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Discussions

Interactive comment on "Indirect flood impacts and cascade risk across interdependent linear infrastructures" *by* Chiara Arrighi et al.

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In this paper, the authors developed a risk analysis of the water distribution system (WSS) and the road network system under flooding events. The case study is the metropolitan area of Florence, which is in a flood-prone area. The paper aims to study the interdependence between the WSS and the road system by evaluating the accessibility to critical components of the WSS. Network models and topological metrics (e.g. the length of the disrupted edges, network service areas) are used to measure the vulnerability of the systems. Overall, I found this paper interesting and relevant to the field of infrastructure resilience. In particular, the paper tries to analyse interconnections between two infrastructure systems by looking at a real-world case study.

Anyway, the paper still needs some work to be ready for publication. Therefore, I hope my comments will help in the revision process.

Reply. Authors thank the reviewers for the comments. The manuscript aims at highlighting how crucial is the understanding of indirect impacts of flooding to critical infrastructures especially where interdependencies exist. A significant effort was put on identifying metrics that could be suitable for both the analysed networks, from an engineering perspective (in terms of 'disrupted' lengths) and from a societal perspective (people cut-off a service). We also show that a critical component of the WSS network becomes even more critical when looking at interdependencies with the road network because of the difficult accessibility. We think our point-by-point reply (and relative edits) will address concerns and improve the manuscript for publication.

- The syntax of the whole text should be revised. In particular, I found sections 2 and 3.1 difficult to read. Moreover, I found many typo errors in the text (for example, line 234: (2-3"), line 388: "be be").

Reply. We will check Sections 2 and 3.1 and rephrase these paragraphs. We will also correct typos.

- In line 37, you presented previously published works and you wrote "Among these works, indirect impacts and cascade effects are mostly addressed with complex conceptual frameworks (Fekete, 2019; Emanuelsson et al., 2014), :" How do you define a "complex conceptual framework"? Please, be more precise when reporting other works.

Reply. We meant that the conceptual framework cited would require a significant number of models and data to describe the complexity of the systems. We will rephrase the citation.

- Line 50: "Modern cities are currently defined as "systems of systems", where the "systems" are Critical Infrastructure (CI) systems (Gardner, 2016)." I do not agree with this definition. For me, a city is made also of people, cultures, the environment, the ecosystem, etc. Falco published a paper about this (Falco (2015) “City Resilience through Data Analytics: A Human-Centric Approach).

Reply. We opted to cite a definition of Critical Infrastructure from the engineering and urban science literature (Gardner, 2016). Authors are aware how relevant is the societal sphere (or system indeed); however, this study's niece area is within engineering and urban science, thus other perspective are out of the scope. We fully understand that considering the human sphere is key in understanding indirect (often intangible) impacts and we tried to go in that direction. In fact, we presented different impact metrics where the people are central by evaluating the population not served and delayed commuters. We will broaden the definition of cities in the paragraph by adding the societal components and the suggested references.

- In the text, you wrote often about the “impedance time”. For example, in line 372: “Service Areas (SAs) are applied to understand which portions of the city are accessible within a given time, i.e. the impedance time.” I have never heard about it. I checked on a vocabulary and it says it is related to electronic measures. Therefore, I am not sure if it is the most correct terminology.

Reply. The concept of Services Areas is well-known in transport and network analysis (here, a quick overview https://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/service-area.htm). We appreciate that the multi-disciplinary audience of this article could not grasp the concept, therefore various references will be added and the concept clarified.

- I found often “silo-based” in the text, but there is not a clear definition of it. I think it is important to add a definition because “silo-based” is a relevant concept for your work.

Reply. Also the concept of “silo” is quite common in network and networked infrastructure studies, and it used as the contrary of “system”. A silo-based approach (or thinking) does not consider the relations among different elements (or components, groups, etc.), as opposed to a system-based approach that analyses the interactions among elements. This will be clarified in the text when "silo" appears for the first time.

