full discussion), or other groups of processes, such as biological hazards (e.g., epidemics), technological hazards (e.g., structural collapse), and anthropogenic processes (e.g., vegetation removal). The latter are discussed in **Section 3.5**.

3.3 Guatemala Interaction Frameworks

Building upon the reflections in **Section 3.1**, and using the hazard classification in **Section 3.2** and evidence in **Section 2**, we now construct and populate interaction frameworks for two different spatial extents in Guatemala.

1. **National** spatial extent (**Section 3.3.1**). We produce a 21×21 interaction framework (matrix form), with 19 relevant hazards. We initially constrain interactions for a national spatial extent using the coarser hazard classification (21 hazard types).
2. **Sub-national** (Southern Highlands of Guatemala) spatial extent (**Section 3.3.2**). We produce an interaction framework (matrix form) using our classification of 37 hazard sub-types, giving a maximum of 37 primary and 37 secondary hazards. We use information from **Section 2** to: (a) explain and justify the selection of the Southern Highlands of Guatemala; (b) determine which of the 37 hazard sub-types are relevant in this spatial extent; and (c) adapt the 21×21 interaction framework to incorporate these hazard sub-types and populate this framework with relevant hazard interactions.

Both interaction frameworks use a matrix visualisation approach.

3.3.1 Guatemala National 21×21 Interaction Framework (Matrix Form)

To develop an interaction framework for the national spatial extent of Guatemala, we start with an existing 21×21 matrix (Gill and Malamud, 2014). From **Table 4~~8~~** we identify that 19 of the 21 natural hazards in this matrix are relevant to Guatemala. Using the evidence in **Section 2**, we systematically examine each matrix cell to consider whether an interaction is possible in Guatemala. We present our completed national-scale, regional interaction framework in **Figure 3**, with 21 primary natural hazards on the vertical axis (of which 19 are relevant), and the same 21 secondary (of which 19 are relevant) natural hazards on the horizontal axis. 50 (11%) of 441 cells are shaded, indicating 50 possible interactions. These include:

i. *Triggering Only*. 15 (30%) of the 50 interactions.

ii. *Increased Probability Only.* 5 (10%) of the 50 interactions.

iii. *Triggering and Increased Probability.* 30 (60%) of the 50 interactions.

The evidence types (**A**–**E**) supporting these 50 hazard interactions ~~is~~ are outlined in **Supplementary Material (Table S5)**. We believe this to be the first national scale assessment of possible hazard interactions in the literature, with our approach being generalizable for other national contexts. We use **Table S5** to inform the development of an additional national-scale 21×21 matrix to communicate uncertainty regarding each interaction, also presented in the **Supplementary Material (Figure S5)**. ~~In **Figure 4**, blue shading indicates the number of evidence types (**A**–**E**) supporting the inclusion of each interaction. Darker shading indicates inclusion based on *more* evidence types and lighter shading indicates inclusion based on *less* evidence types. We group triggering and increased probability interaction types together and indicate the number of evidence types available per *primary hazard-secondary hazard* combination. This is due to the coarse resolution of the data used, and complexities of distinguishing in evidence types between triggered/increased probability interaction types. Using **Figure 4** we note that of the 50 identified interactions:~~

~~2 (4%) have 5 evidence types to support their inclusion. Examples include *storm → landslide*, and *storm → flood.*~~

~~3 (6%) have 4 evidence types to support their inclusion. Examples include *landslide → flood*, and *storm → ground collapse.*~~

~~6 (12%) have 3 evidence types to support their inclusion. Examples include *earthquake → tsunami, landslide → tsunami,* and *extreme temperatures (heat) → wildfire.*~~

~~15 (30%) have 2 evidence types to support their inclusion. Examples include *tsunami → flood, drought → soil subsidence,* and *storm → ground heave.*~~

~~17 (34%) have 1 evidence types to support their inclusion. Examples include *earthquake → volcanic eruption, flood → landslide*, and *storm → tsunami.*~~

~~7 (14%) are included due to globally relevant literature, rather than Guatemala-specific literature. Examples include *impact event → landslide*, and *regional subsidence → flood.*~~ This additional matrix

~~**Figure 4**~~ demonstrates the importance of a multi-methods approach, integrating diverse evidence types to understand relevant hazard interactions. Analysing any one evidence type (**A**–**E**) would only identify a sample of relevant interactions. **Table S5** shows that 13 (26%) of 50 relevant interactions were identified in the workshop of civil protection professionals ~~(**Section 2.6**)~~, 9 (18%) using civil protection bulletins ~~(**Section 2.3**)~~, 28 (56%) using interviews with hazard professionals ~~(**Section 2.5**)~~, and 32 (64%) using international literature ~~(**Section 2.2**)~~. Developing comprehensive regional interaction frameworks requires multiple, diverse evidence types.

3.3.2 Guatemala Southern Highlands 33×33 Interaction Framework (Matrix Form)

We now proceed to develop a regional interaction framework for a sub-national spatial extent. Using physiography, we divide Guatemala into four spatial regions (1) low relief northern plateau, (2) Central Highlands, with deep valleys, (3) Southern Highlands, and (4) Pacific coastal plains, as indicated in **Figure 51**. In **Table 59**, we show the 37 hazard sub-types described in **Section 3.2** and use the evidence in **Section 2** (**A**–**E**) to characterise their spatial relevance in these four regions. More hazards are spatial relevant to the Southern Highlands of Guatemala than other regions in Guatemala. 33 (89%) of 37 possible hazard sub-types are possible in the Southern Highlands of Guatemala, compared with 26 (70%) to 27 (73%) of 37 hazard sub-types relevant in the other regions. The Southern Highlands is a region of variable topography between the Pacific Coast and the Polochic-Motagua-Chamalecón fault system. It incorporates the volcanic arc, with at least three active volcanic systems (Pacaya, Fuego and Santiaguito).

The 33 hazard sub-types relevant in the Southern Highlands are used as primary and secondary hazards in our regional interaction framework. This results in 1089 (33×33) possible interactions between these hazard sub-types. Using existing global interaction frameworks (e.g., Gill and Malamud, 2014) and evidence in **Section 2**, we systematically examine each cell to determine if an interaction could or could not occur. In **Figure 46** we present this 33×33 sub-national interaction framework for the Southern Highlands of Guatemala. **Figure 46** includes 114 (10%) of 1089 cells shaded, indicating 114 possible interactions. These include:

i. *Triggering Only*. 26 (23%) of 114 interactions.

ii. *Increased Probability Only*. 15 (13%) of 114 interactions.

iii. *Triggering and Increased Probability*. 73 (64%) of 114 interactions.

The 114 interactions in **Figure 46** include interactions that occur over large and small spatial areas, with both high and low frequencies, and both high- and low-magnitude events. The temporal relevance of interactions in **Figure 64** may change, for example due to evolving anthropogenic activity (see **Section 3.5**) or environmental change. Interactions include some originating outside of the spatial region of interest, and others that may propagate outside. For example, (i) an earthquake north of the Southern Highlands may result in ground shaking, liquefaction, landslides and other secondary hazards inside the Southern Highlands, (ii) lahars triggered in the Southern Highlands may trigger flooding outside of the Southern Highlands, in the Pacific coastal plains, and (iii) large volcanic eruptions in the Southern Highlands can eject ash/tephra far beyond this extent. Characteristics of interactions (e.g., likelihood) are not included in **Figure 46**, but could be added as additional information layers if further research results were available.

3.4 ~~Networks of~~Multi-Hazard ~~Interacting~~ Interaction Networks ~~Hazards~~ (Cascades)

In addition to one hazard triggering or increasing the probability of another hazard, longer linear or non-linear multi-~~networks of~~ hazard interaction networks (or cascades) can also occur (Han *et al.*, 2007; Choine *et al.*, 2015; Gill and Malamud, 2016; Pescaroli and Alexander, 2018). These networks include both high and low likelihood events, having diverse impacts. Ciurean *et al.* (2018) outline a range of methods for qualitatively and quantitatively characterising such multi-hazard interaction networks. For example, event scenario trees can be used to assess the probabilities of specific hazard cascades (Neri *et al.*, 2008, Neri *et al.*, 2013).

The evidence we have presented in **Section 2** includes many examples of interaction networks. For example, the internationally published literature characterising the 1976 M_w 7.5 Guatemala earthquake, clearly articulates a set of triggered hazards. After the earthquake there was multiple aftershocks and movement on other faults close to Guatemala City, as well as rapid subsidence or ground collapse (Espinosa, 1976; Plafker *et al.*, 1976). The earthquake triggered more than 10,000 landslides, rock falls and debris flows, blocking vital transport routes (Plafker *et al.*, 1976; Harp *et al.*, 1981) and blocking rivers to trigger upstream flooding (Plafker *et al.*, 1976; Harp *et al.*, 1981). Breaches of these landslide dams also resulted in further flooding (Harp *et al.*, 1981).

The civil protection bulletins characterised in **Section 2.3** also include several examples of networks in Guatemala. These include events with primary, secondary and tertiary hazards, as well as events reporting primary hazards changing the likelihood of future hazards. **Table 6~~10~~** gives three~~four~~ diverse examples of networks derived from **Table S2**, demonstrating the complexity of ~~networks of interacting hazards~~hazard interaction networks in Guatemala. **Table 6** also includes a simple visualisation of each example, showing the range of hazards and interaction relationships:

~~i. A primary hazard triggering and increasing the likelihood of multiple secondary hazards (*Example 1*).~~

~~ii.~~i. Linear events where one ~~with~~ primary hazard triggers one~~,~~ secondary hazard which triggers ~~and~~ one tertiary hazard~~s~~ (*Example 1~~2~~*).

~~iii.~~ii. Multi-branch events where~~with~~ a primary hazard may trigger multiple~~,~~ secondary hazards, each triggering one or more t~~and t~~ertiary hazards (*Example 2~~3~~*).

~~iv.~~iii. A primary hazard triggering and increasing the likelihood of multiple secondary hazards during a ~~High~~high-magnitude, complex~~, live~~ event, replicated in multiple areas of Central America ~~(tropical storm) with possible interactions~~ (*Example ~~4~~3*).

Further examples of hazard interaction networks emerged from ~~We can extract additional examples of networks from other evidence in **Section 2**. For example,~~stakeholder ~~stakeholder~~ interviews, including ~~(**Section 2.5**) described~~ volcanic eruptions and heavy rain triggering lahars, which subsequently trigger floods. These ~~Networks~~ networks can be visualised using interaction frameworks, as illustrated in **Figures 5~~7~~** and **6~~8~~**:

i. *Case Study 1 (**Figure ~~7~~5**): Lahars triggered on the flanks of Santiaguito, which result in severe erosion and trigger flooding.* This example featured in evidence in **Sections 2.2**, **2.4** and **2.5**. It occurs annually in the rainy season, while Santiaguito is active and generating large volumes of tephra.

ii. *Case Study 2 (**Figure 6~~8~~**): Hurricane Stan (2005) triggering a debris flow in the mountains adjacent to Lake Atitlán, with this debris flow triggering a tsunami, which caused a small lakeside flood*. This example featured in evidence in **Sections 2.2**, **2.4** and **2.5**. It occurs less frequently than Case Study 1, based on a specific event in 2005, Hurricane Stan (Luna, 2007).

The regional interaction frameworks we present in this paper ~~in **Section 3.3**~~ can help to visualise case studies of cascades identified through various evidence types and identify ~~. We can also use them to consider~~ *potential* networks, given a primary event. For example, given a large earthquake, the possible scenarios that may arise could be visualised using **Figures 3** and **~~6~~4**, and evaluated by hazard professionals. Gill and Malamud (2016) outlined three reasons why the assessment and visualisation of possible interaction networks are of importance to both the theoretical and practical understanding of hazards and disaster risk reduction. These three reasons are as follows:~~.~~

i. ~~The first is that a~~Assessing, managing and reducing disaster risk requires better modelling of the natural environment by moving from understanding discrete, independent events to matching the observed reality by including interaction networks.

ii. ~~The second is that i~~Identifying possible hazard interaction networks may allow improvements to disaster preparedness by better assessing how vulnerability will change during successive hazard events. Aspects of social and/or physical vulnerability may change following the occurrence of a specific natural hazard (e.g., volcanic eruption), before the triggered hazard (e.g., rain triggered lahars) occur.

iii. ~~The third reason is that u~~Understanding how hazard interaction networks are initiated and propagated may help determine how to invest resources to minimise disruption should a specific network of interacting hazards occur.

3.5 Anthropogenic Processes

In **Sections 3.2** to **3.4**, we primarily consider interactions between natural hazards; however, anthropogenic processes can also trigger natural hazards and influence natural hazard interactions (Glade 2003; Knapen *et al.*, 2006; Owen *et al.*, 2008; Gill and Malamud, 2017). Information on relevant anthropogenic processes can support hazard and civil protection professionals to evaluate how anthropogenic activity may trigger hazards and influence hazard interactions.

Using a classification of 18 anthropogenic processes (Gill and Malamud, 2017), and evidence from **Section 2**, we identify 17 relevant anthropogenic processes in Guatemala, listed in the **Supplementary Material** **Table S6**~~**11**~~. Some of these processes are only relevant for small spatial extents (e.g., individual towns), with others more widespread (e.g., in many populated regions). **Table** ~~**11**~~ **S6** includes the evidence (**A**–**E**) used to justify their relevance in Guatemala. Some anthropogenic processes feature multiple times within one evidence type. For example, four interviewees noted road construction (*Infrastructure Construction: Unloading*) and four noted deforestation (*Vegetation Removal*), in the context of triggering landslides. In contrast, only one interview participant mentioned groundwater abstraction as a potential trigger of subsidence.

The spatial and temporal relevance of these 17 anthropogenic processes will vary and could change over time. Anthropogenic processes can start and stop, and both grow and shrink in their spatial extent. The anthropogenic processes in **Table** ~~**11**~~ **S6** should be regularly reviewed to assess their relevance and if other processes have started, and any consequences of this variation on natural hazards and hazard interactions. For example, increased road construction may change the likelihood of landslides during heavy rain.

3.6 Regional Interaction Framework Summary

~~In this section w~~We have integrated diverse evidence types regarding hazards and hazard interactions in Guatemala, and unified them in a formal structure, supported by expert knowledge. We have collated information on relevant single hazards and appropriate ways to classify these in Guatemala, and information on relevant hazard interactions. Using a comprehensive and systematic approach, we have constructed evidenced national and sub-national interaction frameworks in matrix form, considering ~~networks of interacting hazards~~hazard interaction networks and relevant anthropogenic processes. We have demonstrated that our approach is scalable (with national and sub-national applications described) and therefore suggest that it is reproducible in diverse geographical contexts, and at multi-national to local scales~~,~~. *Regional Interaction Frameworks* provide a comprehensive overview of potential hazard interactions that allow agencies responsible for hazard monitoring and response to assess if current disaster risk reduction and response strategies, and communication and collaboration mechanisms, can be enhanced to recognise the complexity represented. ~~to generate useful insights into and assessments of hazards and hazard interactions.~~

~~4 Discussion~~

~~**In this section, we summarise potential limitations and uncertainties within our evidence, approach, and regional interaction frameworks (**Section 4.1**). We contrast our regional interaction frameworks with in-country civil protection perspectives by using a correlation coefficient (**Section 4.2**) and discuss the operationalisation of interaction frameworks (**Section 4.3**). We conclude by discussing the development of regional interaction**~~

frameworks for additional geographical contexts (Section 4.4**).**

4.1 Limitations and Uncertainty.

Evidence types A–E**, characterised in** Section 2**, are each associated with limitations and uncertainties. We note examples of these below:**

***Information Accuracy*. It may be difficult to verify information within grey literature sources, including media articles and textbooks (**Section 2.2**), civil protection bulletins (**Section 2.3**), and personal perspectives offered through interviews (**Section 2.5**) and workshops (**Section 2.6**). Where possible, we evaluated authenticity by cross-referencing grey and older literature with peer-review and recent literature.**

***Bias Towards High-Impact Events*. Civil protection bulletins (**Section 2.3**), like newspaper articles, focus on events that affect the things humans value (Carrara *et al.*, 2003), and thus exclude events with a low societal impact. In contrast to newspaper records, bulletins are less likely to focus on novel events (Moeller, 2006) and it is reasonable to expect a higher level of specialist understanding compared to newspaper journalists (Ibsen and Brunsden, 1996).**

***Information Omission.* Our semi-structured approach to interviews (**Section 2.5**) may make it difficult to focus on important issues (Kitchin and Tate, 2000), increasing the likelihood of missing pertinent topics.**

***Language Barriers.* The evidence in** Section 2 **required working across language barriers. Information bulletins (**Section 2.3**) required translation from English to Spanish (when selecting keywords) and Spanish to English (when analysing keyword search results). We did not translate all text in the 677 pages of the bulletins, but rather searched for keywords within the text, and examined their context. Working in a non-native language may have resulted in missing interactions and/or misunderstanding context. Interviews and the workshop (**Sections 2.5 **to** 2.6**) were conducted in a non-native language (either for us or the interviewee) making it harder to ensure consistency and minimise the omission of information (Squires, 2009). The use of translators may also result in challenges (Temple, 2002; Temple and Young, 2004). Translators can change the meaning of questions, directly or indirectly contribute to answers, or change interview dynamics. Careful selection of translators can minimise the impact of these limitations.**

***Cultural Barriers and Positionality.* Interviews and the workshop (**Sections 2.5 **to** 2.6**) involved working across cultures. Our position in social and cultural structures influences our perspective of the world, and the way that this then influences the conduct and interpretation of stakeholder engagement (e.g., Merriam *et al.*, 2001; Sultana, 2007; Fisher, 2015). Race, nationality, age, gender, social and economic status influence our positionality (Madge, 1993), as do prior experiences pertinent to this research. The interviewer, translator and interviewees may have different perspectives, value systems, customs and social behaviours. Relationships between these groups can be complex and dynamic, with similarities and differences (Merriam *et al.*, 2001). Recognising cultural differences and similarities has implications on how to manage interview contexts to ensure that they are fruitful (Schneider**

and Barsoux, 2002).

Participant Selection. **Hosts at CONRED and INSIVUMEH generally selected interview and workshop participants (**Sections 2.5 **to** 2.6**). We desired participants from a diversity of professional backgrounds and levels of seniority, and this was generally respected. While participant selection was not in our control, the purposeful sampling used was an appropriate approach (MacDougall and Fudge, 2001; Longhurst, 2003; Suri, 2011; Palinkas *et al.*, 2015).**

Power Dynamics. **Age, gender, educational level, ethnicity and socio-economic status can influence an interview or workshop (**Sections 2.5 **to** 2.6**) process and the results (e.g., Valentine, 1997; Edwards, 1998; Kitchin and Tate, 2000; Qu and Dumay, 2011). Genuine rapport, respect, trust, and an understanding of cultural differences can reduce the impact of power dynamics (Kitchin and Tate, 2000; DiCicco-Bloom and Crabtree, 2006).**

Peer Influence. **During the workshop (**Section 2.6**), a controlled environment was encouraged during the completion of tasks. It was, however, difficult to prevent those sitting next to each other from seeing other contributions and speaking about what they were including.**

Hazards and Interaction Classifications. **Gill and Malamud (2016) discussed difficulties in distinguishing between triggering and increased probability interaction types. Workshop participants (**Section 2.6**) may have found this distinction confusing, or defined interaction types and hazard classifications in different ways.**

These examples are likely to have resulted in some uncertainty within the evidence used, and therefore within the interaction frameworks produced using this evidence. Some sources of uncertainty can be mitigated, and appropriate actions were taken to do so. For example, a reflexive and respectful approach can reduce language barriers, cultural barriers and power dynamics on the results of stakeholder engagement, and a critical approach to literature analysis can determine where inaccuracies may exist in grey or historical literature. Integrating multiple evidence types also helps to reduce the impact of uncertainties on regional interaction frameworks. We can cross-reference personal perspectives expressed in interviews, for example, with peer-review literature to explore accuracy. Global interaction frameworks also serve as useful databases of what could occur, helping to evaluate the scope of possible interactions before ascertaining their relevance in Guatemala. We suggest, therefore, that the regional interaction frameworks presented in Section 3 **are robust assessments of potential triggering and increased probability interactions in Guatemala. It is possible, however, that relevant hazard interactions and anthropogenic processes, or the likelihood or spatial distribution of these, will vary over time.**

In addition to the evidence used to populate our regional interaction frameworks, their form (two-parameter matrices) may result in some complex interaction types not being captured. For example, two or more independent hazards may coincide spatially and/or temporally and result in a complex network of hazard interactions. Information in the frameworks could be represented spatially to help examine such scenarios. Two or more independent hazards may also trigger other hazards (e.g., storm and volcanic eruption triggering lahars). While the national framework (Figure 3**) does not capture this example, the sub-national framework (**Figure 6**) with the expanded hazard classification does capture it (illustrated in** Figure 7**). Non-linear examples can be visualised in**

this way.

4.2 Collective Knowledge of Hazard Interactions

Hazard interactions cut across multiple disciplines and so require input from diverse specialisms (Kappes *et al.*, 2012; Scolobig *et al.*, 2013; Scolobig *et al.*, 2017). Interaction frameworks could therefore help to facilitate enhanced cross-institutional dialogue about hazard interactions, their likelihoods and potential impacts. This could help to strengthen collective knowledge of hazard interactions, and the ability of an individual to access this knowledge. By contrasting results from our workshop (**Figure 2**) with our Guatemala national interaction framework (**Figure 3**), we can examine and quantify congruence between the two matrices. **Figure 9** is a 21×21 interaction matrix that combines **Figures 2** and **3** to indicate the number of workshop participants (from a total of 16) that identified an interaction as being relevant to Guatemala (numbers), and the interactions identified within our national interaction framework (grey shading, from **Figure 3**).

