Response to Referee #2

We wish to thank the Referee for his/her time and effort reviewing the manuscript. We greatly appreciate the constructive comments and suggestions, which we have carefully addressed in this response. Where applicable, changes are proposed to the manuscript accordingly (and marked up for clarity). Following the guidelines of the NHESS Editorial Board, the revised manuscript was not prepared at this point.

- This paper only takes us about 60% of the way there. While I do think you have a novel idea of using graph theory to model risk transfer in a way that has not been done, you don't fully show us how to do it conceptually. e.g. you explain how graphs work. and give some discussion of how these graph properties link to vulnerability, resilience, and exposure. But you need to go much further.

This article is organized as two companion papers, and our understanding is that this may have been overlooked by the Referee. The article is organized such that part I provides the theoretical framework, and part II demonstrates how it can be applied using a pilot study. We believe that part II (https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2018-278/) fully covers the issue raised by the Referee.

- What metrics do you propose we use from graph theory that link to which metrics in risk assessment? Maybe this is what you are trying to do with percolation but it is still very unclear. How are you going to get us towards measure cascading risks with your new approach.

These two companion papers, from a theoretical point of view in part I and a practical application in part II, propose a list of selected graph properties and discuss how these can be used in the assessment of the traditional components of risk. In particular, authority, closeness and percolation threshold are proposed respectively as metrics for the risk variables: exposure, vulnerability and resilience. Furthermore, these analogies are summarized in Table 1, and finally most of proposed metrics are applied in a case study in part II.

- Part of the problem is the disorganized literature review and background. You are missing a lot of the resilience literature on this topic, and it feels like you are describing papers selectively. Please organize this into topics, themes, that lead to the demonstrating the gap in the lit that your new graph theory approach will allow us to fill.

We fully agree with the Reviewer that the structure of the literature review of the manuscript can be improved. For this reason, we propose to restructure the Introduction, introduce the reference relevant for to the aim of the introduction, and write a new subsection (1.3) that help positioning the paper among the existing body of literature. These changes are described in detail below:

1. Introduction

1.1 Collective Disaster Risk Assessment: traditional approaches

This subsection provides a brief contextualization of current practice and limitations in disaster risk assessments, making use of key references. Here we propose to add a relevant reference related to multi-hazard risk Zscheischler *et al.* (2018) and Wahl *et al.* (2015) at L59.

1.2 Modelling natural hazard risk in complex systems: state of the art and limitations

This subsection introduces the need for holistic approaches that are able to handle the complexity of contemporary society. This is in contrast with the reductionist approaches presented in subsection 1.1, which only partially contribute to the assessment of the total impact, because they do not consider the connections between the exposed elements. The literature in this subsection aims to give an overview of the state of art and limitations of existing models to study complex systems. We propose to improve it by adding the suggested references listed here:

L70: "Lhomme et al., [2013] showed that the city has to be considered as an entity composed by different elements and not merely as a set of concrete buildings."

L73: "The reductionist approach, in which the "risks are an additive product of their constituent parts" (Clark-Ginsberg *et al.*, 2018), contrasts with the complex nature of disasters."

We than show how the networks are treated in the infrastructure sectors, one of the sectors that are traditionally able to assess the complexity of interdependency. This brings to the concept of systemic vulnerability typical of cascading failures in the network, for which we also propose to add two suggested references Lewis (2014) and Setola *et al.* (2016) at L91. Subsection 1.2 ends with the presentation of the system of system perspective.

1.3 Positioning and aims

The main difference between the original and the revised manuscript will be this subsection, where we wish to clarify:

(1) where our work is positioned in the recent theoretical framework covered by the proposed literature;

(2) the misunderstanding about the use of the network-based analysis: we do not analyse systems already organized as a network (e.g. electric power network), but we instead employ the network to represent a complex system such as an urban environment, and use Graph Theory as a diagnosis tool.

To achieve this, we propose adding the following:

"~~Although t~~The aspects of complexity and interdependency have been investigated by various models of critical infrastructure as a single system, or as systems of ~~systems,~~ systems, which are networks by construction (e.g. drainage system). However, there is still a gap in current practice when it comes to modelling~~we would like to further explore~~ the complexity of interconnections between ~~the~~ individual ~~exposed~~ elements that do not explicitly constitute a network, which tend to be neglected by traditional reductionist risk assessments.~~ and their interconnections,~~ Therefore, in this manuscript we propose an approach to model such interconnections and ~~and propose an approach to~~ develop a more holistic collective risk assessments.

This work proposes an approach to assess the interconnected risk (i.e. complex interaction between human, environment and technological systems) and a potential tool to model cascading risk (i.e. the results of escalation processes) and support more informed DRR decision making (Pescaroli and Alexander, 2018).