- Line 58: "Therefore, CIs cannot be considered independently, and silo-based analyses are completely inadequate to understand the behaviour of a given infrastructure operating in its environment (Dueñas-Osorio et al., 2007; Rinaldi et al., 2001)." This statement sounds a bit strong. I checked the two papers. Duenas-Osorio et al. (2007) wrote in their abstract that "Effective mitigation actions could take advantage of the same network interconnectedness that facilitates cascading failures", while Rinaldi et al. (2001) wrote "When examining the more general case of multiple infrastructures connected as a "system of systems," we must consider interdependencies." You wrote in line 83: "Silo-infrastructure studies are limited in their scope since they ignore cascade effects and thus underestimate impact (De Bruijn et al. 2019)." I think that analyses of a single network system can advance our understanding of specific systems or they can help to find metrics to use for other analyses. In section 3.1, you also analysed the WSS and the road network separately. Based on those results you could measure the Annual Average Loss (AAL) on page 12. Overall, I think that the introduction should be revised from this perspective.

Reply. The analysis of a single network can advance the understanding of impacts; however, when the networks have interdependencies, cascade effects amplify and multiply the impacts. Silo-based studies can partly describe flood consequences and in the authors' opinion dependencies among infrastructures should be carefully analysed. We will amend the introduction to better describe the existence of cascade effects within a single network and the amplification effect due to interdependencies.

- In this paper, you used network models embedded in space for your analyses. Anyway, the paper did not report enough literature about this topic. Moreover, other papers studied the impact of floodings on road networks. For example, Casali and Heinimann (2019) "A topological characterization of flooding impacts on the Zurich road network.

PLoS ONE 14(7)"; Kermanshah and Derrible (2017) "Robustness of road systems to extreme flooding: using elements of GIS, travel demand, and network science." Natural Hazards, 86.

Reply. We will add the two suggested references, and review the literature to briefly mention network models. Our literature review focused on flood indirect impacts and cascade effects evaluation on multiple (interdependent) infrastructures. We are aware that the topic is complex and could embrace an even more comprehensive literature review (inclusive of e.g. flood risk analysis, vulnerability of linear infrastructures, indirect impacts and cascade effects, road transport models, WSS network models, resilience of infrastructures); however, this type of revision would be a review paper itself, rather than the contained background of our piece of work.

- Line 120: "Very few studies (Pant et al., 2018; Dong et al., 2019) developed a truly holistic application to analyse interdependency effects; however, indirect consequences are not investigated, especially regarding the WSS-roads interaction." I found this sentence too strong. I would rephrase it because there are many published works that analyzed cascading effects on networks. Moreover, you reported the work of Dong et al. (2019), who developed percolation analyses on the road networks of different cities, not of interconnected networks. Therefore, why is a percolation analysis a truly holistic application for interdependency? I think that even the study of a single network system can represent a holistic approach since it looks at the network system as a whole. Casali and Heinimann developed a thesis from this concept (Casali (2020), "Topological Assessment of Changes in Road Network Systems in Time, under Discrete Flooding Events, and under Classes of Unexpected Disruptions").

Reply. We will rephrase the sentence. We agree that various existing works analyzed cascading effects on networks. However, no study (at our best knowledge) has so far addressed the quantification of indirect impacts and cascade effects in relation to WSS-roads interaction. Our vision of "holistic approach" includes complexity, which is based on interconnections (which cannot be represented by the analysis of a single system) since a wider ‘system of systems’ should be considered in the analysis. This vision may differ from other interpretation of “holistic approach”, e.g. the analysis of a single network using multiple disciplines. The text will be amended to include both interpretations.

- Why do you use to measure indirect impacts: (i) the length of the disrupted network; and (ii) the population which experiences loss of service? Maybe in section 2.2 you can add more text about the motivations. Moreover, why is the total length of edges a better metric to analyse network vulnerability than other metrics (for example, the number of disrupted edges)?