Figure 9 combines information and knowledge from 16 participants to present something that is 'owned' by no individual. It is collective knowledge, combining information and knowledge owned by multiple people (Antonelli, 2000). We do not expect an individual scientist or hazard professional to map out all relevant interactions. Assessing how an organisation rather than an individual understands interactions demonstrates their collective knowledge. For this knowledge to be truly collective there must be effective communication between participants, and a means by which this knowledge can be accessed, shared and applied (Foray, 2000; Antonelli, 2000; Paton *et al.*, 2008).

Multi-hazard research is complex, and requires scientists and professionals operating in many different disciplines. **Figure 9** demonstrates large variation in perspectives between participants on hazard interactions There is a unanimous consensus (i.e., 16 participants) that an interaction exists in two (0.5%) of 441 possible triggering interactions. To assess congruence between the participants' perspectives (numbers in **Figure 9**) and national interaction framework (grey shading in **Figure 9**), we use Matthews' Correlation Coefficient, or *MCC* (Matthews, 1975). *MCC* values are a function of true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN) and can be expressed as follows (Matthews, 1975; Powers, 2011):

$$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}} \quad \text{(Equation 1)}$$

The *MCC* gives a value of congruence between '−1.0' (zero overlap between the numbers and grey shading in **Figure 9**) and '+1.0' (perfect overlap between the numbers and grey shading in **Figure 9**). An *MCC* = 0.0 suggests that the amount of congruence is no better than a random average (Kaufmann *et al.*, 2012). We use two different approaches:

i. *All identified interactions*. Where ≥1 people note an interaction to be relevant, we consider this part of the group's collective knowledge. From **Figure 9** we identify 86 interactions identified by the 16 workshop participants. This compares to 50 interactions in the national framework, **Figure 3**.

ii. *Interactions identified by '≥x' participants.* A threshold could be applied, in terms of the number of participants identifying a given natural hazard interaction. Only those interactions that reach or exceed this threshold are considered. We select thresholds of ≥3 and ≥5 (out of 16 workshop participants) identifying an interaction as being relevant. From **Figure 9** we identify 32 and 19 possible interactions for these respective scenarios. These thresholds demonstrate a method for considering what constitutes collective knowledge, but others could be selected.

Using three thresholds (≥1, ≥3, ≥5), we calculate Matthews' Correlation Coefficients (*MCC*) using **Equation 1**. These are presented in **Table 12** and are $MCC = 0.28$ when all interactions are considered (≥1), improving to $MCC = 0.51$ with a threshold of ≥3 participants and $MCC = 0.49$ with a threshold of ≥5 participants noting an interaction. Applying a threshold of ≥3 (vs. ≥1) people identifying an interaction has a slight influence on the number of true positives (22 vs. 24 interactions) but significantly reduces the number of false positives (10 vs. 62 interactions). Using a sensitivity test, where the number of TP and TN are varied by +1, *MCC* changes by 0.02 for each additional TP and 0.01 for each additional TN. For example, a participant identifying 12TP and 374TN will have an MCC = 0.25, whereas a participant identifying 13TP and 375TN will have an MCC = 0.28 (=0.25+0.01+0.02).

Matthews' Correlation Coefficient is a simple indicator of agreement, which we use to examine differences between stakeholder perspectives and our national interaction framework (**Figure 3**). When applying a small threshold (≥3 people agreeing on a given interaction) to determine which interactions were analysed, the collective knowledge of 16 participants generated the closest agreement to the national interaction framework ($MCC = 0.51$). This *MCC* is based on 22 (44%) of 50 interactions in **Figure 3** being identified by ≥3 participants, and therefore 28 (56%) of 50 interactions that ≤2 participants identified in the workshop. Of these 27 interactions identified by ≤2 participants, nobody identified 25 different interactions. These results suggest the following:

- *Enhanced communication within and across organisations involved in natural hazards and DRR in Guatemala could help when considering hazard interactions*. Interaction frameworks could help facilitate this communication and elicit additional information about interaction likelihoods and impacts. Ensuring that collective understanding of hazard interactions is operationalised to greatest effect will require strong institutions, and cross-departmental and cross-disciplinary communication (Scolobig *et al.*, 2017).

- *National and sub-national interaction frameworks could promote dialogue on both high- and low-likelihood events.*

Interactions in the national interaction framework (**Figure 3**) include some low-likelihood hazard interactions, such as impact events triggering tsunamis, and storms triggering (meteo)tsunamis. Workshop participants may not consider low-likelihood events due to lack of access to peer-review literature. Only 5 of the 21 interview participants (**Section 2.5**) had access to, or regularly used, peer-review journals. Interview participants predominantly relied on experience and communication with colleagues for further information on natural hazards and interactions.

We can use MCC values to monitor changing understanding and perceptions of natural hazard interactions. MCC **values can be determined before interaction frameworks are introduced into an organisation, and then recalculated weeks, months, or years after individuals have explored, discussed and used them in their work.**

4 Discussion

In this discussion section, we first set out how the approach to constructing regional interaction frameworks we have developed in this paper can be replicated and scaled in diverse settings (**Section 4.1**). We proceed to explore how regional interaction frameworks can be used to enhance understanding of multi-hazard interactions (**Section 4.2**) and opportunities to enhance regional interaction frameworks through new research and practice (**Section 4.3**).

4.1 Scalability and Relevance of Regional Interaction Frameworks for Disaster Risk Reduction

The interdisciplinary, multi-method approach we have set out in **Sections 1** to **3** is scalable and can be applied in diverse geographical settings to generate a comprehensive, systematic, evidenced review of potential hazard interactions. A synthesis of available evidence in any given context (e.g., multi-national, national, sub-national) is necessary to underpin the construction of regional interaction frameworks. Our approach first develops an extensive location-specific hazard classification, and then populates a customised matrix with information about relevant hazard interactions. This contrasts with many existing studies of multi-hazards which are often focussed on the layering of single hazards but not looking at the potential interactions. When potential hazard interactions are consideringed, most studies are not systematic and are which are generally selective about which hazards they include. The studies often and do not describe the evidence for including/excluding certain hazards or interactions between hazards. The regional interaction frameworks we present in **Section 3** include 21 to 33 natural hazards (compared to 6 to 11 natural hazards in the examples summarised in **Table 1**).

Other countries in Central America (e.g., Nicaragua, El Salvador, Costa Rica) have similarities to Guatemala in their multi-hazard landscape. Their national interaction frameworks would likely be similar, although not identical, to Guatemala. Interaction frameworks for other countries may look very different, shaped by the tectonic and meteorological setting. Regional interaction frameworks can also be developed for sub-national scales, including large geographical domains, municipalities, or localised sites important to the development of critical infrastructure.

We propose that comprehensive, systematic and evidenced regional interaction frameworks can improve awareness of complex multi-hazard landscapes and assessment of potential networks of hazard interactions, thus informing disaster risk reduction and response strategies. Detailed and evidenced reviews of multi-hazard interactions are a fundamental first step to understanding the complexity of the multi-hazard landscape and therefore understanding risk (Sendai Framework for Disaster Risk Reduction, Priority for Action 1). In particular, regional interaction frameworks can be a powerful tool for scenario discussions between hazard managers and those responsible for single hazard preparedness and response. Through sitting down and discussing together the potential multi-hazard scenarios that may occur decisions can be made about the preparedness steps required and how different actors would work together to respond. It may be possible to indicate which scenarios have a high-likelihood vs. low-likelihood, and which could have a large impact vs. small impact. When the regional interaction frameworks were used by us in this way in Guatemala during a visit in 2018, some participants questioned the inclusion of particular hazards and/or hazard interactions in the interaction frameworks (e.g., landslides triggering tsunamis). Following discussion of the evidence used to populate the matrix for this scenario, participants reported changes in opinion about the relevance of these interactions and their need for inclusion within planning.

Further ~~E~~examples of how the information within *regional interaction frameworks*, and generated scenarios, can be used by agencies responsible for hazard monitoring, DRR and disaster response are as follows:

- *Scenarios to ensure hazard preparedness and disaster response systems are effective.* The occurrence of one hazard (e.g., a volcanic eruption) may result in the movement of people or assets to another region. Ensuring comprehensive awareness within decision-making agencies of how this hazard has changed the likelihood of other hazards (e.g., lahars, landslides) is necessary to ensure exposure and vulnerability of displaced people is not increased. Developing and discussing scenarios of triggered hazard scenarios, particularly with diverse single-hazard actors all taking part in the discussion, can help explore dynamic vulnerability between successive hazard events, and the steps needed to prevent compounding impacts.

- *Scenarios as an aid for land-use planning.* Urban development is growing in many parts of the world, with cities expanding rapidly. We believe these regional interaction frameworks can be used as scenarios by land-use planners to be much more aware of the multi-hazard landscape and interaction networks, and bring this into their planning. These frameworks can help inform urban planning by creating scenarios where there are potential for interactions between spatially overlapping or contiguous hazards. This can then help to ensure risk is not underestimated and build effective hazard management plans that consider potential cascades of hazards. For example, an underground transport system may need to consider how an earthquake triggering subsidence would affect its susceptibility to groundwater flooding.

- *Educational and preparedness messages delivered to communities.* Many communities are exposed to multiple hazards. Understanding the physical processes that underpin these hazards, and the steps they can take to reduce their risk is acknowledged as important within the Sendai Framework guiding principles (UNISDR, 2015). Building awareness through multiple separate communications, about individual hazards, may result in confusion, fatigue, or missed opportunities to benefit from synergies in preparedness strategies. A regional interaction framework provides professionals responsible for public education and preparedness with a comprehensive list of possible hazards, and a tool through which scenarios of interaction networks can be identified and discussed with those at risk. The regional interaction framework matrices provide a visualization tool for more effective discussions and communications with these at risk communities. When sharing household or individual preparedness steps that could help to reduce vulnerability to one hazard, additional consideration can be given to make sure they don't increase vulnerability to other hazards.

LScenarios as an aid for land-use planning. Urban development is growing in many parts of the world, with cities expanding rapidly. We believe these regional interaction frameworks can be used as scenarios by land-use planners to be much more award of the Characterising multi-hazard landscapes and interaction networks, and bring this into their planning. These frameworks can help can help to inform urban planning by complementingcreating scenarios where the overlay of multiple single-hazard maps to explore appropriate land-use. Recognising the there are potential for interactions between spatially overlapping or contiguous hazards. This can then help to ensure risk is not underestimated and build effective hazard management plans that take into account potential cascades of hazards. For example, an underground transport system may need to consider how an earthquake triggering subsidence would affect its susceptibility to groundwater flooding.

Scenarios to eEnsureing disasterhazard preparedness and disaster response systems are effective. The regional interaction framework can be a powerful tool for scenario discussions between hazard managers and those responsible for single hazard preparedness and response, particularly in the context of Characterising multi-hazard landscapes and interaction networks can help to inform disaster response planning. The occurrence of one hazard (e.g., a volcanic eruption) may result in the movement of people or assets to another region. Ensuring comprehensive awareness within decision-making agencies of how the volcanic eruption has changed the likelihood of other hazards (e.g., lahars, landslides) is necessary to ensure exposure and vulnerability of displaced people is not increased. Developing and discussing scenarios of triggered hazard scenarios, particularly with diverse single-hazard actors all taking part in the discussion,s can help explore dynamic vulnerability between successive hazard events, and the steps needed to prevent compounding impacts.

dynaiFailing to consider multi-hazard interactions can therefore lead to the distortion of management priorities, increased vulnerability to other spatially relevant hazards, overwhelming a community with multiple and sometimes conflicting hazard management strategies for multiple hazards, or an overall underestimation of risk (Tobin and Montz, 1997;

ARMONIA, 2007; Kappes *et al.*, 2010; Budimir *et al.*, 2014; Mignan *et al.*, 2014; Gill and Malamud, 2014). Regional interaction frameworks are a valuable informational compilation and visualization tool for (i) raising awareness of the complexities of the multi-hazard environment, and (ii) extracting and discussing potential scenarios of multi-hazard interaction networks to explore how exposure and vulnerability may change between successive hazard events.

4.2 Using Regional Interaction Frameworks to Enhance Awareness of Multi-Hazard Interactions

Hazard interactions cut across multiple disciplines and so require input from diverse specialisms (Kappes *et al.*, 2012; Scolobig *et al.*, 2013; Scolobig *et al.*, 2017). Interaction frameworks could therefore help to facilitate enhanced cross-institutional dialogue about hazard interactions, their likelihoods and potential impacts. This could help to strengthen collective knowledge of hazard interactions, and the ability of an individual to access this knowledge. By contrasting results from our workshop (**Figure 2**) with our Guatemala national interaction framework (**Figure 3**), we can examine and quantify congruence between the two matrices. **Figure 7** is a 21×21 interaction matrix that combines **Figures 2** and **3** to indicate the number of workshop participants (from a total of 16) that identified an interaction as being relevant to Guatemala (numbers), and the interactions identified within our national interaction framework (grey shading, from **Figure 3**).

Figure 7 combines information and knowledge from 16 participants to present something that is 'owned' by no individual. It is collective knowledge, combining information and knowledge owned by multiple people (Antonelli, 2000). We do not expect an individual scientist or hazard professional to map out all relevant interactions. Assessing how an organisation rather than an individual understands interactions demonstrates their collective knowledge. For this knowledge to be truly collective there must be effective communication between participants, and a means by which this knowledge can be accessed, shared and applied (Foray, 2000; Antonelli, 2000; Paton *et al.*, 2008).

Multi-hazard research is complex, and requires scientists and professionals operating in many different disciplines. **Figure 7** demonstrates large variation in perspectives between participants on hazard interactions. There is a unanimous consensus (i.e., 16 participants) that an interaction exists in two (0.5%) of 441 possible triggering interactions. To assess congruence between the participants' perspectives (numbers in **Figure 7**) and national interaction framework (grey shading in **Figure 7**), we use Matthews' Correlation Coefficient, or *MCC* (Matthews, 1975). *MCC* values are a function of true positives (TP), true negatives (TN), false positives (FP), and false negatives (FN) and can be expressed as follows (Matthews, 1975; Powers, 2011):

$$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}} \qquad \textbf{(Equation. 1)}$$

The *MCC* gives a value of congruence between '−1.0' (zero overlap between the numbers and grey shading in **Figure 7**) and '+1.0' (perfect overlap between the numbers and grey shading in **Figure 7**). An *MCC* = 0.0 suggests that the amount of congruence is no better than a random average (Kaufmann *et al.*, 2012). We use two different approaches:

i. *All identified interactions*. Where ≥1 people note an interaction to be relevant, we consider this part of the group's collective knowledge. From **Figure 7** we identify 86 interactions identified by the 16 workshop participants. This compares to 50 interactions in the national framework, **Figure 3**.

ii. *Interactions identified by '≥ x' participants.* A threshold could be applied, in terms of the number of participants identifying a given natural hazard interaction. Only those interactions that reach or exceed this threshold are considered. We select thresholds of ≥3 and ≥5 participants (out of 16 workshop participants) identifying an interaction as being relevant. From **Figure 7** we identify 32 and 19 possible interactions for these respective scenarios. These thresholds demonstrate a method for considering what constitutes collective knowledge, but others could be selected.

Using three thresholds (≥1, ≥3, ≥5 participants), we calculate Matthews' Correlation Coefficients (*MCC*) using **Eq.~~uation~~ 1**. These thresholds are selected arbitrarily to demonstrate how this approach could be adjusted to remove those interactions only volunteered by one (or a small number of) professionals, thus acting as a form of quality control. Other thresholds could be used. Coefficients for thresholds ≥1, ≥3, and ≥5 participants are presented in **Table 7** and are *MCC* = 0.28 when all interactions are considered (≥1), improving to *MCC* = 0.51 with a threshold of ≥3 participants and *MCC* = 0.49 with a threshold of ≥5 participants noting an interaction. Applying a threshold of ≥3 (vs. ≥1) people identifying an interaction has a slight influence on the number of true positives (22 vs. 24 interactions) but significantly reduces the number of false positives (10 vs. 62 interactions). Using a sensitivity test, where the number of TP and TN are varied by +1, *MCC* changes by 0.02 for each additional TP and 0.01 for each additional TN. For example, a participant identifying 12TP and 374TN will have an MCC = 0.25, whereas a participant identifying 13TP and 375TN will have an MCC = 0.28 (=0.25+0.01+0.02).

Matthews' Correlation Coefficient is a simple indicator of agreement, which we use to examine differences between stakeholder perspectives and our national interaction framework (**Figure 3**). When applying a small threshold (≥3 people agreeing on a given interaction) to determine which interactions were analysed, the collective knowledge of 16 participants generated the closest agreement to the national interaction framework (*MCC* = 0.51). This *MCC* is based on 22 (44%) of 50 interactions in **Figure 3** being identified by ≥3 participants, and therefore 28 (56%) of 50 interactions that ≤2 participants identified in the workshop. Of these 27 interactions identified by ≤2 participants, nobody identified 25 different interactions. These results suggest the following:

- *Enhanced communication within and across organisations involved in natural hazards and DRR in Guatemala could* *help when considering hazard interactions.* When co-created by diverse stakeholders, interaction frameworks can help to facilitate communication across specialisms engaged in hazard monitoring and civil protection. Interaction frameworks could also help elicit additional information to characterise interactions, such as which are most likely to occur and which could cause the greatest damage about interaction likelihoods and impacts. Ensuring that collective understanding of hazard interactions is operationalised to greatest effect will require strong institutions, and cross-departmental and cross-disciplinary communication (Scolobig *et al.*, 2017).

- *National and sub-national interaction frameworks could promote dialogue on both high- and low-likelihood events.* Interactions in the national interaction framework (**Figure 3**) include some low-likelihood hazard interactions, such as impact events triggering tsunamis, and storms triggering (meteo)tsunamis. Workshop participants may not consider low-likelihood events due to lack of access to peer-review literature. Only 5 of the 21 interview participants (**Section 2.5**) had access to, or regularly used, peer-review journals. Interview participants predominantly relied on experience and communication with colleagues for further information on natural hazards and interactions.

- *We can use MCC values to monitor changing awareness and perceptions of natural hazard interactions. MCC* values can be determined before interaction frameworks are introduced into an organisation, and then recalculated weeks, months, or years after individuals have explored, discussed and used them in their work.

The results of this exercise demonstrate that there are knowledge gaps that the development of comprehensive and evidenced frameworks of interactions could help to address, and provides a tool that could help to monitor changes in awareness of hazard interactions over time.

4.~~3~~ 3 Future Research and Practice to Enhance Regional Interaction Frameworks

We have set out an approach in **Sections 1** to **3** that integrates diverse evidence sources from the natural and social sciences through a visual database to give a comprehensive, systematic, and evidenced review of the multi-hazard interactions for a regional spatial extent. We believe this approach builds on and enhances existing forms of regional interaction framework, such as those described in **Table 1**. Additional research can further enhance regional interaction frameworks (**Section 4.3.1**), as can better understanding how to embed research outputs into relevant agencies through meaningful stakeholder dialogue (**Section 4.3.2**). Engagement with hazard and civil protection professionals, academics, the private sector and intergovernmental organisations in Guatemala informed our development of regional interaction frameworks. Understanding stakeholder requirements (e.g., terminology, spatial scales and temporal scales) helps to ensure that frameworks are fit-for-purpose. Draft results were discussed with many of these stakeholders in Guatemala in 2018, prior to publishing. We shared our interaction frameworks through seminars, roundtable discussions and interviews to document perspectives on (i) the structure and content of the interaction frameworks, (ii) use of the interaction frameworks, and (iii) future research and innovation opportunities. We highlight some of the common themes in the following two sub-sections.

4.3.1 Future Research Directions

Three broad areas where additional research could help to enhance regional interaction frameworks include (i) expanding the range of interaction types considered, (ii) increasing the number of layers within regional interaction frameworks to better characterise interactions, and (iii) quantifying more complex scenarios derived from regional interaction frameworks.

In the regional interactions frameworks we have developed, we have particularly focused on triggering and increased probability interaction types, and the way in which these can connect to form multi-hazard interaction networks. Other interaction types are also important and emphasised in the Sendai Framework, notably where hazardous events occur simultaneously or cumulatively over time. Additional literature searches, fieldwork, data interrogation and/or stakeholder engagement could be used to document particular physical and social impacts of two or more independent hazards occurring simultaneously or consecutively in a region of interest (e.g., the near simultaneous eruption of Volcán de Pacaya and Tropical Storm Agatha in Guatemala in 2010). Examining the impacts of simultaneous or consecutive events on physical infrastructure, response systems, and community wellbeing could identify particular strengths or weaknesses where investment or capacity strengthening could help to reduce vulnerability to the broad multi-hazard landscape (de Ruiter *et al.*, 2018).

A second stream of research that could enhance regional interaction frameworks is the development and inclusion of additional layers of information such as how often each interaction occurs, possible thresholds, likelihoods and scales of impact. For each interaction, understanding the frequency-magnitude of occurrence and the range of potential impacts would involve the collation of additional and extensive evidence. We previously noted that some of this information could be elicited from diverse stakeholders, including through forensic studies of past and ongoing disasters to generate new insights into potential impacts. A 'multi-hazards observatory' could also enable the collection of diverse data to better characterise these layers of information. Information to characterise multi-hazard interactions would help to inform decision making about which interactions primarily need to be addressed to reduce disaster risk.