In particular, we understand that it is necessary to better analyse the interaction between these elements at risk and their influences on indirect impact assessment. The analyses of interaction and influence are assessed in this work by adopting the framework of Graph Theory, the branch of mathematics for the treatment of networks. Since its birth in 1736, Graph Theory has witnessed many exciting developments, and has been able to provide answers to a wide range of practical questions in many sectors (Boccaletti *et al.*, 2006). Given this context, this paper proposes an insight into collective risk assessment from an innovative holistic perspective.

The aims of this paper are: (…)"

We believe that this new structure of the Introduction and its proposed improvements address the Referee's comment and provide a much more logical sequence and organization for these topics. It is worth noting that the purpose of this section is not to provide an exhaustive literature review of a specific sector (e.g. resilience or critical infrastructure), but to engage with literature that is representative of the state of the art in this field, providing a concise overview (i.e. brief but comprehensive) to readers, and then position this work among the existing body of literature.

- This idea has a lot of promise, but needs work. The conclusion should make me feel like I have a new tool and idea to measure risk. But I am left feeling confused.

Presumably this comment applies to part I of the article. We believe that the Referee's idea, with which we agree, is covered by the full article (i.e. both companion papers together). Nevertheless, note that this topic warrants further research, which is duly acknowledged in the manuscript.

- Line 45. Vulnerability does consider social conditions. That is a wrong statement

We agree and do not state otherwise. The contrast presented here is between social and *physical* vulnerability, as explicitly written in the previous line of the manuscript.

- Line 59. See the work on compound flood risk. Eg. Wahl, Thomas, Shaleen Jain, Jens Bender, Steven D. Meyers, and Mark E. Luther. "Increasing risk of compound flooding from storm surge and rainfall for major US cities." Nature Climate Change 5, no. 12 (2015): 1093. Zscheischler, J., Westra, S., Hurk, B.J., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T. and Zhang, X., 2018. Future climate risk from compound events. Nature Climate Change, p.1.

We agree on the relevance of both references and propose adding them to the article at L59

- Line 80. Great examples. Surprise to see lack of citatations for the large literature on compo unding risk and cascading failtures from the resilience field. E.g. Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. Nature, 464(7291), 1025. Chicago

We will add the suggested reference in the Introduction.

- Line 84. I have never heard of this rinaldi paper. I doubt it is the most quoted.

Rinaldi et al. (2001) is an essential reference in the assessment of critical infrastructure risks, with currently over 2000 citations on Google Scholar for example, as also underlined by Referee #1 "*A large literature builds on Rinaldi et al. (2001) to use graph theory to assess critical infrastructure risks*". We recognize that this article may be not as well known in other neighbouring fields of science (e.g. other sectors of risk, or applications of graph theory), but the validity of this statement is indisputable and we therefore propose to keep it.

- In general this literature review feels selective and disorganized. Use subheadings. What is the gap you are filling? Are you really the only/first people to use graph theory to assess risk. I somehow doubt it. A simple google scholar search revealed many articles:

Heckmann, T., Schwanghart, W., & Phillips, J. D. (2015). Graph theoryâATRecent developments of its application in geomorphology. Geomorphology, 243, 130-146. Holmgren, Åke J. "Using graph models to analyze the vulnerability of electric power networks." Risk analysis 26, no. 4 (2006): 955-969. Lhomme, S., Serre, D., Diab, Y., & Laganier, R. (2013). Analyzing resilience of urban networks: a preliminary step towards more flood resilient cities. Natural hazards and earth system sciences, 13(2), 221-230.

Also see risk transfer analysis 1. Sapountzaki, K. Social resilience to environmental risks: A mechanism of vulnerability transfer? Manag. Environ. Qual. An Int. J. 18, 274–297 (2007).

We agree with the Reviewer that the structure of the literature review of the manuscript can be improved, and above we proposed a significant number of improvements to address this issue. In the revised manuscript we will also add the following references suggested by the Referee: Åke J. Holmgren (2006); Lhomme et al. (2013) and Sapountzaki (2007).

Note that the manuscript does not claim in any way to "*be the only/first people to use Graph Theory to assess risk*": As we underline above, the literature on the use Graph Theory in risk assessment is large, but also (and more importantly here) extremely diverse. Many (if not most) of the articles that show up on a "*simple google scholar search*" actually have little relevance given the scope of our manuscript. The manuscript includes the references that we believe are most relevant and representative of the state of the art in this field (i.e. natural hazard risk modelling of systems that are not explicitly arranged as a network but whose underlying connections can significantly magnify impacts and risk), and could help the reader to understand the purpose of the proposed approach.

- Page 165. Its hard to read all your definitions in prose. Made a table or a diagram that shows in a depiction each term. Add more to figure 1.