Reply. Authors aimed at calculating two different types of impact metrics with different perspective: (i) an engineering measure of total length, which can be used as a proxy of potential damage/recovery costs (e.g. the cost of flushing a contaminated pipe with disinfectants is expressed in €km of pipe); (ii) a people-centered measure which describes the amount of population experiencing the interruption/delay of service. This choice is also the result of an effort in identifying metrics suitable for both networks. Moreover, the number of disrupted edges does not provide a quantitative measure since single edges can be 100 or 1000 meters long especially when the study area spans in urban, suburban and rural areas and includes a varying density of infrastructures.

- In the methodology section, I found that not all the information is reported fully. I do not find a definition for the Annual Average Loss (AAL) and details about how you calculated the PPH. Moreover, you introduced the Pressure Driven Demand (PDD), and it can be useful if you will add more information about it.

Reply. AAL is the frequency-weighted amount of loss that can occur on average in any year, we will add a definition and reference to a widely used manual by USACE who introduced its application to a broad audience. (USACE, 1989 - USACE: Expected annual flood damage computation [available online at https://www.hec.usace.army.mil/publications/ComputerProgramDocumentation/CPD-30.pdf] last access 2-5-21, 1989. In the design of WSS networks the demands can be assumed as defined input data since the main objective is simulating correctly operated networks, this is the standard approach in modelling codes such as EPANET. However, when simulating strongly off-design networks, nodes featuring a reduced pressure are quite common, so that a PDD approach is needed (Arrighi et al., 2017). In PDD models nodal demands are not attributed a priori; instead, their value depends on the current local pressure. In particular, and consistently with practice, the model assumes that each node is in one of three states: fully-served (pressure equal or higher than nominal pressure, partially-served (positive pressure, but lower than nominal pressure), not-served (zero pressure) (see further details in Arrighi et al., 2017). We will add further explanation on this point in the text. PPH (People per Hour) was defined in Sec 2.2 and the definition will be improved.

- In the methodology section, I did not find precise information about how you modelled the networks. For example, what are exactly a node and an edge in the WSS and the road networks? Which software did you use to model them? I understood that the road network extended to a larger area than the WSS network, is that correct? Did the road network add some weights to the edges? For example, in line 217, you wrote that "for the flooded scenarios, the network properties of a link (i.e. travelling speed) are modified according to the functions, and traffic parameters recalculated for the perturbed state." This means that you used the travelling speed in the analyses of the road network. Therefore, how did you calculate the travelling speed?

Reply. In the WSS model the network is composed by edges, i.e. pipes with assigned diameter that transport potable water from the treatment plant to the users, which intersect each other at nodes of known elevation (below the ground) and where a nominal demand is assigned depending on PE. The network is modelled with EPANET (see section 2.2) with a user modified PDD calculation scheme (see reply to previous comment). The analyzed road network extends to a larger area because indirect impacts to commuters extend beyond the municipalities served by the WSS. Regarding the road network, the perturbed travelling speed of flooded roads was computed using the flood-transport function of Pregnolato et al. (2017b), as mentioned. We agree this was poorly explained and will be improved.

- You used the SA (network service area) to look at accessible areas. Did you consider also directions of roads when you analyse the shortest paths?

Reply. As reviewers have appreciated, this study is highly complex and multi-disciplinary; moreover, it is based on publicly available data. Therefore, some modelling simplifications were necessary. Network SAs used regional cartography road data, which lacks complete information, and applied through an ArcGIS model, which unfortunately could not create road directions. Improving the sophistication of the model is definitely in the future development of this piece of research; this will be added in the appropriate section.

- Line 226: " The widely accepted definition of resilience is the ability to overcome an impactful event and return to normal condition through a quick recovery;" There are many authors that defined resilience in recent years. You can add a reference to a published work on infrastructure resilience.

Reply. We will add a reference on the definition of resilience which is indeed defined in several ways according to literature, for example the recent review by McClymont et al. (2020): McClymont et al. (2020), Flood resilience: a systematic review, Journal of Environmental Planning and Management, 63:7, 1151-1176, DOI: 10.1080/09640568.2019.1641474

- Figure 4: you can improve the resolution of the figure. Moreover, I cannot see the edges of the urban network in figure a.