Building on the enhanced characterisation of potential interactions outlined above, a third stream of research is the quantification of more complex scenarios (interaction networks) derived from regional interaction frameworks. There is a gap for more modelling of real multi-hazard situations, involving multiple natural hazard types, anthropogenic processes, and a range of interaction types. A review of multi-hazard literature completed by Ciurean *et al.* (2018) highlighted that much of the current literature described simulated environments for a limited number of hazard and interaction types. This is potentially due to challenges in access to the data needed to characterise these complex multi-hazard environments, and the need to integrate data from difference disciplines. One approach to collate relevant data and improve the characterisation of hazard interactions is to use an online wiki-style system where relevant papers, datasets, and assessments of frequency-magnitude can be uploaded.

Multi-Hazard Research. Additional information layers (e.g., thresholds, likelihoods, scales of impact) could inform decision making around natural hazards. This requires new research to understand hazard and disaster dynamics in Guatemala. A 'multi-hazards' observatory could enable the collection of diverse data to better characterise these layers of information. Forensic studies of past and ongoing disasters, using interdisciplinary approaches, would generate new insights into potential impacts.

Furthermore, interaction frameworks can also be used as a tool to *guide* future research priorities, by determining where there is a lack of evidence and/or understanding of certain interactions. For example, in the context of the frameworks developed in **Section 3** for Guatemala, there were conflicting statements by stakeholders about the potential for both seismic and landslide-triggered tsunamis in the Pacific Ocean and lake systems. Further research about the history and impact of hazards in Central America could therefore be suggested as a priority to better inform the regional interaction framework.

4.3.2 Embedding and Enhancing Regional Interaction Frameworks through Stakeholder DialogueOperationalisation of Interaction Frameworks

Embedding regional interaction frameworks into key agencies responsible for hazard monitoring, disaster risk reduction, and disaster response can contribute to improved decision making by having a more holistic understanding of the multi-hazard landscape. Engagement with hazard and civil protection professionals, academics, the private sector and intergovernmental organisations informed our development of regional interaction frameworks for Guatemala. Understanding stakeholder requirements (e.g., terminology, spatial scales and temporal scales) can ensure frameworks are fit-for-purpose. In 2018, we returned to Guatemala and shared our interaction frameworks through seminars, roundtable discussions and interviews. We elicited perspectives on (i) the structure and content of the interaction frameworks, (ii) use of the interaction frameworks, and (iii) future research and innovation opportunities. This engagement highlighted some common themes:

Understanding Multi-Hazard Interactions. The iInteraction frameworks are a visual synthesis of diverse knowledge, traditionally 'owned' by diverse disciplinary groups. This They can help to enhance awareness of the spectrum of hazards and hazard interactions in a given territory, and strengthen communication across disciplinary boundaries. Interaction frameworks allow those undertaking research into any particular single hazard to place their work within the context of other natural hazards, thus fostering communication between hazard specialists and encouraging a more interdisciplinary approach. When reviewing the draft regional interaction frameworks for Guatemala, One one interview participant noted that (translated from Spanish) '*sometimes knowledge is in a head, but now it is in a visual summary* [that can be used by a range of people]'. Furthermore, sOther interviewome participants questioned the inclusion of particular hazards and/or hazard interactions in the interaction frameworks. Examples include, earthquakes triggering volcanic eruptions, floods triggering volcanic eruptions, landslides triggering tsunamis. Following discussion of the evidence used to populate the matrix, participants reported changes in opinion about their relevance of these interactions and their need for inclusion within planning.

One future step to help embed regional interaction frameworks into decision making is to consider the scale of spatial extent for which they are prepared. Multi-Hazard Research. Additional information layers (e.g., thresholds, likelihoods, scales of impact) could inform decision making around natural hazards. This requires new research to understand hazard and disaster dynamics in Guatemala. A 'multi-hazards' observatory could enable the collection of diverse data to better characterise these layers of information. Forensic studies of past and ongoing disasters, using interdisciplinary approaches, would generate new insights into potential impacts.

Scales of Interest. Many participants Many participants suggested that municipalities are the preferred scale of interest for further multi-hazard tools. Guatemala currently has 340 municipalities, across 22 Departments. The emphasis on municipalities likely arises from the political context in Guatemala, with municipal authorities being the final users of information. Other stakeholders noted that it may not be most effective (or efficient) to produce municipal-scale hazard assessments as hazards cross municipal, departmental, and national boundaries (Gill, 2016). Tools can therefore be prepared at scales that both provide useful information to those working at a municipal scale and recognise the artificial nature of these boundaries. T

Preferred Tools and Technologies. Participants were interested in tools that allowing the spatial representation of information in **Section 3**. could facilitate this, seeing both municipal perspectives and cross-border challenges. A GIS tool allowing the creation of municipal multi-hazard risk maps was a high priority of stakeholders, allowing the identification of hazard hotspots, improved disaster preparation (e.g., evacuation routes), and enhanced response through improved communication of potential secondary hazards. Spatial representation of information could help to identify regions where secondary hazards are more likely after a primary hazard, and the assessment of disaster impacts, including those generated through secondary hazards, by overlay of exposure and multi-hazard maps.

In addition to these generalised themes relating to next steps, pParticipants also noted specific ways that they could use our hazardregional interaction frameworks in their ongoing work. INSIVUMEH, CONRED and UN-OCHA indicated that they could use interaction frameworks as reference tools to strengthen preparedness and response to hazards. CONRED suggested they could integrate secondary hazards information into their public information bulletins and requested blank matrices to complete for specific high-risk municipalities. Finally, universities indicated that they would use this research and our systematic classification of hazards in Guatemala in their teaching. Fully realising the impact of regional interaction frameworks, and ensuring positive social impact, will require sustained collaborative engagement with user communities. The potential developments and applications outlined ~~above~~ through **Section 4.3** would support the embedding and operationalisation of this research in Guatemala with the lessons learned helping other regions and the wider hazard/disaster risk community ~~and may prove insightful in other settings~~.

~~o~~

~~**4.4 Application of Methods to Other Contexts**~~

~~Our approach, set out through **Sections 1** to **3**, is scalable and can be applied in diverse geographical contexts. A synthesis of available evidence in any given context (e.g., multi-national, national, sub-national) is necessary to underpin the construction of regional interaction frameworks. This process, outlined in **Section 3**, first develops a location-specific hazard classification, and then populates a customised matrix with information about relevant hazard interactions. Other countries in Central America (e.g., Nicaragua, El Salvador, Costa Rica) have similarities to Guatemala in their hazard landscape. Their national interaction frameworks would likely be similar, although not identical, to Guatemala. Interaction frameworks for other countries may look very different, shaped by the tectonic and meteorological setting.~~

~~Regional interaction frameworks can also be developed for sub-national scales, including large geographical domains, municipalities, or localised sites important to the development of critical infrastructure. We propose that comprehensive, systematic and evidenced regional interaction frameworks can be developed for and operationalised in diverse settings to improve DRR and response. When co-created by diverse stakeholders, interaction frameworks can help to facilitate communication across specialisms engaged in hazard monitoring and civil protection. Through dialogue, it may be possible to further characterise interactions, identifying those that are most likely to occur and those that could cause the greatest damage. This may help to improve decision making in key agencies engaged in DRR and civil protection.~~

~~5~~ 5 Conclusions

~~In this paper, we have described an approach to develop comprehensive, systematic and evidenced regional interaction frameworks that~~ Understanding and characterising the multi-hazard landscape of a region directly supports the implementation of the Sendai Framework (UNISDR, 2015).~~inform multi-hazard approaches to DRR, as encouraged by the Sendai Framework for DRR.~~ In this paper, ~~We~~ we have addressed three research questions, originally outlined in **Section 1**:

1. *For a defined spatial region, how does one construct and populate a synthesis of all relevant potential natural*

hazard interactions using blended sources of evidence for past case histories and theoretical future possibilities from that region's characteristics?

2. *How do interactions documented in the literature contrast with the knowledge of hazard/civil protection professionals operating in the region?*
3. *What are the implications of our regional interaction frameworks for multi-hazard methodologies to support disaster risk reduction, management and response?*

We develop and describe an approach to understand the multi-hazard landscape through comprehensive, systematic and evidenced regional interaction frameworks. We apply this approach in~~have applied this methodology to~~ Guatemala, ~~presenting~~ generating regional interaction frameworks for the national spatial extent of Guatemala and sub-national spatial extent of the Southern Highlands of Guatemala. Five evidence types (internationally accessible publications and reports, locally accessible civil protection bulletins, field observations, semi-structured stakeholder interviews, and a stakeholder workshop) underpin the construction and population of these frameworks.~~, and w~~We use this evidence to~~ do the following~~:

i. *Determine an appropriate classification scheme.* For Guatemala, this consists of six natural hazard groups, 19 hazard types, and 37 hazard sub-types.

ii. *Identify potential natural hazard interactions.* For a national spatial extent in Guatemala, we identify 50 possible interactions between 19 relevant natural hazard types. For the Southern Highlands of Guatemala, we identify 114 possible interactions between 33 relevant natural hazard sub-types.

Interaction frameworks can help to improve understanding of the multi-hazard landscape of a given region and potential scenarios of multi-hazard interaction networks. We present information in accessible visualisations, primarily interaction matrices. The use of accessible visualisation tools, such as matrices, to represent complex hazard interactions contributes to knowledge exchange across different disciplines. ~~The national and regional multi-hazard interaction frameworks presented here are communication tools that can enhance the application of multi-hazard research and collective knowledge in DRR management and policy.~~ We demonstrate through *Matthews' Correlation Coefficient*, a simple indicator of agreement, that there are many differences between stakeholder perspectives and our national interaction framework. The development of comprehensive and evidenced frameworks of interactions could help to increase awareness of multi-hazard interactions, and ~~The national and regional multi-hazard interaction frameworks presented here are communication tools that can~~strengthen communication between different stakeholders so as to improve collective knowledge. They could also be ~~enhance the application of multi-hazard research and collective knowledge in DRR management and policy.~~ used as a tool to monitor changes in understanding of hazard interactions over time.

~~We also consider potential networks of hazard interactions, and constrain relevant anthropogenic processes using the evidence outlined above.~~ Our approach allows those working on any individual hazard in Guatemala to place their work within the context of other natural hazards. When taking draft~~our~~ regional interaction frameworks back to Guatemala, we observed them fostering communication between hazard specialists and encouraging integrated multi-hazard approaches to DRR.

We believe our approach is scalable and can be replicated in diverse geographical settings. While examples of regional interaction frameworks exist in the literature, these often do not include a systematic assessment of possible natural hazards and interactions for a defined spatial extent.

By integrating diverse evidence types, we have developed a~~ systematic ~~n approach that constrains relevant interactions between a comprehensive selection of natural hazards~~.~~, ~~We ~~simplifying a broad array of complex information to facilitate an effective analysis by those working on reducing and managing the risk from natural hazards within both policy and practitioner sectors. We believe our approach can support the scientific community to construct more evidenced and detailed profiles of relevant interactions for diverse user groups, identify and explore multi-hazard interaction scenarios and how they may result in changes to exposure and vulnerability (potentially exacerbating risk), as well as extract locally-specific research and innovation gaps.

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References

Alvarado, G. E., Soto, G. J., Pullinger, C. R., Escobar, R., Bonis, S., Escobar, D., and Navarro, M.: Volcanic Activity, Hazards and Monitoring, in: J. Bundschuh, and G.E. Alvarado (eds.), Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, UK, 1155–1188, 2007.

Antonelli, C.: Collective knowledge communication and innovation: the evidence of technological districts, Regional studies, 34(6), 535-547, doi:10.1080/00343400050085657, 2000.

ARMONIA: Assessing and mapping multiple risks for spatial planning, European Union 6th Framework Programme Reports, European Union, 2007.

Bommer, J. J. and Rodríguez, C. E.: Earthquake-induced landslides in Central America, Engineering Geology, 63(3), 189–220, doi:10.1016/S0013-7952(01)00081-3, 2002.

Brown, S. K., Sparks, R. S. J., Mee, K., Vye-Brown, C., Ilyinskaya, E., Jenkins, S. F., and Loughlin, S. C.: Country and regional profiles of volcanic hazard and risk (Appendix B), in: S. C. Loughlin, R. S. J. Sparks, S. K. Brown, S. F. Jenkins and C. Vye-Brown (eds.) Global Volcanic Hazards and Risk, Cambridge: Cambridge University Press, doi: 10.1017/CBO9781316276273.030, 2015.

Bucknam, R. C., Coe, J. A., Chavarría, M. M., Godt, J. W., Tarr, A. C., Bradley, L. A., Rafferty, S., Hancock, D., Dart, R. L., and Johnson, M. L.: Landslides triggered by hurricane Mitch in Guatemala: Inventory and discussion. US Geological Survey Open File Report 01–443, US Department of the Interior, 38 p, 2001.

Budimir, M. E. A., Atkinson, P. M. and Lewis, H. G.: Earthquake-and-landslide events are associated with more fatalities than earthquakes alone, Nat. Hazards, 72, 895–914, 2014.

Bündnis Entwicklung Hilft/United Nations University: World Risk Report 2017. Berlin: Bündnis Entwicklung Hilft, 48 p, 2017.

Bundschuh, J., and Alvarado, G. E. (eds.): Central America Geology, Resources and Hazards (Two Volume Set), Taylor and Francis, London, UK, 1131 p., 2007.

Cahoon, D. R., and Hensel, P.: Hurricane Mitch: a regional perspective on mangrove damage, recovery and sustainability: USGS Open File Report 03-183, 31 p., 2002

Carrara, A., Crosta, G. and Frattini, P.: Geomorphological and historical data in assessing landslide hazard. Earth Surface Processes and Landforms, 28(10), 1125-1142, doi:10.1002/esp.545, 2003.

Charvériat, C.: Natural Disasters in Latin America and the Caribbean: An Overview of Risk, Working Paper, Inter-American Development Bank, Research Department, No. 364 [online] Available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1817233 (accessed 29 November 2018), 2000.

Choine, M. N., O'Connor, A., Gehl, P., D'Ayala, D., García-Fernández, M., Jiménez, M. J., Gavin, K., Van Gelder, P., Salceda, T., and Power, R.: A multi hazard risk assessment methodology accounting for cascading hazard events, 12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12 Vancouver, Canada, July 12-15 [online] Available at: https://open.library.ubc.ca/cIRcle/collections/53032/items/1.0076192 (accessed 29 November 2018), 2015.

CIA: Guatemala Physiography [online] Available at: https://www.cia.gov/library/publications/resources/cia-maps-publications/Guatemala.html (accessed 29 November 2018), 2001.

Ciurean, R., Gill, J. C., Reeves, H., O'Grady S. K., Donald, K., and Aldridge, T.: Review of multi-hazards research and risk assessments. British Geological Survey Engineering Geology & Infrastructure Programme, Open Report OR/18/057, 2018.

Claxton, R.H.: Weather-based Hazards in Colonial Guatemala, Studies in the Social Sciences, 25, 139–163, 1986.

CONRED: Boletínes Informativos. Available at: https://conred.gob.gt/site/Boletines-Informativos (accessed 19 November 2018), 2018b.

CONRED: CONRED (Coordinadora Nacional para la Reducción de Desastres) home page [online] Available at: www.conred.gob.gt (accessed 29 November 2018), 2018a.

Cooper, A. H. and Calow, R. C.: Avoiding gypsum geohazards: guidance for planning and construction, British Geological Survey, Technical Report WC/98/5, UK NG125GG [online] Available at: http://nora.nerc.ac.uk/14146/1/Cooper_Callow_1998_DIFID_Gypsum_and_planning_WC_98_005_COL.pdf (accessed 29 November 2018), 1998.

CRED: EM-DAT: The International Disaster Database. Available online: https://www.emdat.be/database (accessed 29 November 2018), 2018.

De Pippo, T., Donadio, C., Pennetta, M., Petrosino, C., Terlizzi, F., and Valente, A.: Coastal hazard assessment and mapping in Northern Campania, Italy, Geomorphology, 97(3), 451-466, doi:10.1016/j.geomorph.2007.08.015., 2008.

De Ruiter, M. C., Couasnon, A., van den Homberg, M., Ward, P., & Daniell, J. E.: How Do Consecutive Disasters Affect Damages and the Post-Disaster Recovery Process?. In *AGU Fall Meeting Abstracts*, 2018, December.

DesInventar: Guatemala [online] Available at: http://www.desinventar.net/DesInventar/profiletab.jsp#more_info (accessed 29 November 2018), 2016.

DiCicco-Bloom, B., and Crabtree, B. F.: The qualitative research interview, Medical education, 40(4), 314–321, doi:10.1111/j.1365-2929.2006.02418.x, 2006.

Duncan, M., Edwards, S., Kilburn, C., Twigg, J.: An interrelated hazards approach to anticipating evolving risk. GFDRR (Ed.) The Making of a Riskier Future: How Our Decisions Are Shaping Future Disaster Risk, Global Facility, 2016.

Edwards, R.: A critical examination of the use of interpreters in the qualitative research process, Journal of Ethnic and Migration Studies, 24(1), 197–208, doi:10.1080/1369183X.1998.9976626, 1998.

Fernández, M., and Ortiz, M.: Earthquake triggered tsunamis. In: J. Bundschuh, J. and G.E. Alvarado (eds.) Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, UK, 1257–1265, 2007.

Fisher, K. T.: Positionality, subjectivity, and race in transnational and transcultural geographical research, Gender, Place and Culture, 22(4), 456–473, doi:10.1080/0966369X.2013.879097, 2015.

Foray, D.: Characterising the knowledge base: available and missing indicators, in (OECD eds.) Knowledge management in the learning society, Paris, France, 239–255, 2000.

Gill, J. C., and Malamud, B. D. (2017). Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework. Earth-Science Reviews, 166, 246-269.

Gill, J. C., and Malamud, B. D. Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. Earth System Dynamics, 7(3), 659, 2016.

Gill, J. C., and Malamud, B. D.: Reviewing and visualizing the interactions of natural hazards. Reviews of Geophysics, 52(4), 680-722, 2014.

Gill, J. C.: Increasing the Understanding and Characterisation of Natural Hazard Interactions. Doctoral Thesis, King's College London, 2016

Glade, T.: Landslide occurrence as a response to land use change: a review of evidence from New Zealand, Catena, 51(3–4), 297–314, doi:10.1016/S0341-8162(02)00170-4, 2003.

Global Volcanism Program: Volcanoes of the World [online] Available at: http://volcano.si.edu/ (accessed 29 November 2018), 2013.

Guzzetti, F., Cardinali, M., and Reichenbach, P.: The AVI project: a bibliographical and archive inventory of landslides and floods in Italy, Environmental Management, 18(4), 623–633, doi:10.1007/BF02400865, 1994.

Han, J., Wu, S., and Wang, H.: Preliminary study on geological hazard chains, Earth Science Frontiers, 14(6), 11–20, doi:10.1016/S1872-5791(08)60001-9, 2007.

Harris, A. J., Vallance, J. W., Kimberly, P., Rose, W. I., Matías, O., Bunzendahl, E., Flynn, L. P., and Garbeil, H. Downstream aggradation owing to lava dome extrusion and rainfall runoff at Volcan Santiaguito, Guatemala, Geological Society of America Special Papers, 412, 85–104, doi:10.1130/2006.2412(05), 2006.

Havenith, H. B., Strom, A., Jongmans, D., Abdrakhmatov, A., Delvaux, D., and Tréfois, P.: Seismic triggering of landslides, Part A: Field evidence from the Northern Tien Shan. Natural Hazards and Earth System Science, 3(1/2), 135-149, 2003.

Hermosilla, R. G.: The Guatemala City sinkhole collapses, Carbonates and evaporites, 27(2), 103-107, doi:10.1007/s13146-011-0074-1, 2012

Hodell, D. A., Brenner, M., Curtis, J. H. and Guilderson, T. Solar forcing of drought frequency in the Maya lowlands. Science, 292(5520), 1367–1370, doi:10.1126/science.1057759, 2001.

Hunt, R.E.: Geotechnical Engineering Investigation Handbook. CRC Press, Florida, USA, 1088 p, 2005.

Ibsen, M. L., and Brunsden, D.: The nature, use and problems of historical archives for the temporal occurrence of landslides, with specific reference to the south coast of Britain, Ventnor, Isle of Wight. Geomorphology, 15(3), 241–258, doi:10.1016/0169-555X(95)00073-E, 1996.

IFFN: Fire Situation in Guatemala [online] Available at: http://www.fire.uni-freiburg.de/iffn/country/gt/gt_1_eng.htm (accessed 29 November 2018), 2002.

INSIVUMEH: Home page. Available at: www.insivumeh.gob.gt (accessed 29 November 2018), 2018.

Kappes, M. S., Keiler, M., and Glade, T. From Single- to Multi-Hazard Risk Analyses: a concept addressing emerging challenges, in: J. P. Malet, T. Glade, and N. Casagli (eds.) Mountain Risks: Bringing Science to Society, CERG Editions, Strasbourg, France, 351–356, 2010.

Kappes, M. S., Keiler, M., von Elverfeldt, K., and Glade, T.: Challenges of analyzing multi-hazard risk: a review. Natural hazards, 64(2), 1925-1958, 2012

Kaufmann, O., Deceuster, J., and Quinif, Y.: An electrical resistivity imaging-based strategy to enable site-scale planning over covered palaeokarst features in the Tournaisis area (Belgium), Engineering Geology, 133, 49–65, doi:10.1016/j.enggeo.2012.01.017, 2012.

Kitchin, R. and Tate, N. J.: Conducting research into human geography. Theory, Methodology and Practice, Pearson Education Limited, Harlow, UK, 330 p., 2000.

Knapen, A., Kitutu, M. G., Poesen, J., Breugelmans, W., Deckers, J., and Muwanga, A.: Landslides in a densely populated county at the footslopes of Mount Elgon (Uganda): characteristics and causal factors, Geomorphology, 73(1), 149–165, doi:10.1016/j.geomorph.2005.07.004, 2006.