We agree, and propose adding the following table at L151 to address this issue:

Table 1: Graph properties description

Graph properties	**Description**
Degree (k)	The number of edges incident with the node
Path length	The geodesic length from node i to node j
Closeness	The distance (number of links) of a node to all others
Betweenness	The shortest paths between pairs of nodes that pass through a given node
Authority	Value of a node proportional to the sum of the node hubs pointing to it
Hub	Value of a node proportional to the sum of authority of nodes pointing to it
Percolation threshold (pc)	The minimum value of fraction of remaining nodes (p) that leads to the connectivity phase of the graph

- Line 196. What is pc. What is k.

The definitions of pc and k are presented at L194 and L197, respectively.

- Line 265. It is not until here that you tell me what graph theory contributes to vulnerability analysis.

This follows the logic behind the structure of the manuscript, where we first provide context for the research (Introduction), then present some relevant aspects of graph theory, followed by the workflow that we propose in our approach, and finally show the analogy between graph properties and exposure, vulnerability and resilience. We believe this aids overall clarity and organization.

- WHY is current risk analysis lacking and WHAT does graphs uniquely help us understand.

We believe that the main shortcoming of current reductionist approaches is the impossibility to consider the connections between exposed elements, as also underlined by the suggested reference Lhomme et al. (2013). Our manuscript proposes an approach based on Graph Theory that aims to take into consideration these connections, and treat the exposed elements as part of a whole system. The analogy proposed in part I and the application in part II show how the properties of a graph can provide information on the risk variables.

- 330. I have never heard of this definition of resilience. This need to be motivated by the enourmous literature on the topic to some degree.

The definition of resilience is proposed at line 48 ("system's capacity to cope with stress and failures and to return to its previous state"). Instead, at L330 we specifically underline the dynamic features of resilience compared to vulnerability. Since this was not clear enough, we are now suggesting a modification that also incorporates two references proposed by the Reviewer L328-L331:

"Resilience differentiates from vulnerability in terms of dynamic features of the system as a whole. The properties and functions used to model vulnerability are static characteristics that do not consider any time evolution, or using the words of Sapountzaki (2007), "*vulnerability is a state, while resilience is a process*"; ~~instead,~~ in fact the definition of resilience implies a time evolution of the characteristics of the whole system. In addition, Lhomme et al. (2013) underline "*the need to move beyond reductionist approaches, trying, instead, to understand the behaviour of a system as a whole*". These two different features, dynamic aspect and whole system~~This difference~~ can be expressed by a cinematography analogy: vulnerability is a single frame of the resilience video."

References:

Åke J. Holmgren. 2006. "Using Graph Models to Analyze the Vulnerability of Electric Power Networks." *Risk Analysis* 26(4):955–69.

Boccaletti, Stefano, V. Latora, Y. Moreno, M. Chavez, and D. U. Hwang. 2006. "Complex Networks: Structure and Dynamics." *Physics Reports* 424(4–5):175–308.

Clark-Ginsberg, Aaron, Leili Abolhassani, and Elahe Azam Rahmati. 2018. "Comparing Networked and Linear Risk Assessments: From Theory to Evidence." *International Journal of Disaster Risk Reduction* 30(April):216–24. Retrieved (https://doi.org/10.1016/j.ijdrr.2018.04.031).

Lewis, Ted G. 2014. *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation*. John Wiley & Sons.

Lhomme, S., D. Serre, Y. Diab, and R. Laganier. 2013. "Analyzing Resilience of Urban Networks: A Preliminary Step towards More Flood Resilient Cities." *Natural Hazards and Earth System Science* 13(2):221–30.

Pescaroli, Gianluca and David Alexander. 2018. "Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework." *Risk Analysis* 38(11):2245–57.

Rinaldi, Steven M., James P. Peerenboom, and Terrence K. Kelly. 2001. "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies." *IEEE Control Systems Magazine* 21(6):11–25.

Sapountzaki, K. 2007. "Social Resilience to Environmental Risks: A Mechanism of Vulnerability Transfer?" *Management of Environmental Quality: An International Journal* 18(3):274–97.

Setola, Roberto, Vittorio Rosato, Elias Kyriakides, and Erich Rome. 2016. *Managing the Complexity of Critical Infrastructures*. Springer Nature.

Wahl, Thomas, Shaleen Jain, Jens Bender, Steven D. Meyers, and Mark E. Luther. 2015. "Increasing Risk of Compound Flooding from Storm Surge and Rainfall for Major US Cities." *Nature Climate Change* 1093–97.

Zscheischler, Jakob et al. 2018. "Future Climate Risk from Compound Events." *Nature Climate Change* 8(6):469–77. Retrieved (http://dx.doi.org/10.1038/s41558-018-0156-3).