Kreft, S., Eckstein, D., Dorsch, L. and Fischer, L.: Global Climate Risk Index 2016: Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2014 and 1995 to 2014 [online] Available at: http://germanwatch.org/fr/download/13503.pdf (accessed 29 November 2018), 2015.

Kueny, J.A. and Day, M.J.: Designation of protected karstlands in Central America: a regional assessment, Journal of Cave and Karst Studies, 64(3), 165–174, 2002.

LAHT: Guatemala to Deliver Food to 170,000 Families Affected by Heatwave [online] Available at: http://www.laht.com/article.asp?ArticleId=2347276andCategoryId=23558 (accessed 29 November 2018), 2014.

Lindholm C.D., Climent, A., Camacho, E., Strauch, W., Cepeda, J., Cáceras, D., Ligorría, J.P., and Bungum, H.: Seismic hazard and microzonation, in: J. Bundschuh, and G.E. Alvarado (eds.), Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, 1099–1118, 2007.

Liu, B., Siu, Y.L., and Mitchell, G.: Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment, Natural Hazards and Earth System Sciences, 16(2), 629–642, doi:10.5194/nhess-16-629-2016, 2016.

Longhurst, R.: Semi-structured interviews and focus groups, in N.J. Clifford and G. Valentine (eds.) Key Methods in Geography, SAGE Publications, London, 117–132, 2003.

Luna, B.: Assessment and Modeling of two Lahars caused by ‘Hurricane Stan’ at Atitlan, Guatemala, October, 2005 (Doctoral dissertation, MSc. Thesis, University of Oslo, Oslo) [online] Available at: https://www.duo.uio.no/handle/10852/12448 (accessed 29 November 2018), 2007.

MacDougall, C., and Fudge, E.: Planning and recruiting the sample for focus groups and in-depth interviews, Qualitative health research, 11(1), 117-126, 2001.

Madge, C.: Boundary disputes: comments on Sidaway (1992), Area, 25(3), 294–299, 1993.

MAGA/PEDN: Annual Average Precipitation Map, Guatemala [online] Available at: http://www.sigmaga.com.gt/imagenes/mapas/clima/precipitacion-anual.pdf (accessed 29 November 2018), 2002b.

MAGA/PEDN: Soil Types, Guatemala [online] Available at: http://www.sigmaga.com.gt/imagenes/mapas/suelos/3-

taxonomia-suelos-ordenes.pdf (accessed 29 November 2018), 2002a.

MAGA: Frost/Ice Hazard Map, Guatemala [online] Available at: http://www.sigmaga.com.gt/imagenes/mapas/amenazas_naturales/amenaza_heladas.pdf (accessed 29 November 2018), 2002.

Mahood, Q., Van Eerd, D., & Irvin, E.: Searching for grey literature for systematic reviews: challenges and benefits. Research synthesis methods, 5(3), 221-234, 2014.

Matthews, B. W.: Comparison of the predicted and observed secondary structure of T4 phage lysozyme, Biochimica et Biophysica Acta (BBA)-Protein Structure, 405(2), 442–451, doi:10.1016/0005-2795(75)90109-9, 1975.

McGuire, B., and Maslin, M. A. (eds.): Climate Forcing of Geological Hazards, Wiley-Blackwell, 311 p, 2012.

Merriam, S. B., Johnson-Bailey, J., Lee, M. Y., Kee, Y., Ntseane, G., and Muhamad, M.: Power and positionality: Negotiating insider/outsider status within and across cultures, International Journal of Lifelong Education, 20(5), 405–416, doi:10.1080/02601370120490, 2001.

Mignan, A., Wiemer, S. and Giardini, D.: The quantification of low-probability–high-consequences events: Part I. A generic multi-risk approach, Nat. Hazards, 73, 1999–2022, 2014.

Moeller, S. D.: Regarding the Pain of Others: Media, Bias and the Coverage of International Disasters, Journal of International Affairs, 173–196, 2006.

Moreno, A.R.: Climate change and human health in Latin America: drivers, effects, and policies, Regional Environmental Change, 6(3), 157-164, doi:10.1007/s10113-006-0015-z, 2006.

NASA@: Patterns of Lightning Activity [online] Available at: http://earthobservatory.nasa.gov/IOTD/view.php?id=6679andeocn=imageandeoci=related_image (accessed 29 November 2018), 2006.

Neri, A., Aspinall, W. P., Cioni, R., Bertagnini, A., Baxter, P. J., Zuccaro, G., Andronico, D., Barsotti, S., Cole, P. D., Espoti-Ongaro, T., Hincks, T. K., Macedonio, G., Papale, P., Rosi, M., Santacroce, R., and Woo, G.: Developing an event tree for probabilistic hazard and risk assessment at Vesuvius, Journal of Volcanology and Geothermal Research, 178(3), 397–415, doi:10.1016/j.jvolgeores.2008.05.014, 2008.

Neri, M., Le Cozannet, G., Thierry, P., Bignami, C., and Ruch, J.: A method for multi-hazard mapping in poorly known volcanic areas: an example from Kanlaon (Philippines), Natural Hazards and Earth System Sciences, 13, 1929–1943, 2013, doi:10.5194/nhess-13-1929-2013, 2013.

OEC: Economic Complexity of Guatemala [online] Available at: http://atlas.media.mit.edu/en/profile/country/gtm/ (accessed 29 November 2018), 2016.

Owen, L. A., Kamp, U., Khattak, G. A., Harp, E. L., Keefer, D. K., and Bauer, M. A.: Landslides triggered by the 8 October 2005 Kashmir earthquake, Geomorphology, 94(1), 1–9, doi:10.1016/j.geomorph.2007.04.007, 2008.

Palinkas, L. A., Horwitz, S.M., Green, C. A., Wisdom, J. P., Duan, N. and Hoagwood, K.: Purposeful sampling for qualitative data collection and analysis in mixed method implementation research, Administration and Policy in Mental Health and Mental Health Services Research, 42(5), 2015.

Paton, D., Smith, L., Daly, M., and Johnston, D.: Risk perception and volcanic hazard mitigation: Individual and social perspectives, Journal of Volcanology and Geothermal Research, 172(3), 179-188, doi:10.1016/j.jvolgeores.2007.12.026, 2008.

Pescaroli, G., and Alexander, D.: Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. Risk analysis, 2018.

Pielke Jr, R.A., Rubiera, J., Landsea, C., Fernández, M. L., and Klein, R.: Hurricane vulnerability in Latin America and the Caribbean: Normalized damage and loss potentials, Natural Hazards Review, 4(3), 101–114, doi:10.1061/(ASCE)1527-6988(2003)4:3(101), 2003.

Porfido, S., Esposito, E., Spiga, E., Sacchi, M., Molisso, F. and Mazzola, S.: Re-evaluation of the 1976 Guatemala earthquake taking into account the environmental effects, 11th EGU General Assembly, Vienna, Austria, 27 April–2 May 2014, Geophys. Res. Abs., 16, EGU2014–6525, 2014.

Powers, D. M. W.: Evaluation: from Precision, Recall and F-measure to ROC, Informedness, Markedness and Correlation, Journal of Machine Learning Technologies, 2(1), 37–63, 2011.

Qu, S. Q., and Dumay, J.: The qualitative research interview, Qualitative Research in Accounting and Management, 8(3), 238-264, doi:10.1108/11766091111162070, 2011.

Raška, P., Zábranský, V., Dubišar, J., Kadlec, A., Hrbáčová, A., and Strnad, T.: Documentary proxies and interdisciplinary research on historic geomorphologic hazards: a discussion of the current state from a central European perspective, Natural hazards, 70(1), 705–732, doi:10.1007/s11069-013-0839-z, 2014.

Relief Web: Situation Reports for Central America following Tropical Storm Nate. Available online: https://reliefweb.int/disaster/tc-2017-000148-nic/thumb (accessed 29 November 2018), 2018.

ReliefWeb: Guatemala Boletínes Informativos [online] Available at: http://reliefweb.int/updates?search=Boletin%20informativos (accessed 29 November 2018), 2016.

Rodríguez, C.E.: Earthquake-induced landslides, in J. Bundschuh, and G.E. Alvarado (eds.), Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, 1217–1255, 2007.

Rose, W. I. (Ed.): Natural hazards in El Salvador (Vol. 375). Geological Society of America, 2004.

Salini Impregilo: Pueblo Viejo Dam on the Chixoy river [online] Available at: http://www.salini-impregilo.com/en/projects/completed/dams-hydroelectric-plants/pueblo-viejo-dam-on-the-chixoy-river.html (accessed 29 November 2018), 2014.

Satarugsa, P.: The Lessons Learnt from Geophysical Investigation of Sinkholes in Rock Salt in Thailand, International Conference on Geology, Geotechnology and Mineral Resources of Indochina (GEOINDO 2011) 1-3 December 2011, Khon Kaen, Thailand, [online] Available at: http://home.kku.ac.th/peangta/peangta-final-sinkhole2011.pdf (accessed 29 November 2018), 2011.

Schneider, S. C., and Barsoux, J. L.: Managing across cultures, Pearson Education, 352 p, 2002.

Schuster, R. L., Bucknam, R. C. and Mota, M. A.: Stability assessment of a Hurricane Mitch-induced landslide dam on the Rio La Lima, Sierra de Las Minas, eastern Guatemala, Open File Report 01-120, US Geological Survey, US Department of the Interior, USA, 2001.

Scolobig A, Vinchon C, Komendantova N, Bengoubou-Valerius M, and Patt A.: Social and institutional barriers to effective multi-hazard and multi-risk decision making and governance. Deliverable 6.3, FP7 MATRIX Project - New Multi-Hazard and Multi-Risk Assessment Methods for Europe (30 September 2013), 2013.

Scolobig, A., Nadejda, K. and Arnaud, M.: Mainstreaming Multi-Risk Approaches into Policy. Geosciences, 7(4), p.129, 2017.

Seed, H. B., Arango, I., Gomez-Masso, A., Ascoli, R. G. and Chan, C.: Earthquake-induced liquefaction near lake Amatitlan, Guatemala, Journal of Geotechnical and Geoenvironmental Engineering, 107(ASCE 16212), 1981.

Siebert, L., Alvarado, G. E., Vallance, J. W., and De Vries, B. V. W.: Large-volume volcanic edifice failures in Central America and associated hazards, Geological Society of America Special Papers, 412, 1–26, doi:10.1130/2006.2412(01), 2006.

Soto, A. J., Rodhe, A., Pohjola, V., and Boelhouwers, J.: Spatial distribution of disasters caused by natural hazards in the Samala River catchment, Guatemala, Geografiska Annaler: Series A, Physical Geography, 97(1), 181–196, doi:10.1111/geoa.12097, 2015.

Squires, A.: Methodological challenges in cross-language qualitative research: a research review, International Journal of Nursing Studies, 46(2), 277–287, doi:10.1016/j.ijnurstu.2008.08.006, 2009.

Stewart, S. R., and Cangialosi, J. P.: Eastern North Pacific Hurricane Season of 2010, Monthly Weather Review, 140(9), 2769–2781, doi:10.1175/MWR-D-11-00152.1, 2012.

Stewart, S. R.: Eastern North Pacific Hurricanes 2010 - Flooding in a Slow Season, Weatherwise, 64(3), 38–45, doi:10.1080/00431672.2011.566819, 2011.

Sultana, F.: Reflexivity, positionality and participatory ethics: Negotiating fieldwork dilemmas in international research, ACME: An International E-Journal for Critical Geographies, 6(3), 374–385, 2007.

Suri, H.: Purposeful sampling in qualitative research synthesis, Qualitative Research Journal, 11(2), 63–75, 2011.

Tappin, D. R.: Submarine mass failures as tsunami sources: their climate control, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 368(1919), 2417–2434, doi:10.1098/rsta.2010.0079, 2010.

Tarvainen, T., Jarva, J., and Greiving, S.: Spatial pattern of hazards and hazard interactions in Europe, in: P. Schmidt-Thomé (ed.) Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, 42, Geological Survey of Finland, 83–91, 2006.

Taylor, F. E., Malamud, B. D., Freeborough, K., and Demeritt, D.: Enriching Great Britain's National Landslide Database by searching newspaper archives, Geomorphology, 249, 52-68, doi:10.1016/j.geomorph.2015.05.019, 2015.

Temple, B., and Edwards, R.: Interpreters/translators and cross-language research: Reflexivity and border crossings, International Journal of Qualitative Methods, 1(2), 1–12, doi:10.1177/160940690200100201, 2002.

Temple, B., and Young, A.: Qualitative research and translation dilemmas, Qualitative Research, 4(2), 161–178, doi:10.1177/1468794104044430, 2004.

Tilloy, A, Malamud, BD, Winter, HA, Joly-Laugel.: A review of quantification methodologies for multi-hazard interrelationships. Earth-Science Reviews (In press), 2019.

Tobin, G. A., and Montz, B. E.: Natural Hazards: Explanation and Integration, Guilford Press, New York, 1997.

Trimble, S. W.: The use of historical data and artifacts in geomorphology, Progress in Physical Geography, 32(1), 3–29, doi:10.1177/0309133308089495, 2008.

UNISDR: DRR Terminology, Available online: www.unisdr.org/we/inform/terminology (accessed 29 November 2018), 2017.

UNISDR: Sendai Framework for Disaster Risk Reduction, United Nations, Geneva, 37 p, 2015.

USGeothermal: El Ceibillo Geothermal Project Overview [online] Available at: http://www.usgeothermal.com/projects/4/El%20Ceibillo%20-%20Guatemala (accessed 29 November 2018), 2016.

Valentine, G.: Tell me about… using interviews as a research methodology, in: R. Flowerdew and D. Martin (eds.) Methods in human geography: A guide for students doing a research project, Prentice Hall, Harlow, UK, 110–126, 1997.

van Westen, C. J., Kappes, M. S., Luna, B. Q., Frigerio, S., Glade, T., and Malet, J-P.: Medium-scale multi-hazard risk assessment of gravitational processes, in: T. van Asch, J. Corominas, S. Greiving, J-P. Malet and S. Sterlacchini (eds.) Mountain risks: from prediction to management and governance, Springer, Netherlands, 201–231, doi:10.1007/978-94-007-6769-0_7, 2014.

von Huene, R., Ranero, C.R. and Watts, P.: Tsunamigenic slope failure along the Middle America Trench in two tectonic settings, Marine Geology, 203(3), 303–317, doi:10.1016/S0025-3227(03)00312-8, 2004.

Welle, T., Birkmann, J., Rhyner, J., Witting, M., and Wolfertz., J.: World Risk Index 2013, in: L. Jeschonnek (ed.) World Risk Report 2013, Alliance Development Works, Berlin, Germany, 45–56, 2013.

World Bank: Precipitation in Guatemala 1900-2012 [online] Available at: http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climateandThisRegion=North%20AmericaandThisCCode=GTM# (accessed 29 November 2018), 2016.

~~Alvarado, G. E., Soto, G. J., Pullinger, C. R., Escobar, R., Bonis, S., Escobar, D., and Navarro, M.: Volcanic Activity, Hazards and Monitoring, in: J. Bundschuh, and G.E. Alvarado (eds.), Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, UK, 1155–1188, 2007.~~

Antonelli, C.: Collective knowledge communication and innovation: the evidence of technological districts, Regional studies, 34(6), 535-547, doi:10.1080/00343400050085657, 2000.

Bommer, J. J. and Rodríguez, C .E.: Earthquake-induced landslides in Central America, Engineering Geology, 63(3), 189–220, doi:10.1016/S0013-7952(01)00081-3, 2002.

Brown, S. K., Sparks, R. S. J., Mee, K., Vye-Brown, C., Ilyinskaya, E., Jenkins, S. F., and Loughlin, S. C.: Country and regional profiles of volcanic hazard and risk (Appendix B), in: S. C. Loughlin, R. S. J. Sparks, S. K. Brown, S. F. Jenkins and C. Vye-Brown (eds.) Global Volcanic Hazards and Risk, Cambridge: Cambridge University Press, doi: 10.1017/CBO9781316276273.030, 2015.

Bucknam, R. C., Coe, J. A., Chavarría, M. M., Godt, J. W., Tarr, A. C., Bradley, L. A., Rafferty, S., Hancock, D., Dart, R. L., and Johnson, M. L.: Landslides triggered by hurricane Mitch in Guatemala: Inventory and discussion. US Geological Survey Open File Report 01–443, US Department of the Interior, 38 p, 2001.

Bündnis Entwicklung Hilft/United Nations University: World Risk Report 2017. Berlin: Bündnis Entwicklung Hilft, 48 p, 2017.

Bundschuh, J., and Alvarado, G. E. (eds.): Central America Geology, Resources and Hazards (Two Volume Set), Taylor and Francis, London, UK, 1131 p., 2007.

Cahoon, D. R., and Hensel, P.: Hurricane Mitch: a regional perspective on mangrove damage, recovery and sustainability: USGS Open File Report 03-183, 31 p., 2002

Carrara, A., Crosta, G. and Frattini, P.: Geomorphological and historical data in assessing landslide hazard. Earth Surface Processes and Landforms, 28(10), 1125-1142, doi:10.1002/esp.545, 2003.

Charvériat, C.: Natural Disasters in Latin America and the Caribbean: An Overview of Risk, Working Paper, Inter-American Development Bank, Research Department, No. 364 [online] Available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1817233 (accessed 29 November 2018), 2000.

Choine, M. N., O'Connor, A., Gehl, P., D'Ayala, D., García-Fernández, M., Jiménez, M. J., Gavin, K., Van Gelder, P., Salceda, T., and Power, R.: A multi hazard risk assessment methodology accounting for cascading hazard events, 12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP12 Vancouver, Canada, July 12-15 [online] Available at: https://open.library.ubc.ca/cIRcle/collections/53032/items/1.0076192 (accessed 29 November 2018), 2015.

CIA: Guatemala Physiography [online] Available at: https://www.cia.gov/library/publications/resources/cia-maps-publications/Guatemala.html (accessed 29 November 2018), 2001.

Claxton, R.H.: Weather-based Hazards in Colonial Guatemala, Studies in the Social Sciences, 25, 139–163, 1986.

CONRED: CONRED (Coordinadora Nacional para la Reducción de Desastres) home page [online] Available at: www.conred.gob.gt (accessed 29 November 2018), 2018a.

CONRED: Boletínes Informativos. Available at: https://conred.gob.gt/site/Boletines-Informativos (accessed 19 November 2018), 2018b.

Cooper, A. H. and Calow, R. C.: Avoiding gypsum geohazards: guidance for planning and construction, British Geological Survey, Technical Report WC/98/5, UK NG125GG [online] Available at: http://nora.nerc.ac.uk/14146/1/Cooper_Callow_1998_DIFID_Gypsum_and_planning_WC_98_005_COL.pdf (accessed 29 November 2018), 1998.

CRED: EM-DAT: The International Disaster Database. Available online: https://www.emdat.be/database (accessed 29 November 2018), 2018.

De Pippo, T., Donadio, C., Pennetta, M., Petrosino, C., Terlizzi, F., and Valente, A.: Coastal hazard assessment and mapping in Northern Campania, Italy, Geomorphology, 97(3), 451-466, doi:10.1016/j.geomorph.2007.08.015., 2008.

DesInventar: Guatemala [online] Available at: http://www.desinventar.net/DesInventar/profiletab.jsp#more_info (accessed 29 November 2018), 2016.

DiCicco-Bloom, B., and Crabtree, B. F.: The qualitative research interview, Medical education, 40(4), 314–321, doi:10.1111/j.1365-2929.2006.02418.x, 2006.

Duncan, M., Edwards, S., Kilburn, C., Twigg, J.: An interrelated hazards approach to anticipating evolving risk. GFDRR (Ed.) The Making of a Riskier Future: How Our Decisions Are Shaping Future Disaster Risk, Global Facility, 2016.

Edwards, R.: A critical examination of the use of interpreters in the qualitative research process, Journal of Ethnic and Migration Studies, 24(1), 197–208, doi:10.1080/1369183X.1998.9976626, 1998.

Fernández, M., and Ortiz, M.: Earthquake triggered tsunamis. In: J. Bundschuh, J. and G.E. Alvarado (eds.) Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, UK, 1257–1265, 2007.

Fisher, K. T.: Positionality, subjectivity, and race in transnational and transcultural geographical research, Gender, Place and Culture, 22(4), 456–473, doi:10.1080/0966369X.2013.879097, 2015.

Foray, D.: Characterising the knowledge base: available and missing indicators, in (OECD eds.) Knowledge management in the learning society, Paris, France, 239–255, 2000.

Gill, J. C., and Malamud, B. D.: Reviewing and visualizing the interactions of natural hazards. Reviews of Geophysics, 52(4), 680-722, 2014.

Gill, J. C., and Malamud, B. D. Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. Earth System Dynamics, 7(3), 659, 2016.

Gill, J. C., and Malamud, B. D. (2017). Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework. Earth-Science Reviews, 166, 246-269.

Gill, J. C.: Increasing the Understanding and Characterisation of Natural Hazard Interactions. Doctoral Thesis, King's College London, 2016

Glade, T.: Landslide occurrence as a response to land use change: a review of evidence from New Zealand, Catena, 51(3–4), 297–314, doi:10.1016/S0341-8162(02)00170-4, 2003.

Global Volcanism Program: Volcanoes of the World [online] Available at: http://volcano.si.edu/ (accessed 29 November 2018), 2013.

Guzzetti, F., Cardinali, M., and Reichenbach, P.: The AVI project: a bibliographical and archive inventory of landslides and floods in Italy, Environmental Management, 18(4), 623–633, doi:10.1007/BF02400865, 1994.

Han, J., Wu, S., and Wang, H.: Preliminary study on geological hazard chains, Earth Science Frontiers, 14(6), 11–20, doi:10.1016/S1872-5791(08)60001-9, 2007.

Harris, A. J., Vallance, J. W., Kimberly, P., Rose, W. I., Matías, O., Bunzendahl, E., Flynn, L. P., and Garbeil, H. Downstream aggradation owing to lava dome extrusion and rainfall runoff at Volcan Santiaguito, Guatemala, Geological Society of America Special Papers, 412, 85–104, doi:10.1130/2006.2412(05), 2006.

Havenith, H. B., Strom, A., Jongmans, D., Abdrakhmatov, A., Delvaux, D., and Tréfois, P.: Seismic triggering of landslides, Part A: Field evidence from the Northern Tien Shan. Natural Hazards and Earth System Science, 3(1/2), 135-149, 2003.

Hermosilla, R. G.: The Guatemala City sinkhole collapses, Carbonates and evaporites, 27(2), 103-107, doi:10.1007/s13146-011-0074-1, 2012

Hodell, D. A., Brenner, M., Curtis, J. H. and Guilderson, T. Solar forcing of drought frequency in the Maya lowlands. Science, 292(5520), 1367–1370, doi:10.1126/science.1057759, 2001.

Hunt, R.E.: Geotechnical Engineering Investigation Handbook. CRC Press, Florida, USA, 1088 p, 2005.

Ibsen, M. L., and Brunsden, D.: The nature, use and problems of historical archives for the temporal occurrence of landslides, with specific reference to the south coast of Britain, Ventnor, Isle of Wight. Geomorphology, 15(3), 241–258, doi:10.1016/0169-555X(95)00073-E, 1996.

IFFN: Fire Situation in Guatemala [online] Available at: http://www.fire.uni-freiburg.de/iffn/country/gt/gt_1_eng.htm (accessed 29 November 2018), 2002.

INSIVUMEH: Home page. Available at: www.insivumeh.gob.gt (accessed 29 November 2018), 2018.

Kappes, M. S., Keiler, M., von Elverfeldt, K., and Glade, T.: Challenges of analyzing multi-hazard risk: a review. Natural hazards, 64(2), 1925-1958, 2012

Kappes, M. S., Keiler, M., and Glade, T. From Single- to Multi-Hazard Risk Analyses: a concept addressing emerging challenges, in: J. P. Malet, T. Glade, and N. Casagli (eds.) Mountain Risks: Bringing Science to Society, CERG Editions, Strasbourg, France, 351–356, 2010.

Kaufmann, O., Deceuster, J., and Quinif, Y.: An electrical resistivity imaging-based strategy to enable site-scale planning over covered palaeokarst features in the Tournaisis area (Belgium), Engineering Geology, 133, 49–65, doi:10.1016/j.enggeo.2012.01.017, 2012.

Kitchin, R. and Tate, N. J.: Conducting research into human geography. Theory, Methodology and Practice, Pearson Education Limited, Harlow, UK, 330 p., 2000.

Knapen, A., Kitutu, M. G., Poesen, J., Breugelmans, W., Deckers, J., and Muwanga, A.: Landslides in a densely populated county at the footslopes of Mount Elgon (Uganda): characteristics and causal factors, Geomorphology, 73(1), 149–165, doi:10.1016/j.geomorph.2005.07.004, 2006.

Kreft, S., Eckstein, D., Dorsch, L. and Fischer, L.: Global Climate Risk Index 2016: Who Suffers Most From Extreme Weather Events? Weather-related Loss Events in 2014 and 1995 to 2014 [online] Available at: http://germanwatch.org/fr/download/13503.pdf (accessed 29 November 2018), 2015.

Kueny, J.A. and Day, M.J.: Designation of protected karstlands in Central America: a regional assessment, Journal of Cave and Karst Studies, 64(3), 165–174, 2002.

LAHT: Guatemala to Deliver Food to 170,000 Families Affected by Heatwave [online] Available at: http://www.laht.com/article.asp?ArticleId=2347276andCategoryId=23558 (accessed 29 November 2018), 2014.

Lindholm C.D., Climent, A., Camacho, E., Strauch, W., Cepeda, J., Cáceras, D., Ligorría, J.P., and Bungum, H.: Seismic hazard and microzonation, in: J. Bundschuh, and G.E. Alvarado (eds.), Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, 1099–1118, 2007.

Liu, B., Siu, Y.L., and Mitchell, G.: Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment, Natural Hazards and Earth System Sciences, 16(2), 629–642, doi:10.5194/nhess-16-629-2016, 2016.

Longhurst, R.: Semi-structured interviews and focus groups, in N.J. Clifford and G. Valentine (eds.) Key Methods in Geography, SAGE Publications, London, 117–132, 2003.

Luna, B.: Assessment and Modeling of two Lahars caused by 'Hurricane Stan' at Atitlan, Guatemala, October, 2005 (Doctoral dissertation, MSc. Thesis, University of Oslo, Oslo) [online] Available at: https://www.duo.uio.no/handle/10852/12448 (accessed 29 November 2018), 2007.

MacDougall, C., and Fudge, E.: Planning and recruiting the sample for focus groups and in-depth interviews, Qualitative health research, 11(1), 117-126, 2001.

Madge, C.: Boundary disputes: comments on Sidaway (1992), Area, 25(3), 294–299, 1993.

MAGA: Frost/Ice Hazard Map, Guatemala [online] Available at: http://www.sigmaga.com.gt/imagenes/mapas/amenazas_naturales/amenaza_heladas.pdf (accessed 29 November 2018), 2002.

MAGA/PEDN: Soil Types, Guatemala [online] Available at: http://www.sigmaga.com.gt/imagenes/mapas/suelos/3-taxonomia-suelos-ordenes.pdf (accessed 29 November 2018), 2002a.

MAGA/PEDN: Annual Average Precipitation Map, Guatemala [online] Available at: http://www.sigmaga.com.gt/imagenes/mapas/clima/precipitacion-anual.pdf (accessed 29 November 2018), 2002b.

Matthews, B. W.: Comparison of the predicted and observed secondary structure of T4 phage lysozyme, Biochimica et Biophysica Acta (BBA)-Protein Structure, 405(2), 442–451, doi:10.1016/0005-2795(75)90109-9, 1975.

McGuire, B., and Maslin, M. A. (eds.): Climate Forcing of Geological Hazards, Wiley-Blackwell, 311 p, 2012.

Merriam, S. B., Johnson-Bailey, J., Lee, M. Y., Kee, Y., Ntseane, G., and Muhamad, M.: Power and positionality: Negotiating insider/outsider status within and across cultures, International Journal of Lifelong Education, 20(5), 405–416, doi:10.1080/02601370120490, 2001.

Moeller, S. D.: Regarding the Pain of Others: Media, Bias and the Coverage of International Disasters, Journal of International Affairs, 173–196, 2006.

Moreno, A.R.: Climate change and human health in Latin America: drivers, effects, and policies, Regional Environmental Change, 6(3), 157-164, doi:10.1007/s10113-006-0015-z, 2006.

NASA@: Patterns of Lightning Activity [online] Available at: http://earthobservatory.nasa.gov/IOTD/view.php?id=6679andeocn=imageandeoci=related_image (accessed 29 November 2018), 2006.

Neri, A., Aspinall, W. P., Cioni, R., Bertagnini, A., Baxter, P. J., Zuccaro, G., Andronico, D., Barsotti, S., Cole, P. D., Espoti Ongaro, T., Hincks, T. K., Macedonio, G., Papale, P., Rosi, M., Santacroce, R., and Woo, G.: Developing an event tree for probabilistic hazard and risk assessment at Vesuvius, Journal of Volcanology and Geothermal Research, 178(3), 397–415, doi:10.1016/j.jvolgeores.2008.05.014, 2008.

Neri, M., Le Cozannet, G., Thierry, P., Bignami, C., and Ruch, J.: A method for multi-hazard mapping in poorly known volcanic areas: an example from Kanlaon (Philippines), Natural Hazards and Earth System Sciences, 13, 1929–1943, 2013, doi:10.5194/nhess-13-1929-2013, 2013.

OEC: Economic Complexity of Guatemala [online] Available at: http://atlas.media.mit.edu/en/profile/country/gtm/ (accessed 29 November 2018), 2016.

Owen, L. A., Kamp, U., Khattak, G. A., Harp, E. L., Keefer, D. K., and Bauer, M. A.: Landslides triggered by the 8 October 2005 Kashmir earthquake, Geomorphology, 94(1), 1–9, doi:10.1016/j.geomorph.2007.04.007, 2008.

Palinkas, L. A., Horwitz, S.M., Green, C. A., Wisdom, J. P., Duan, N. and Hoagwood, K.: Purposeful sampling for qualitative data collection and analysis in mixed method implementation research, Administration and Policy in Mental Health and Mental Health Services Research, 42(5), 2015.

Paton, D., Smith, L., Daly, M., and Johnston, D.: Risk perception and volcanic hazard mitigation: Individual and social perspectives, Journal of Volcanology and Geothermal Research, 172(3), 179-188, doi:10.1016/j.jvolgeores.2007.12.026, 2008.

Pescaroli, G., and Alexander, D.: Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. Risk analysis, 2018.

Pielke Jr, R.A., Rubiera, J., Landsea, C., Fernández, M. L., and Klein, R.: Hurricane vulnerability in Latin America and the Caribbean: Normalized damage and loss potentials, Natural Hazards Review, 4(3), 101-114, doi:10.1061/(ASCE)1527-6988(2003)4:3(101), 2003.

Porfido, S., Esposito, E., Spiga, E., Sacchi, M., Molisso, F. and Mazzola, S.: Re-evaluation of the 1976 Guatemala earthquake taking into account the environmental effects, 11th EGU General Assembly, Vienna, Austria, 27 April–2 May 2014, Geophys. Res. Abs., 16, EGU2014–6525, 2014.

Powers, D. M. W.: Evaluation: from Precision, Recall and F-measure to ROC, Informedness, Markedness and Correlation, Journal of Machine Learning Technologies, 2(1), 37–63, 2011.

Qu, S. Q., and Dumay, J.: The qualitative research interview, Qualitative Research in Accounting and Management, 8(3), 238-264, doi:10.1108/11766091111162070, 2011.

Raška, P., Zábranský, V., Dubišar, J., Kadlec, A., Hrbáčová, A., and Strnad, T.: Documentary proxies and interdisciplinary research on historic geomorphologic hazards: a discussion of the current state from a central European perspective, Natural hazards, 70(1), 705–732, doi:10.1007/s11069-013-0839-z, 2014.

Relief Web: Situation Reports for Central America following Tropical Storm Nate. Available online:

https://reliefweb.int/disaster/tc-2017-000148-nic/thumb (accessed 29 November 2018), 2018.

ReliefWeb: Guatemala Boletínes Informativos [online] Available at: http://reliefweb.int/updates?search=Boletin%20informativos (accessed 29 November 2018), 2016.

Rodríguez, C.E.: Earthquake-induced landslides, in J. Bundschuh, and G.E. Alvarado (eds.), Central America, Two Volume Set: Geology, Resources and Hazards. Taylor and Francis, London, 1217–1255, 2007.

Rose, W. I. (Ed.): Natural hazards in El Salvador (Vol. 375). Geological Society of America, 2004.

Salini Impregilo: Pueblo Viejo Dam on the Chixoy river [online] Available at: http://www.salini-impregilo.com/en/projects/completed/dams-hydroelectric-plants/pueblo-viejo-dam-on-the-chixoy-river.html (accessed 29 November 2018), 2014.

Satarugsa, P.: The Lessons Learnt from Geophysical Investigation of Sinkholes in Rock Salt in Thailand, International Conference on Geology, Geotechnology and Mineral Resources of Indochina (GEOINDO 2011) 1-3 December 2011, Khon Kaen, Thailand, [online] Available at: http://home.kku.ac.th/peangta/peangta-final-sinkhole2011.pdf (accessed 29 November 2018), 2011.

Schneider, S. C., and Barsoux, J. L.: Managing across cultures, Pearson Education, 352 p, 2002.

Schuster, R. L., Bucknam, R. C. and Mota, M. A.: Stability assessment of a Hurricane Mitch-induced landslide dam on the Rio La Lima, Sierra de Las Minas, eastern Guatemala, Open-File Report 01-120, US Geological Survey, US Department of the Interior, USA, 2001.

Scolobig A, Vinchon C, Komendantova N, Bengoubou-Valerius M, and Patt A.: Social and institutional barriers to effective multi-hazard and multi-risk decision making and governance. Deliverable 6.3, FP7 MATRIX Project - New Multi-Hazard and Multi-Risk Assessment Methods for Europe (30 September 2013), 2013.

Scolobig, A., Nadejda, K. and Arnaud, M.: Mainstreaming Multi-Risk Approaches into Policy. Geosciences, 7(4), p.129, 2017.

Seed, H. B., Arango, I., Gomez-Masso, A., Ascoli, R. G. and Chan, C.: Earthquake-induced liquefaction near lake Amatitlan, Guatemala, Journal of Geotechnical and Geoenvironmental Engineering, 107(ASCE 16212), 1981.

Siebert, L., Alvarado, G. E., Vallance, J. W., and De Vries, B. V. W.: Large-volume volcanic edifice failures in Central America and associated hazards, Geological Society of America Special Papers, 412, 1–26, doi:10.1130/2006.2412(01), 2006.

Soto, A. J., Rodhe, A., Pohjola, V., and Boelhouwers, J.: Spatial distribution of disasters caused by natural hazards in the Samala River catchment, Guatemala, Geografiska Annaler: Series A, Physical Geography, 97(1), 181–196, doi:10.1111/geoa.12097, 2015.

Squires, A.: Methodological challenges in cross-language qualitative research: a research review, International Journal of Nursing Studies, 46(2), 277–287, doi:10.1016/j.ijnurstu.2008.08.006, 2009.

Stewart, S. R.: Eastern North Pacific Hurricanes 2010 - Flooding in a Slow Season, Weatherwise, 64(3), 38–45, doi:10.1080/00431672.2011.566819, 2011.

Stewart, S. R., and Cangialosi, J. P.: Eastern North Pacific Hurricane Season of 2010, Monthly Weather Review, 140(9), 2769–2781, doi:10.1175/MWR-D-11-00152.1, 2012.

Sultana, F.: Reflexivity, positionality and participatory ethics: Negotiating fieldwork dilemmas in international research, ACME: An International E-Journal for Critical Geographies, 6(3), 374–385, 2007.

Suri, H.: Purposeful sampling in qualitative research synthesis, Qualitative Research Journal, 11(2), 63–75, 2011.

Tappin, D. R.: Submarine mass failures as tsunami sources: their climate control, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 368(1919), 2417–2434, doi:10.1098/rsta.2010.0079, 2010.

Tarvainen, T., Jarva, J., and Greiving, S.: Spatial pattern of hazards and hazard interactions in Europe, in: P. Schmidt-Thomé (ed.) Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions, 42, Geological Survey of Finland, 83–91, 2006.

Taylor, F. E., Malamud, B. D., Freeborough, K., and Demeritt, D.: Enriching Great Britain's National Landslide Database by searching newspaper archives, Geomorphology, 249, 52-68, doi:10.1016/j.geomorph.2015.05.019, 2015.

Temple, B., and Edwards, R.: Interpreters/translators and cross-language research: Reflexivity and border crossings, International Journal of Qualitative Methods, 1(2), 1–12, doi:10.1177/160940690200100201, 2002.

Temple, B., and Young, A.: Qualitative research and translation dilemmas, Qualitative Research, 4(2), 161–178, doi:10.1177/1468794104044430, 2004.

Trimble, S. W.: The use of historical data and artifacts in geomorphology, Progress in Physical Geography, 32(1), 3–29, doi:10.1177/0309133308089495, 2008.

UNISDR: Sendai Framework for Disaster Risk Reduction, United Nations, Geneva, 37 p, 2015.

UNISDR: DRR Terminology, Available online: www.unisdr.org/we/inform/terminology (accessed 29 November 2018), 2017.

USGeothermal: El Ceibillo Geothermal Project Overview [online] Available at: http://www.usgeothermal.com/projects/4/El%20Ceibillo%20-%20Guatemala (accessed 29 November 2018), 2016.

Valentine, G.: Tell me about… using interviews as a research methodology, in: R. Flowerdew and D. Martin (eds.) Methods in human geography: A guide for students doing a research project, Prentice Hall, Harlow, UK, 110–126, 1997.

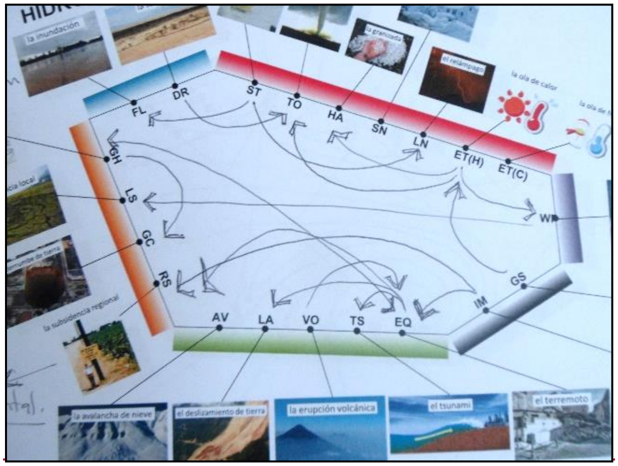
van Westen, C. J., Kappes, M. S., Luna, B. Q., Frigerio, S., Glade, T., and Malet, J-P.: Medium-scale multi-hazard risk assessment of gravitational processes, in: T. van Asch, J. Corominas, S. Greiving, J-P. Malet and S. Sterlacchini (eds.) Mountain risks: from prediction to management and governance, Springer, Netherlands, 201–231, doi:10.1007/978-94-007-6769-0_7, 2014.

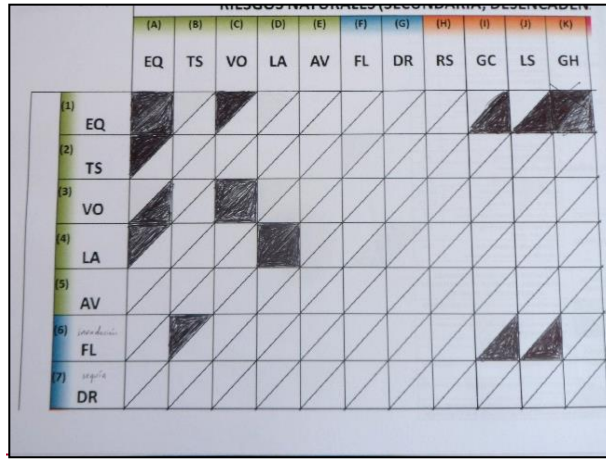
von Huene, R., Ranero, C.R. and Watts, P.: Tsunamigenic slope failure along the Middle America Trench in two tectonic settings, Marine Geology, 203(3), 303–317, doi:10.1016/S0025-3227(03)00312-8, 2004.

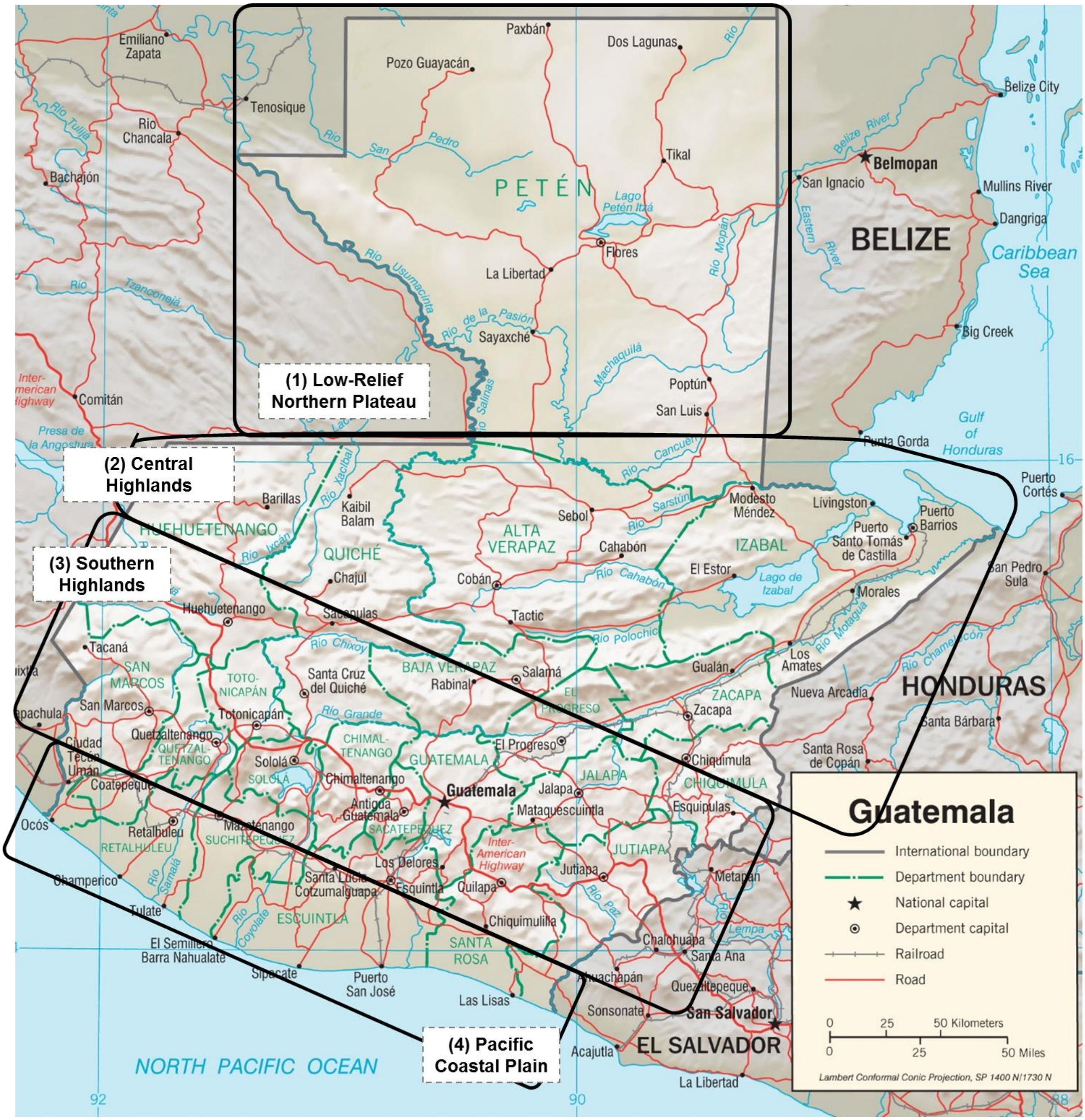
Welle, T., Birkmann, J., Rhyner, J., Witting, M., and Wolfertz., J.: World Risk Index 2013, in: L. Jeschonnek (ed.) World Risk Report 2013, Alliance Development Works, Berlin, Germany, 45–56, 2013.

World Bank: Precipitation in Guatemala 1900-2012 [online] Available at: http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climateandThisRegion=North%20AmericaandThisCCode=GTM# (accessed 29 November 2018), 2016.

~~Figures and Tables~~







<u>**Figure 1. Guatemala Map: Key Locations and Physiography (CIA, 2001), using CIA Base 802723AI (C00113) 12-00.** A combined political and physiographic map of Guatemala, showing differential relief (greyscale shading), Departmental boundaries (green lines and text), key locations (black text), rivers (blue lines and text) and roads (red lines). We group Guatemala into four broad regions (1–4) based on physiography. We refer particularly to the Southern Highlands (Region 3) throughout this paper.</u>

~~**Figure 1. Stakeholder identification of possible hazard interactions in Guatemala.** Two examples of visual records collected in~~

~~Guatemala, including (A) a network linkage diagram for 21 hazards, and (B) a 7 × 11 hazard interaction matrix. Both were completed during a workshop in Guatemala on 6 March 2014. The workshop is described in **Section 2.6**, and all images from the workshop (16 network linkage diagrams, and 15 hazard interaction matrices) are included in the **Supplementary Material (Figures S1** and **S2)**.~~

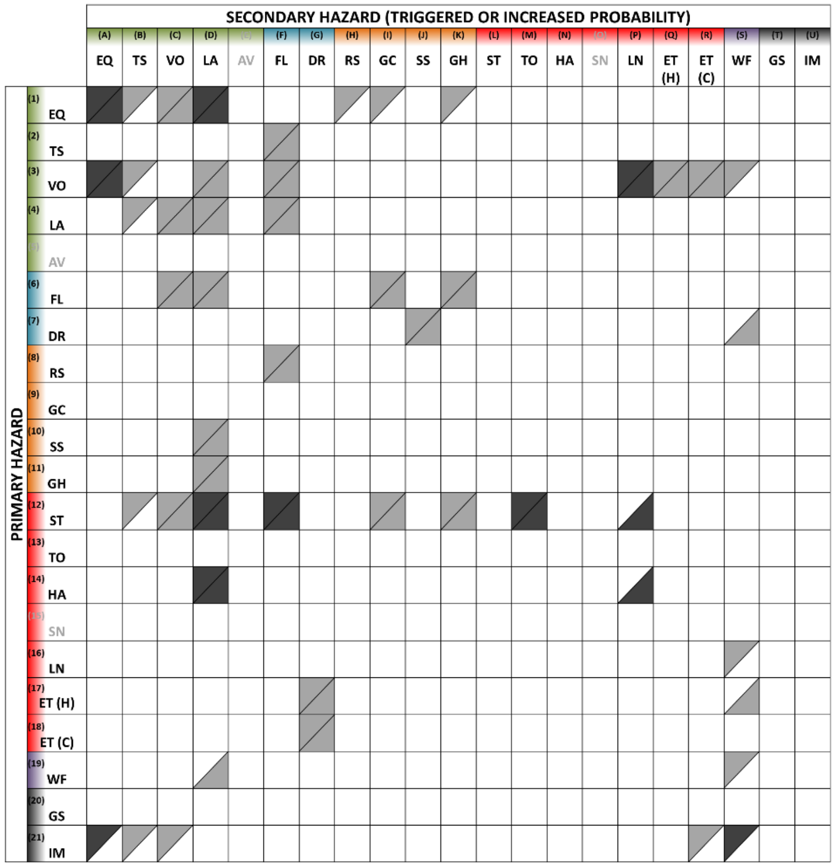
	SECONDARY HAZARD (TRIGGERED OR INCREASED PROBABILITY)																				
PRIMARY HAZARD	(A) EQ	(B) TS	(C) VO	(D) LA	(E) AV	(F) FL	(G) DR	(H) RS	(I) GC	(J) SS	(K) GH	(L) ST	(M) TO	(N) HA	(O) SN	(P) LN	(Q) ET (H)	(R) ET (C)	(S) WF	(T) GS	(U) IM
(1) EQ	5	11	4	16	2	2		7	8	8	13	1							1		
(2) TS						4															
(3) VO	8	2		7	1			2	1	1	1								4		
(4) LA					1			1	1	1	3										
(5) AV																					
(6) FL							1			1	1										
(7) DR						1		1					1						5		
(8) RS									1	1	1										
(9) GC						1		1		1	2										
(10) SS								2	1		1								1		
(11) GH	2							1	2	2											
(12) ST				12	1	16		3	9	5	5			3		4					
(13) TO						1						1				1					
(14) HA					1							1									
(15) SN					1							1									
(16) LN																			8		
(17) ET (H)							12						1	1					11		
(18) ET (C)					1							1	1	6	4						
(19) WF				1			3														
(20) GS																	3		2		
(21) IM	3			1				3	1	1	2								3		

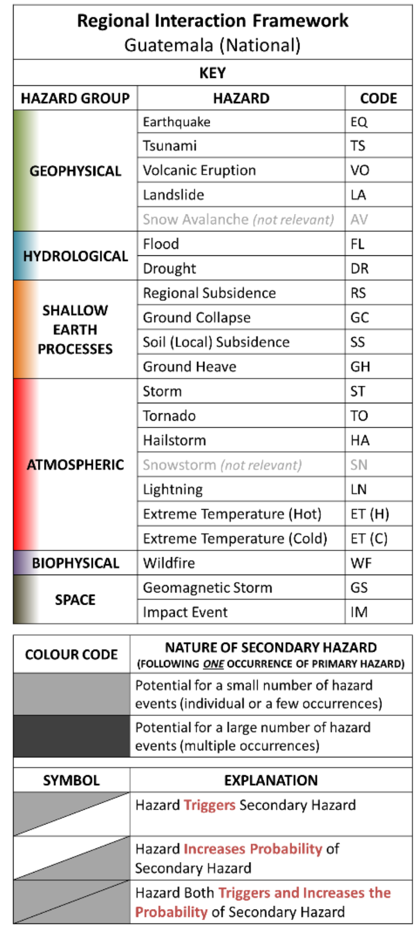
KEY

HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche *(not relevant)*	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm *(not relevant)*	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfire	WF
SPACE	Geomagnetic Storm	GS
	Impact Event	IM

SYMBOL	EXPLANATION
12	Number of workshop participants (*n=16*) identifying interactions as relevant in Guatemala using hazard linkage diagrams (example below)

Figure 2. Stakeholder identification of possible hazard interactions in Guatemala, using network linkage diagrams produced by 16 civil protection professionals in Guatemala. A 21 × 21 matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis. These hazards are coded, as explained in the key. Numbers indicate the number of stakeholders (from a maximum of 16) proposing each hazard interaction as being possible in Guatemala. This information was collected using blank network linkage diagrams for 21 hazards during a workshop in Guatemala on 6 March 2014. The workshop is described in **Section 2.6**, and all images from the workshop are included in the **Supplementary Material (Figures S1 and S2)**.

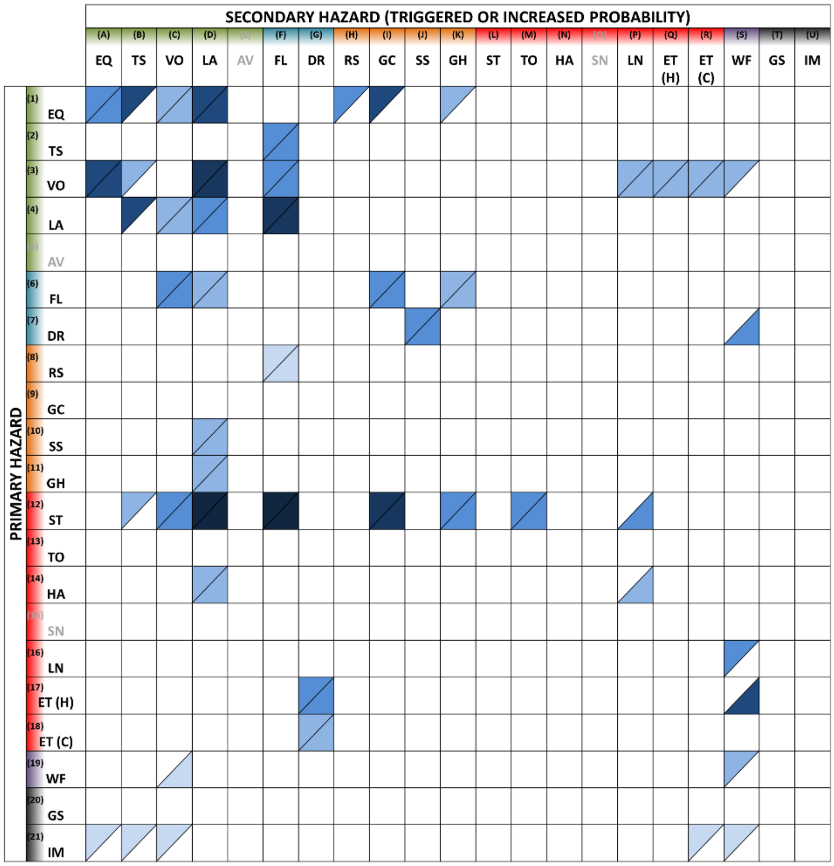




Footnotes

[1B, 4B] Earthquakes and landslides may trigger marine and/or freshwater (lake) tsunamis.
[1C,H; 12M] There was uncertainty about the nature of these relationships.
[1I,K] Earthquakes may trigger collapse/heave primarily through liquefaction.
[3B] Volcanic explosions may trigger freshwater tsunamis in the Lakes of Guatemala.
[3Q/R] Volcanic eruptions can trigger temperature changes if they are of sufficient magnitude.
[6,12C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.
[8F] Although regional subsidence triggering flooding was not noted in any evidence sources consulted, this is an inevitable consequence of the lowering of the ground surface.
[12B] Pressure changes associated with storms may trigger meteotsunamis in marine environments.
[21A-C,R,S] Identified as being generally possible, supported by globally-relevant literature rather than location-specific evidence.

Figure 3. National Interaction Framework for Guatemala. A 21×21 matrix with 21 primary natural hazards on the vertical axis, and 21 secondary natural hazards on the horizontal axis. Interactions (shaded cells) include primary hazards triggering a secondary hazard, and primary hazards increasing the probability of a secondary hazard. This matrix is populated using different evidence types, as outlined through **Section 2**. Visualisation structure based on Gill and Malamud (2014). We also include an additional matrix in the **Supplementary Material (Figure S5)** showing the number of evidence types used for each hazard interaction pairing when populating **Figure 3.**



Regional Interaction Framework
Guatemala (National)

KEY

HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche *(not relevant)*	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm *(not relevant)*	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfire	WF
SPACE	Geomagnetic Storm	GS
	Impact Event	IM

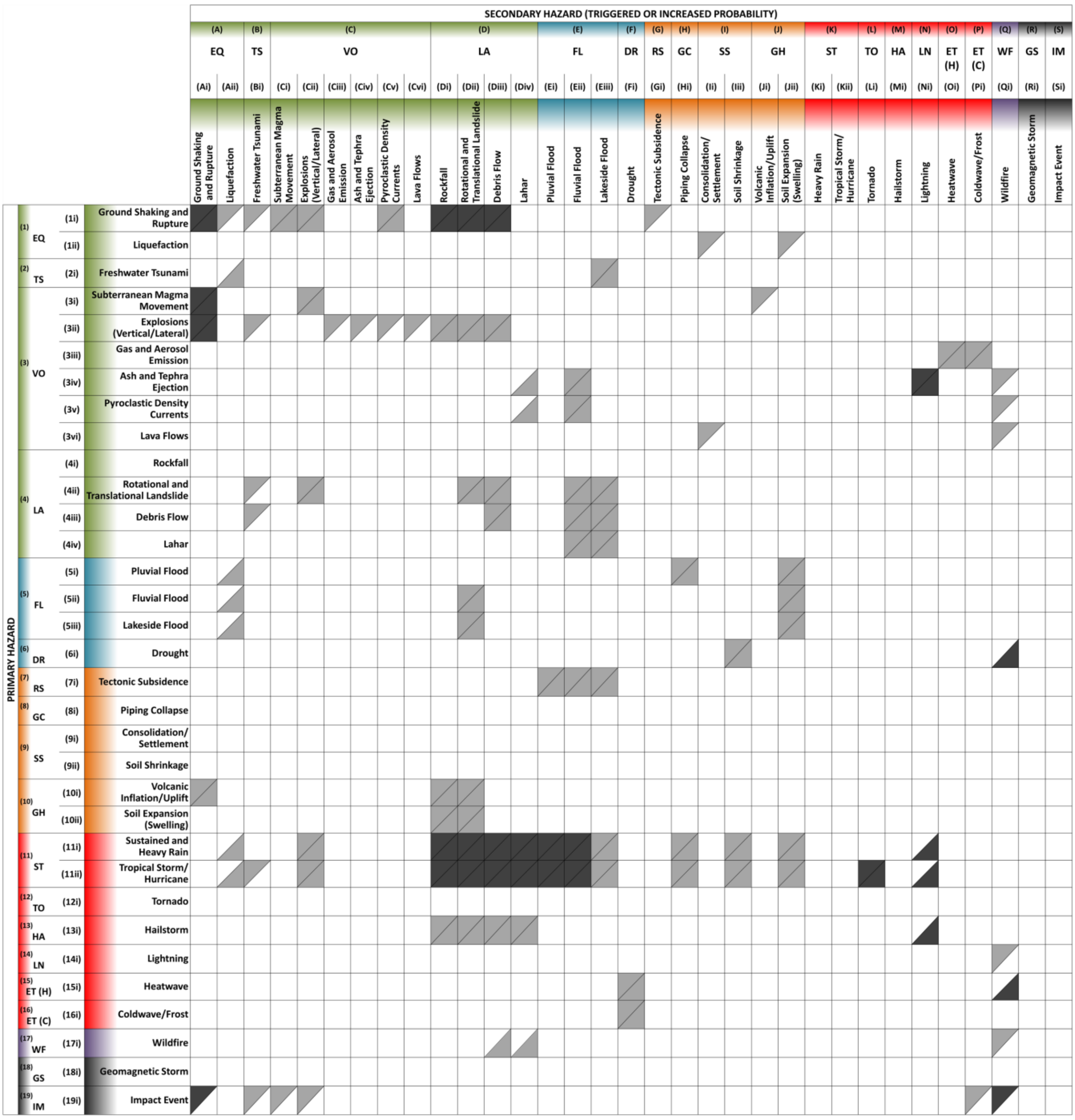
SYMBOL	EXPLANATION
	Hazard Triggers Secondary Hazard
	Hazard Increases Probability of Secondary Hazard
COLOUR CODE	**NUMBER OF EVIDENCE SOURCES USED (SEE APPENDIX **)**
	5/5 Different Evidence Sources Used
	4/5 Different Evidence Sources Used
	3/5 Different Evidence Sources Used
	2/5 Different Evidence Sources Used
	1/5 Different Evidence Sources Used
	Some Global Literature Supporting Inclusion

Footnotes

[1B, 4B] Earthquakes and landslides may trigger marine and/or freshwater (lake) tsunamis.
[1C,H; 12M] There was uncertainty about the nature of these relationships.
[1I,K] Earthquakes may trigger collapse/heave primarily through liquefaction.
[3B] Volcanic explosions may trigger freshwater tsunamis in the Lakes of Guatemala.
[3Q/R] Volcanic eruptions can trigger temperature changes if they are of sufficient magnitude.
[6,12C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.
[8F] Although regional subsidence triggering flooding was not noted in any evidence sources consulted, this is an inevitable consequence of the lowering of the ground surface.
[12B] Pressure changes associated with storms may trigger meteotsunamis in marine environments.
[21A-C,R,S] Identified as being generally possible, supported by globally-relevant literature rather than location-specific evidence.

Figure 4. Evidence types used in the construction of a National Interaction Framework for Guatemala. A 21×21 matrix with 21 primary natural hazards on the vertical axis, and 21 secondary natural hazards on the horizontal axis. Interactions (shaded cells) include primary hazards triggering a secondary hazard, and primary hazards increasing the probability of a secondary hazard. This matrix is populated using different evidence types, as outlined through **Section 2**. Blue shading indicates the number of evidence types used to populate each matrix cell, as described in the key. The coarse resolution of the data used, and complexities of distinguishing between triggered/increased probability interaction types, means we group both interaction types together when indicating the number of evidence types. Visualisation structure based on Gill and Malamud (2014).

Figure 5. Guatemala Map: Key Locations and Physiography (CIA, 2001). A combined political and physiographic map of Guatemala, showing differential relief (greyscale shading), Departmental boundaries (green lines and text), key locations (black text), rivers (blue lines and text) and roads (red lines). The Southern Highlands are also labelled (referred to throughout this paper.


SECONDARY HAZARD (TRIGGERED OR INCREASED PROBABILITY)
(A) EQ (Ai) Ground Shaking and Rupture (Aii) Liquefaction
(B) TS (Bi) Freshwater Tsunami
(C) VO (Ci) Subterranean Magma Movement (Cii) Explosions (Vertical/Lateral) (Ciii) Gas and Aerosol Emission (Civ) Ash and Tephra Ejection (Cv) Pyroclastic Density Currents (Cvi) Lava Flows
(D) LA (Di) Rockfall (Dii) Rotational and Translational Landslide (Diii) Debris Flow (Div) Lahar
(E) FL (Ei) Pluvial Flood (Eii) Fluvial Flood (Eiii) Lakeside Flood
(F) DR (Fi) Drought
(G) RS (Gi) Tectonic Subsidence
(H) GC (Hi) Piping Collapse
(I) SS (Ii) Consolidation/ Settlement (Iii) Soil Shrinkage
(J) GH (Ji) Volcanic Inflation/Uplift (Jii) Soil Expansion (Swelling)
(K) ST (Ki) Heavy Rain (Kii) Tropical Storm/ Hurricane
(L) TO (Li) Tornado
(M) HA (Mi) Hailstorm
(N) LN (Ni) Lightning
(O) ET (H) (Oi) Heatwave
(P) ET (C) (Pi) Coldwave/Frost
(Q) WF (Qi) Wildfire
(R) GS (Ri) Geomagnetic Storm
(S) IM (Si) Impact Event
PRIMARY HAZARD
(1) EQ (1i) Ground Shaking and Rupture (1ii) Liquefaction
(2) TS (2i) Freshwater Tsunami
(3) VO (3i) Subterranean Magma Movement (3ii) Explosions (Vertical/Lateral) (3iii) Gas and Aerosol Emission (3iv) Ash and Tephra Ejection (3v) Pyroclastic Density Currents (3vi) Lava Flows
(4) LA (4i) Rockfall (4ii) Rotational and Translational Landslide (4iii) Debris Flow (4iv) Lahar
(5) FL (5i) Pluvial Flood (5ii) Fluvial Flood (5iii) Lakeside Flood
(6) DR (6i) Drought
(7) RS (7i) Tectonic Subsidence
(8) GC (8i) Piping Collapse
(9) SS (9i) Consolidation/ Settlement (9ii) Soil Shrinkage
(10) GH (10i) Volcanic Inflation/Uplift (10ii) Soil Expansion (Swelling)
(11) ST (11i) Sustained and Heavy Rain (11ii) Tropical Storm/ Hurricane
(12) TO (12i) Tornado
(13) HA (13i) Hailstorm
(14) LN (14i) Lightning
(15) ET (H) (15i) Heatwave
(16) ET (C) (16i) Coldwave/Frost
(17) WF (17i) Wildfire
(18) GS (18i) Geomagnetic Storm
(19) IM (19i) Impact Event

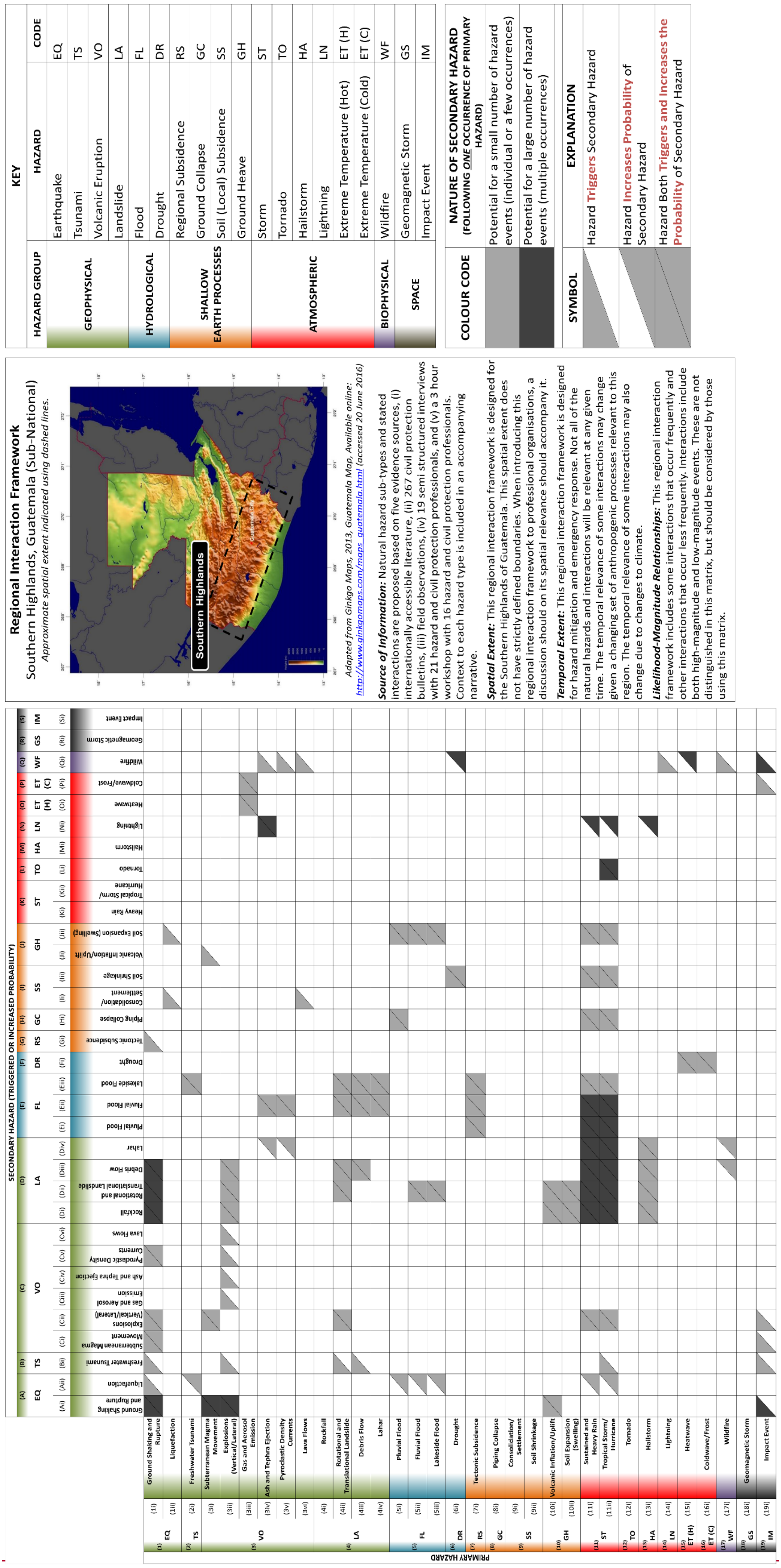


Figure ~~6~~4. Southern Highlands (Sub-National) Interaction Framework, Guatemala. A 33×33 matrix with 33 primary natural hazard sub-types on the vertical axis, and 33 secondary natural hazard sub-types on the horizontal axis. Interactions (shaded cells) include primary hazards triggering a secondary hazard, and primary hazards increasing the probability of a secondary hazard. This matrix is populated using different evidence types, as outlined through **Section 2**. The symbols and coding are the same as **Figure 3**.

and we direct the reader to the key in that figure.

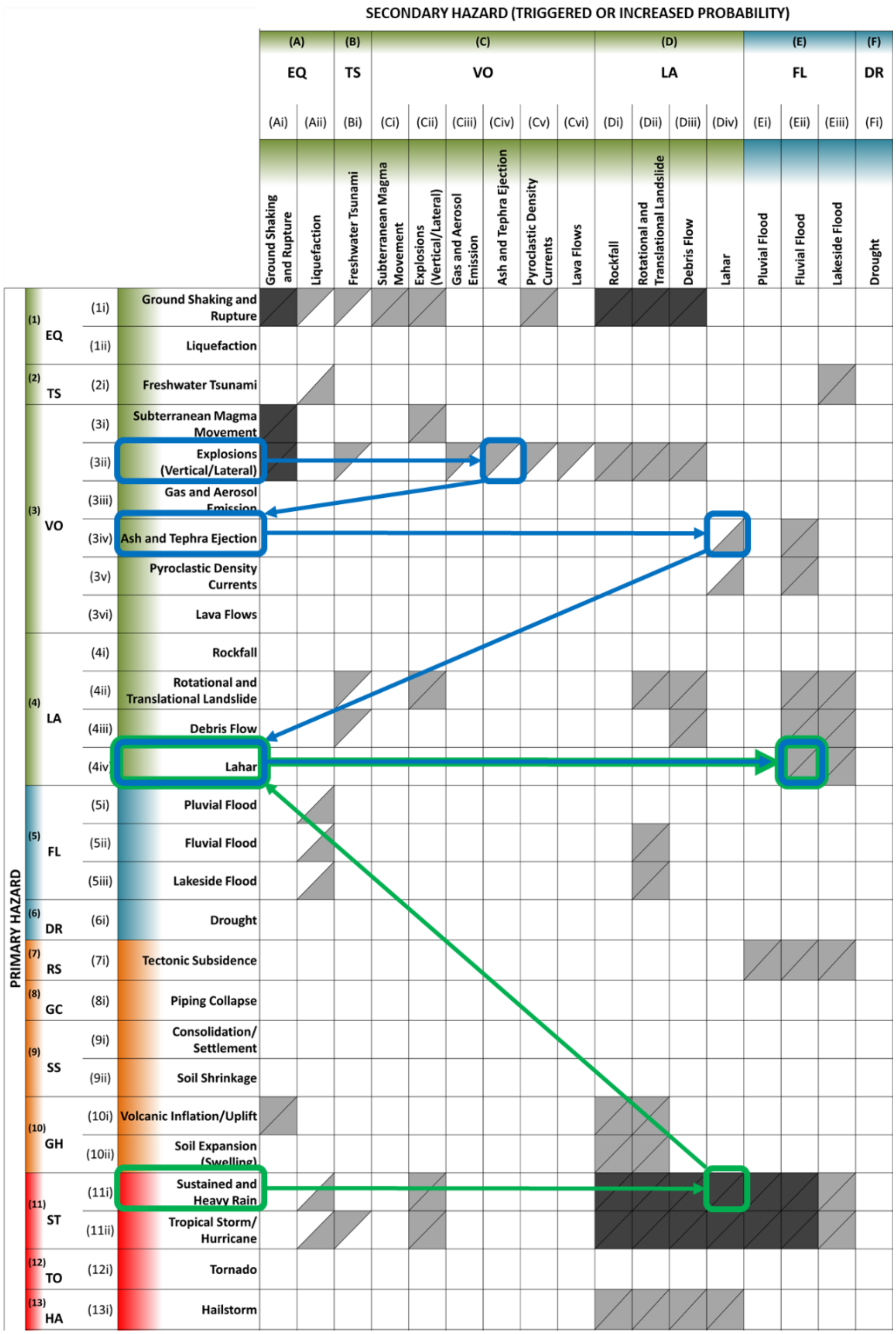


Figure ~~7~~5. Network of Hazard Interactions (Example 1), Southern Highlands, Guatemala. A 26 × 17 extract of the 33×33 sub-national interaction framework presented in **Figure ~~6~~4**, with an example of a network of hazard interactions (cascade). This example shows (i) volcanic explosions triggering the ejection of ash and tephra, (ii) ash and tephra increasing the likelihood of lahars, (iii) heavy rain (together with the existing tephra and ash) combining to trigger a lahar. (iv) lahars triggering flooding. Evidence for this network is stated in the text.

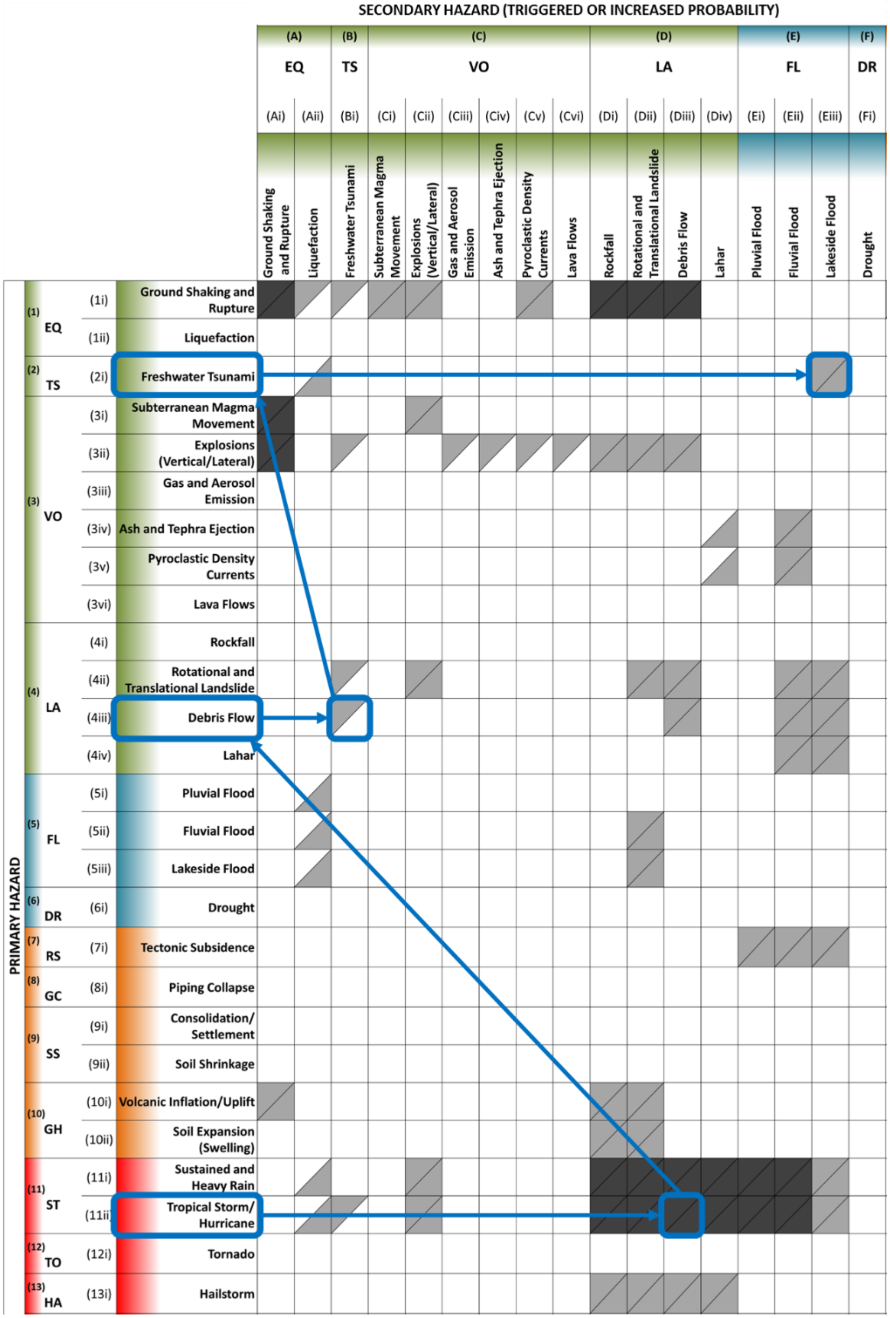


Figure ~~8~~6. Network of Hazard Interactions (Example 2), Southern Highlands, Guatemala. A 26 × 17 extract of the 33×33 sub-national interaction framework presented in **Figure ~~6~~4**, with an example of a network of hazard interactions (cascade). This example shows (i) Hurricane Stan triggering a debris flow, (ii) debris flows triggering a freshwater tsunami in Lake Atitlan, and (iii) freshwater tsunami triggering a lakeside flood. Evidence for this network is stated in the text.

SECONDARY HAZARD (TRIGGERED OR INCREASED PROBABILITY)

PRIMARY HAZARD	(A) EQ	(B) TS	(C) VO	(D) LA	(E) AV	(F) FL	(G) DR	(H) RS	(I) GC	(J) SS	(K) GH	(L) ST	(M) TO	(N) HA	(O) SN	(P) LN	(Q) ET (H)	(R) ET (C)	(S) WF	(T) GS	(U) IM
(1) EQ	5	11	4	16	2	2		7	8	8	13	1							1		
(2) TS						4															
(3) VO	8	2		7	1			2	1	1	1								4		
(4) LA					1			1	1	1	3										
(5) AV																					
(6) FL							1			1	1										
(7) DR						1		1					1						5		
(8) RS									1	1	1										
(9) GC						1		1		1	2										
(10) SS								2	1		1								1		
(11) GH	2							1	2	2											
(12) ST				12	1	16		3	9	5	5			3		4					
(13) TO						1						1				1					
(14) HA					1							1									
(15) SN					1							1									
(16) LN																			8		
(17) ET (H)							12						1	1					11		
(18) ET (C)					1							1	1	6	4						
(19) WF				1			3														
(20) GS																	3		2		
(21) IM	3			1				3	1	1	2								3		

Regional Interaction Framework
Guatemala (National)

KEY

HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche *(not relevant)*	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm *(not relevant)*	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfire	WF
SPACE	Geomagnetic Storm	GS
	Impact Event	IM

COLOUR CODE	NATURE OF SECONDARY HAZARD (FOLLOWING *ONE* OCCURRENCE OF PRIMARY HAZARD)
(light grey)	Potential for a small number of hazard events (individual or a few occurrences)
(dark grey)	Potential for a large number of hazard events (multiple occurrences)

SYMBOL	EXPLANATION
(upper triangle)	Hazard Triggers Secondary Hazard
(lower triangle)	Hazard Increases Probability of Secondary Hazard
(both triangles)	Hazard Both Triggers and Increases the Probability of Secondary Hazard

Footnotes

[1B, 4B] Earthquakes and landslides may trigger marine and/or freshwater (lake) tsunamis.
[1C,H; 12M] There was uncertainty about the nature of these relationships.
[1I,K] Earthquakes may trigger collapse/heave primarily through liquefaction.
[3B] Volcanic explosions may trigger freshwater tsunamis in the Lakes of Guatemala.
[3Q/R] Volcanic eruptions can trigger temperature changes if they are of sufficient magnitude.
[6,12C] Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption.
[8F] Although regional subsidence triggering flooding was not noted in any evidence sources consulted, this is an inevitable consequence of the lowering of the ground surface.
[12B] Pressure changes associated with storms may trigger meteotsunamis in marine environments.
[21A-C,R,S] Identified as being generally possible, supported by globally-relevant literature rather than location-specific evidence.

	SECONDARY HAZARD (TRIGGERED OR INCREASED PROBABILITY)																				
PRIMARY HAZARD	(A) EQ	(B) TS	(C) VO	(D) LA	(E) AV	(F) FL	(G) DR	(H) RS	(I) GC	(J) SS	(K) GH	(L) ST	(M) TO	(N) HA	(O) SN	(P) LN	(Q) ET (H)	(R) ET (C)	(S) WF	(T) GS	(U) IM
(1) EQ	5	11	4	16	2	2		7	8	8	13	1							1		
(2) TS						4															
(3) VO	8	2		7	1			2	1	1	1								4		
(4) LA					1			1	1	1	3										
(5) AV																					
(6) FL							1			1	1										
(7) DR						1		1					1						5		
(8) RS									1	1	1										
(9) GC						1		1		1	2										
(10) SS								2	1		1								1		
(11) GH	2							1	2	2											
(12) ST				12	1	16		3	9	5	5			3		4					
(13) TO						1						1				1					
(14) HA					1							1									
(15) SN					1							1									
(16) LN																			8		
(17) ET (H)							12						1	1					11		
(18) ET (C)					1							1	1	6	4						
(19) WF				1			3														
(20) GS																	3		2		
(21) IM	3			1				3	1	1	2								3		

Regional Interaction Framework
Guatemala (National)

KEY

HAZARD GROUP	HAZARD	CODE
GEOPHYSICAL	Earthquake	EQ
	Tsunami	TS
	Volcanic Eruption	VO
	Landslide	LA
	Snow Avalanche *(not relevant)*	AV
HYDROLOGICAL	Flood	FL
	Drought	DR
SHALLOW EARTH PROCESSES	Regional Subsidence	RS
	Ground Collapse	GC
	Soil (Local) Subsidence	SS
	Ground Heave	GH
ATMOSPHERIC	Storm	ST
	Tornado	TO
	Hailstorm	HA
	Snowstorm *(not relevant)*	SN
	Lightning	LN
	Extreme Temperature (Hot)	ET (H)
	Extreme Temperature (Cold)	ET (C)
BIOPHYSICAL	Wildfire	WF
SPACE	Geomagnetic Storm	GS
	Impact Event	IM

Footnotes: **[1B, 4B]** Earthquakes and landslides may trigger marine and/or freshwater (lake) tsunamis. **[1C,H; 12M]** There was uncertainty about the nature of these relationships. **[1I,K]** Earthquakes may trigger collapse/heave primarily through liquefaction. **[3B]** Volcanic explosions may trigger freshwater tsunamis in the Lakes of Guatemala. **[3Q/R]** Volcanic eruptions can trigger temperature changes if they are of sufficient magnitude. **[6,12C]** Water input triggers or increases the probability of a phreatic/phreatomagmatic eruption. **[8F]** Although regional subsidence triggering flooding was not noted in any evidence sources consulted, this is an inevitable consequence of the lowering of the ground surface. **[12B]** Pressure changes associated with storms may trigger meteotsunamis in marine environments. **[21A-C,R,S]** Identified as being generally possible, supported by globally-relevant literature rather than location-specific evidence.

Figure ~~9~~7. Stakeholder identification of possible hazard interactions in Guatemala, overlain over the national interaction framework developed in Figure 3. A 21×21 matrix with primary hazards on the vertical axis and secondary hazards on the horizontal axis. These hazards are coded, as explained in the key. These matrices show cases where a primary hazard could trigger and/or increase the probability of a secondary hazard. Grey cell shading indicates the interaction was identified in the national hazard interaction matrix presented in **Figure 3**. Numbers indicate the total number (from a maximum of 16) of stakeholders proposing each hazard interaction as being possible in Guatemala.

Table 1. Examples of seven regional interaction frameworks, including a summary of the spatial extent, hazards and processes considered, and interaction types. ~~Summaries of seven regional interaction frameworks~~.

Authors	Summary *(Spatial extent, hazards and processes considered, and interaction types)*
Tarvainen *et al.* (2006)	• **Continental** spatial extent (Europe). • **Binary matrix**. • Identifies interactions between **eleven natural hazards** (*avalanche, drought, earthquake, extreme temperature, flood, forest fire, landslide, storm surge, tsunami, volcanic eruption, winter storm*) and **four technological hazards** (*air traffic accident, chemical plant, nuclear power plant, oil processing/ transport/ storage*). • Interactions are determined based on physical processes (**causal correlation**), and are only considered when hazard intensities in a given region exceed an average value.
De Pippo *et al.* (2008)	• **Sub-national** spatial extent (Northern Campanian coast, Italy). • **Descriptive matrix** is used **to characterise interactions** between hazards, which are weighted according to their importance in different zones along the coast. • **Semi-quantitative method** to quantify, rank and map the distribution of hazard. • Considers the effect of **six hazards** (*shoreline erosion, riverine flooding, surge, landslide, seismicity and volcanism*) and the effect of manufactured structures.
Kappes *et al.* (2010)	• **Sub-national** spatial extent (French Alpine region of Barcelonnette). • Uses a combination of **binary** and **descriptive matrices**. • Considers both **triggering interactions** and **interactions where a hazard changes the disposition** or general setting that favours another hazard process. • **Seven primary natural hazards** (*avalanche, debris flow, rock fall, landslide, flood, heavy rainfall, and earthquake*).
van Westen *et al.* (2014)	• **Sub-National** (European mountainous environments) • Possible interactions are mapped out using a **network flow diagram**, including interactions between the seven resulting (secondary hazards).Considers **two primary triggers** (*earthquake, meteorological extremes*), and **seven resulting natural hazards** (*mass movement, snow avalanche, forest fire, land degradation, flooding, seiche, technological hazard*).
Neri *et al.* (2008)	• **Sub-National** (Vesuvius volcano, Italy). • Uses a **quantitative** (**probabilistic**) **approach** to map out possible future eruptive scenarios. • Scenarios consider **ten hazards** (*volcanic eruption, fallout, ballistics, pyroclastic density current, debris avalanche, tsunami, flood, landslide, lahar, mudslide, heavy rain*).
Neri *et al.* (2013)	• **Sub-National** (Kanlaon volcano, Philippines) • Presented using an **event/scenario tree**. • Uses a **semi-quantitative method**, combing geological and historical data to consider hazard events. • **Eight hazards considered** (*volcanic eruption, fallout, ballistics, pyroclastic density current, debris avalanche, tsunami, flood, lahar/mudslide*).
Liu *et al.* (2016)	• **Sub-National** (Yangtze River Delta, China). • **Zones** of similar hazards and hazard interactions are identified and **spatially mapped**. • Hazard interactions classification is **based on the '*the hazard-forming environment*'**, defined as the geophysical environment that natural hazards arise from. • **Four interactions types** are considered • **Ten natural hazards** (*earthquakes, volcanic eruption, tropical cyclone, slow riverine flood, fast riverine flood, coastal flood, pluvial flood, landslide, avalanche, drought*), with a selection of these being relevant to the Yangtze River Delta case study.

Table 2. Government organisations contributing to DRR in Guatemala. All information taken from their respective websites (CONRED, 2018a; INSIVUMEH, 2018).

Acronym	**Full Name**	**Organisational Remit**
CONRED	Coordinadora Nacional para la Reducción de Desastres *(National Coordinator for Disaster Reduction)*	Established in 1996 and responsible for preventing, mitigating, attending and participating in the rehabilitation and reconstruction of damage arising from disasters. Responsible for coordinating with public and private institutions, national and international organizations, civil society at various regional and sectoral levels, on matters relating to disaster risk management as a strategy contributing to sustainable development in Guatemala. Website: www.conred.gob.gt
INSIVUMEH	Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología *(National Institute for Seismology, Volcanology, Meteorology and Hydrology)*	Established in 1976 as a scientific agency of the Guatemalan government. Responsible for the monitoring of hazards across areas of seismology, volcanology, meteorology and hydrology. Tasked with communicating this information to other government agencies, to inform decision-making. Website: www.insivumeh.gob.gt

Table ~~3~~2. Examples of five diverse evidence types that might indicate the relevance of a given multi-hazard interaction.

Evidence Types	Examples
1. Publications and Reports	Public and confidential government, technical, private sector and/or civil society reports
	Peer-reviewed and other research publications
	Maps and archive documents
	Student projects (e.g., dissertations, theses)
	Books
	Diaries
2. Social and Other Media	Photographs and video clips (e.g., from print and online newspapers, blogs, websites, tweets, citizen science)
	Newspaper articles
	Social media posts (e.g., 'Tweets')
3. Field Evidence	Observations from the impact on the built environment (e.g., marks on vertical services to indicate flooding occurred, or the minimum extent flood water reached)
	Geological mapping and any field identification of evidence of the hazard occurring (e.g., flood deposits)
4. Stakeholder Engagement	Interviews with the public, hazard professionals, and civil protection officials
	Focus Groups
	Workshops
5. Miscellaneous	Insurance records
	Instrumental records and associated notes
	Emergency call out and incident records from emergency services
	Remote sensing images

Table 4. Five components of a regional interaction framework. A description of the evidence used in this paper to address and compile the five components of a regional interaction framework.

Component of Regional Interaction Framework	**Relevant Sections**	**Additional Information and Literature**
Visualisation framework	N/A	Visualisations presented in Gill and Malamud (2014, 2016, 2017), integrated with the conclusions of Gill (2016) to enhance these frameworks.
Inclusion and classification of natural hazard types	**Sections 2.2** to **2.6**	Classification of 21 natural hazards (Gill and Malamud, 2014).
Population of framework with relevant natural hazard interactions	**Sections 2.2** to **2.6**	Matrix of globally possible interactions (Gill and Malamud, 2014).
Examples of networks of hazard interactions	**Sections 2.3** to **2.6**	Visualisation approaches presented in Gill and Malamud (2016).
Anthropogenic processes	**Sections 2.2** to **2.6**	Classification of 18 anthropogenic processes (Gill and Malamud, 2017).

Table 5. Information bulletin keywords and number of keyword search results. Six keywords searched for in the information bulletins (English form and abbreviated Spanish verb base), and the number of results generated by each word. Multiple results could be identified in one bulletin.

English Form	**Abbreviated Spanish Verb Base** *(used in the keyword search)*	**Number of Keyword Search Results** *(in the 267 bulletins)*
Triggering	Desenca…	0
Provoking	Provoc…	26
Generating	Genera…	58
Causing	Caus…	22
Producing	Produ…	37
Catalysing	Catál…	0

Table 6. Case study locations. Four case study locations and examples of hazard interactions relevant to these locations.

Details of Field Visit		**Details of Interaction Event**	
Location	**Date of Field Visit**	**Summary of Interactions**	**Date** *(where appropriate)*
Lake Atitlan (San Pedro La Laguna)	19–29 Jan 2014	Tropical storm → landslide	29–30 May 2010
		Landslide → flooding	Slow, continuous process
		Rainfall → flooding	Slow, continuous process
Fuego	08–12 Feb 2014	Tephra + rain → lahar → flood	Frequent
Lake Atitlan (Tolimán and Panabaj)	13–15 Feb 2014	Hurricane → landslide	5 October 2005
		Hurricane → landslide → tsunami → flood	October 2005
Santiaguito	16–19 Feb 2014	Tephra + rain → lahar → flood	Frequent

Table ~~7~~3. Consideration of ~~Challenges 1–6~~six themes (identified in Gill, 2016) with respect to Guatemala. A description is given of how ~~Challenges 1–6~~ each theme ~~are~~ is addressed in this regional interaction framework, using stakeholder comments discussed in **Sections 2.5** (interviews) and **Section 2.6** (workshop results) to inform this process.

Challenge	**Relevance in Context of Guatemalan Case Study**
Spatial Extent	Interview evidence suggested that national and sub-national spatial extents were suitable for regional interaction frameworks. The Southern Highlands of Guatemala, identified in **Figure 7**, includes large population centres and critical infrastructure. We therefore produce regional interaction frameworks for Guatemala (using political boundaries) and the Southern Highlands of Guatemala (using non-political boundaries. For both scales, we consider hazards and interactions that cut across the determined boundaries.
Temporal Extent	Interview evidence suggested that regional interaction frameworks be developed for both preparation (before a primary event) and response (immediate aftermath of a primary event). Not all of the natural hazards and interactions will be relevant at any given time. The temporal relevance of interactions may change given a changing set of anthropogenic processes relevant to this region. The temporal relevance of interactions may also change in response to natural and human driven climate change. The frameworks should be viewed as being dynamic, and regularly reviewed and updated to remain relevant.
Likelihood-Magnitude Relationships	Interview evidence suggested a desire for additional information on likelihood-magnitude relationships of interactions. This could be done through an expert elicitation method once a completed interaction framework is prepared. Interaction matrices published in this paper can be taken and additional layers of complexity added, according to user requirements. This could include information on likelihood-magnitude relationships or other parameters of interest (e.g., mitigation approaches).
Selection and Classification of Hazards	Interview evidence suggested an expanded natural hazards classification would improve understanding and communication of potential hazard interactions. We therefore develop an expanded classification of natural hazards in **Section 3.2**. The review of a broad range of evidence types allows the identification of multiple relevant hazards, seeking to be as comprehensive as possible rather than focusing on specific natural hazard groups. 17 of 21 interview participants (**Section 2.5**) noted anthropogenic processes to be important for consideration, and we discuss these in **Section 3.5**.
Identifying Relevant Hazard Interactions	Workshop evidence indicated different stakeholder opinions on the relevance of specific hazard interactions in Guatemala. The use of multiple evidence types can help to populate regional interaction frameworks in a systematic manner.
Visualisation Style and User Communities	Interview evidence suggested that a matrix visualisation format would be suitable for hazard and civil protection professionals, our indented user group. We prepare frameworks in English, but these can subsequently be translated into Spanish. Explanations of vocabulary can accompany interaction visualisations.

Table ~~8~~4. Detailed classification of six hazard groups, 19 natural hazard types, and 37 hazard sub-types relevant to Guatemala. An outline of a possible hazard classification scheme relevant to Guatemala. Evidence (from **Section 2**) is used to justify the inclusion of each hazard sub-type, and noted in the table, with references from international literature.

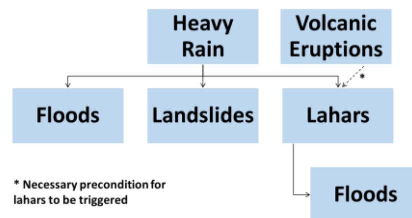
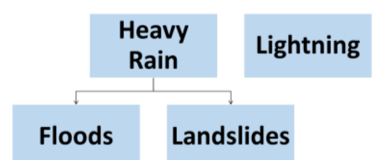
Hazard Group	**Hazard Type**	**Hazard Sub-Type**	**Evidence** A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop *(≥50% people)*	**References** *(International Literature)*
Geophysical	Earthquake (**EQ**)	Ground Shaking/Rupture	A C D E	Lindholm *et al.* (2007)
		Liquefaction	A D	Seed *et al.* (1981); Porfido *et al.* (2014)
	Tsunami (**TS**)	Marine Tsunami	A D E	Fernández and Ortiz (2007)
		Freshwater Tsunami	A C D E	Siebert *et al.* (2006); Luna (2007)
	Volcanic Activity/ Eruption (**VO**)	Subterranean Magma Movement	A D E	
		Volcanic Explosions (Vertical/Lateral)	A B C D E	
		Volcanic Gas/Aerosol Emission	A E	Alvarado *et al.* (2007); Global Volcanism Program (2013); Brown *et al.* (2015)
		Volcanic Ash/Tephra Ejection	A B C D E	
		Pyroclastic Density Currents	A B C D E	
		Lava Flows	A C D E	
	Landslide (**LA**)	Submarine Landslide	A	Von Huene *et al.* (2004); Tappin (2010)
		Subaerial Rockfall	A B C D E	Rodríguez (2007)
		Subaerial Rotational/Translational Landslide	A B C D E	Bommer and Rodríguez (2002); Rodríguez (2007)
		Subaerial Debris Flow	A B C D E	Bucknam *et al.* (2001); Rodríguez (2007); Luna (2007)
		Subaerial Lahar	A B C D E	Bucknam *et al.* (2001); Harris *et al.* (2006)
Hydrological	Flood (**FL**)	Pluvial Flood	A B D E	Claxton (1986); Stewart and Cangialosi (2012)
		Fluvial Flood	A B D E	Schuster *et al.* (2001); Harris *et al.* (2006); Soto *et al.* (2015)
		Coastal Flood	A D E	Cahoon and Hensel (2002)
		Lakeside Flood	A C D E	Luna (2007)
	Drought (**DR**)	Drought	A D E	Claxton (1986); Hodell *et al.* (2001); Moreno (2006)
Shallow Earth Processes (adapted from Hunt, 2005)	Regional Subsidence (**RS**)	Tectonic Subsidence	D	
	Ground Collapse (**GC**)	Karst/Evaporite Collapse	A D	Cooper and Calow (1998); Kueny and Day (2002)
		Piping Collapse	A B D E	Stewart (2011); Satarugsa (2011); Hermosilla (2012)
	Soil (Local) Subsidence (**SS**)	Soil Shrinkage	A D E	MAGA/PEDN (2002a)
		Consolidation/Settlement	A E	Ebmeier *et al.* (2012); Porfido *et al.* (2015)
	Ground Heave (**GH**)	Volcanic Inflation/Uplift	A C D	Johnson *et al.* (2008); Johnson and Lees (2010)
		Soil Expansion (Swelling)	A D E	MAGA/PEDN (2002a)
Atmospheric	Storm (**ST**)	Heavy Rain	A B D E	MAGA/PEDN (2002b); World Bank (2016)
		Tropical Storm/Hurricane	A B D E	Pielke Jr *et al.* (2003); Stewart and Cangialosi (2012)

Hazard Group	Hazard Type	Hazard Sub-Type	Evidence A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop *(≥50% people)*	References *(International Literature)*
	Tornado (**TO**)	Tornado	A D	DesInventar (2016)
	Hailstorm (**HA**)	Hailstorm	A D	DesInventar (2016)
	Lightning (**LN**)	Lightning	A B D E	NASA (2006); DesInventar (2016)
	Extreme Temperature (Heat) (**ET (H)**)	Heatwave	A D E	LAHT (2014)
	Extreme Temperature (Cold) (**ET (C)**)	Coldwave/Frost	A D	MAGA (2002); DesInventar (2016)
Biophysical	Wildfire (**WF**)	Wildfire	A C D E	Charvériat (2000); IFFN (2002); DesInventar (2016)
Space	Geomagnetic Storms (**GS**)	Geomagnetic Storms	*No location specific evidence, however these are globally relevant natural hazards, and therefore may affect Guatemala.*	
	Impact Events (**IM**)	Impact Events		

Table ~~9~~5. Spatial distribution of 37 natural hazard sub-types in Guatemala. A synthesis table to characterise which regions in Guatemala are susceptible to each of the 37 natural hazard sub-types. Selected regions are (1) low relief northern plateaus, (2) Central Highlands, with deep valleys, (3) Southern Highlands, and (4) Pacific coastal plains.

Hazard Group	Hazard Type	Hazard Sub-Type	Spatial Regions [1,2,3,4]	**Evidence** A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop *(≥50% people)*				
Geophysical	Earthquake (**EQ**)	Ground Shaking/Rupture	1, 2, 3, 4	A		C	D	E
		Liquefaction	1, 2, 3, 4	A			D	
	Tsunami (**TS**)	Marine Tsunami	2, 4	A			D	E
		Freshwater Tsunami	1, 2, 3	A		C	D	E
	Volcanic Activity/ Eruption (**VO**)	Subterranean Magma Movement	3	A			D	E
		Volcanic Explosions (Vertical/Lateral)	3	A	B	C	D	E
		Volcanic Gas/Aerosol Emission	3	A				E
		Volcanic Ash/Tephra Ejection	1, 2, 3, 4	A	B	C	D	E
		Pyroclastic Density Currents	3	A	B	C	D	E
		Lava Flows	3	A		C	D	E
	Landslide (**LA**)	Submarine Landslide	2, 4	A				
		Subaerial Rockfall	1, 2, 3, 4	A	B	C	D	E
		Subaerial Rotational and Translational Landslide	1, 2, 3, 4	A	B	C	D	E
		Subaerial Debris Flow	1, 2, 3, 4	A	B	C	D	E
		Subaerial Lahar	3	A	B	C	D	E
Hydrological	Flood (**FL**)	Pluvial Flood	1, 2, 3, 4	A	B		D	E
		Fluvial Flood	1, 2, 3, 4	A	B	C	D	E
		Coastal Flood	2, 4	A			D	E
		Lakeside Flood	1, 2, 3	A		C	D	E
	Drought (**DR**)	Drought	1, 2, 3, 4	A			D	E
Shallow Earth Processes (adapted from Hunt, 2005)	Regional Subsidence (**RS**)	Tectonic Subsidence	1, 2, 3, 4				D	
	Ground Collapse (**GC**)	Karst/Evaporite Collapse	1	A			D	
		Piping Collapse	3	A	B		D	E
	Soil (Local) Subsidence (**SS**)	Soil Shrinkage	1, 4	A			D	E
		Consolidation/ Settlement	1, 2, 3, 4	A				E
	Ground Heave (**GH**)	Volcanic Inflation/Uplift	3	A		C	D	
		Soil Expansion (Swelling)	1, 2, 3, 4	A			D	E
Atmospheric	Storm (**ST**)	Heavy Rain	1, 2, 3, 4	A		B	D	E
		Tropical Storm/Hurricane	1, 2, 3, 4	A	B		D	E
	Tornado (**TO**)	Tornado	1, 2, 3, 4	A			D	
	Hailstorm (**HA**)	Hailstorm	1, 2, 3, 4	A			D	
	Lightning (**LN**)	Lightning	1, 2, 3, 4	A	B		D	E
	Extreme Temperature (Heat) (**ET (H)**)	Heatwave	1, 2, 3, 4	A			D	E
	Extreme Temperature (Cold) (**ET (C)**)	Coldwave/Frost	1, 2, 3, 4	A			D	
Biophysical	Wildfire (**WF**)	Wildfire	1, 2, 3, 4	A		C	D	E
Space	Geomagnetic Storms (**GS**)	Geomagnetic Storms	1, 2, 3, 4					
	Impact Events (**IM**)	Impact Events	1, 2, 3, 4					

Table 6~~10~~. Four examples of ~~networks of~~ multi-hazard interaction networks, extracted from the CONRED civil protection bulletins. Each example (1–4) is characterised by bulletin number, date, location, and event descriptions.

Example	Bulletin #	Bulletin Date	Location	Event Description ~~Narrative Summary~~	Visual Summary
~~2~~1. Mixco, Zone 6, Guatemala City	1062	23-Aug-10	Mixco (Zone 6), Guatemala City	~~The collapse of a hillside into a river caused damage, with dredging of the river required.~~ Rain ~~triggers~~ triggered a landslide. This landslide ~~enters~~ entered a river, which subsequently ~~needs~~ needed dredging. Landslide therefore either blocked the river and caused flooding or increased the likelihood of flooding.	
~~3~~2. Quetzaltenango Department	1126 1129	09-Sep-10	Quetzaltenango, Chimaltenango, Alta Verapaz San Sebastian, Retalhuleu, Santiaguito	~~Rains produced floods, landslides/ mudslides.~~ Heavy rain in Quetzaltenango and other Departments ~~triggers~~ triggered floods, landslides and lahars. Lahars (requiring ash/tephra deposition) associated with Santiaguito volcano caused flooding of the Samalá river, causing damage to bridges. ~~Santiaguito volcano lahars caused flooding of the Samalá river, causing damage to bridges.~~	
~~4~~3. Storm Matthew	1174 1175 1183 1184 1185 1186	23-Sep-10 24-Sep-10 25-Sep-10	*General* Nicaragua, Honduras *General* Motagua River, Morales, Izabal *General* *General*	~~Monitoring of rivers during Storm Matthew as it could provoke damage~~ ~~Storm winds and rainfall, cause flash floods, landslides and mudslides~~ ~~Tropical Storm Matthew produces heavy rains which causes rivers to rise. Rains~~	 (Replicated in Nicaragua, Honduras and Guatemala)

Example	Bulletin		Location	Event Description ~~Narrative Summary~~	Visual Summary
	#	Date			
	1199		Centre and South Guatemala	~~cause soil saturation, expected that rivers will exceed water levels and flooding occur. Tropical Storm Matthew causes heavy rains and Motagua river to increase in volume. Overflow of Motagua river caused a flood. Saturated soils could cause landslides or mudslides. Tropical Storm Matthew causes heavy rains, rising tides and floods. Low pressure system generates clouds, showers and lightning.~~ A warning was issued that Storm Matthew could trigger damage, and was associated with flash floods, landslides and mudslides in Nicaragua and Honduras. On 25 September 2015, Tropical Storm Matthew ~~impacts~~ impacted Guatemala directly, causing river levels to rise and saturate soils, with a warning that flooding may occur. The next bulletins reported flooding, an increased likelihood of landslides, and lightning.	

~~**Table 11. Relevant anthropogenic process types in Guatemala.** A description of the four evidence types A–E, together with additional references, used to identify 17 anthropogenic process types as being spatially relevant in Guatemala.~~

~~**Anthropogenic Process Type**~~	~~**Evidence** A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop (*anthropogenic processes not discussed*) * (Reference) = Additional citations, beyond A–E.~~			
~~Groundwater Abstraction~~			~~D~~	
~~Oil/Gas Extraction~~				~~* (OEC, 2016)~~
~~Subsurface Infrastructure Construction~~	~~A~~		~~D~~	
~~Subsurface Mining~~				~~* (OEC, 2016)~~
~~Material (Fluid) Injection~~				~~* (USGeothermal, 2016)~~
~~Vegetation Removal~~	~~A~~	~~C~~	~~D~~	
~~Agricultural Practice Change~~		~~C~~	~~D~~	
~~Urbanisation~~		~~C~~	~~D~~	
~~Infrastructure Construction (Unloading)~~			~~D~~	
~~Quarrying/Surface Mining (Unloading)~~				~~* (OEC, 2016)~~

Anthropogenic Process Type	Evidence A = International Literature B = Civil Protection Bulletins C = Field Observations D = Stakeholder Interviews E = Workshop (*anthropogenic processes not discussed*) * (Reference) = Additional citations, beyond A–E.				
Infrastructure (Loading)			C	D	
Infilled (Made) Ground	A				
Reservoir and Dam Construction	A			D	* (Salini Impregilo, 2014)
Drainage and Dewatering	A	B		D	
Water Addition	A	B		D	
Chemical Explosion					*Inferred relevant*
Fire				D	

Table 7~~12~~. Calculation of Matthews' Correlation Coefficient (*MCC*) to assess agreement between the collective knowledge of 16 workshop participants (Figure 2) and national interaction framework (Figure ~~5~~3). Three different thresholds, each relating to the number of workshop participants (out of 16) identifying a particular interaction, are used to determine collective knowledge of hazard interactions. The number of 'agreements' and 'disagreements' between the workshop participants' response and national interaction framework (see column headers for descriptions) is shown. For each row, the sum of True Positives (TP) and False Negatives (FN) is 50, and the sum of True Negatives (TN) and False Positives (FP) is 392. *MCC* values are determined using **Eq.~~uation~~ 1**. An *MCC* ~~score of~~= +1.0 means complete agreement; an *MCC* =~~score of~~ −1.0 means complete disagreement.

Workshop Participants Identifying an Interaction *(n = 16)*	**# Interactions Identified by ≥ x participants (TP + FP)**	**AGREEMENT** *[Participants' Collective Framework and National Interaction Framework Agree]*		**DISAGREEMENT** *[Participants' Collective Framework and National Interaction Framework Do Not Agree]*		**Matthews' Correlation Coefficient** *(**Eq.~~uation~~ 1**)*
		Interaction Occurs in **Both Frameworks** *True Positives (TP)*	**Interaction Does Not Occur** in **Either Framework** *True Negatives (TN)*	**Interaction Occurs** in **National Framework** but **not Participants' Collective Framework** *False Negatives (FN)*	**Interaction Occurs** in **Participants' Collective Framework** but **not National Framework** *False Positives (FP)*	
≥ 1	86	25	330	25	61	0.28
≥ 3	32	22	381	28	10	0.51
≥ 5	19	16	388	34	3	0.49