Reply. Full resolution figures will be submitted with the revised manuscript. The urban network is extremely dense in the area so a light grey color was selected, but we will try to find a better compromise to obtain a clearer visualization.

- Figure 5: I cannot read legend of figure b. The description of figure c is missing. You can improve the resolution of this figure. Moreover, what does it mean "low", "medium" and "high" in legend of figure c?

Reply. The legend will be improved, and the description of panel c will be added. The meaning of “high” is that the municipality is affected by a loss of functionality of the unique source of water supply, “medium” is when a municipality might rely upon an alternative water source but still will experience some loss of service; “low” is when the municipality does not experience loss of service (see description of the municipal WSS connection in sect.2 ll. 277-284). This more detailed description will be added to the text.

- Section 3.1 “Silo base analyses”: you can add a topic sentence to introduce the “silo-based analyses”.

Reply. The concept of “silo” has been clarified in the text when “silo” appears for the first time (L59), as suggested in previous comments.

- Caption Table 2: I would repeat here that the WSS is not affected for 30 and 100 years events.

Reply. We will modify the caption accordingly.

- Figure 6: it is not clear how did you choose the interval limits for this figure because it is not reported in the method section.

Reply. The detail about how the interval limits were defined are not present because we did not think it was relevant; in fact, the classification of Fig. 6 is not used throughout the text but for visualization only (and of Fig. 6 only). The actual numbers of PPH were used for analysis and drawing conclusions; nevertheless, we thought that a qualitative representation of the distribution of PPH could have been a nice (graphic) addition to the paper.

- Table 3: why there is not Florence in this table? Then, I would order the municipalities as in table 2.

Reply. Table 3 shows the impact on the commuting population to Florence. Therefore, Florence is not represented because internal commuting within Florence is not considered (due to lack of data). Tables will be both ordered by magnitude: Table 2 will rank elements using PE (the first line will have the highest PE), while Table 3 using PPH (the first line has the highest PPH). We think this visualization has a good rationale, and we will amend Table 2 with this approach.

- Lifting stations are important for the analyses of this paper. You can describe more the geography of lifting stations, for example, how many and where are lifting stations? Therefore, I ask the authors to provide more description of the topology of the WSS in the result section.

Reply. The main lifting station of the WSS system is located downstream of the treatment plant of the city as depicted in Fig. 4 with orange triangle symbols. This lifting station is located very close to the river and it is affected for medium-low recurrence intervals event with the effects described in the whole manuscript. The water undergoes treatment and reaches the lifting station, where six 710kW pumps ensure a maximum head of 60m and feed the distribution network. The 17 storage tanks are mostly located at high altitudes and feature a total operative volume of 48 620m3. The storage tanks are equipped with smaller pumps to ensure their day-night operativity. In case of power shutdown, the transient behaviour of the system is determined by the amount of water stored in tanks. In a previous work (Arrighi et al., 2017) a sensitivity analysis of the WSS behavior with respect to the tanks level has identified two conditions. Water levels variations in low-altitude tanks strongly impact most network nodes; high-altitude tanks, have a smaller area of influence limited to the immediate surroundings of the tank itself. We will add a better description of the topology as suggested.

- In Line 389 you wrote, “The first recommendation is then to develop ad-hoc emergency plans by identifying potential critical hotspots (e.g. WSS lifting stations), and to analyse the accessibility to these sites." Therefore, you concluded that identifying critical components in a single network can help to improve emergency plans. Is my interpretation correct?

Reply. We think both, i.e. identifying critical hotspots in one network is important (this was done by previous studies) and in particular the identification of those hotspots where the cascading effects is more relevant (and here we can refer back to our case study). The identification of critical components in a single network is helpful, but preparedness plans should also consider how the network interacts with other infrastructures. In our case study we demonstrate that if the lifting station is affected, one can assume that an immediate assistance can be provided to restart the pumps with limited effects on the water supply. However, this is not possible if the area is not accessible and the consequent 'unexpected' delay further aggravates the impacts (see Fig. 5, b). In conclusion, a critical component of the WSS is not just a node/section that can be affected causing wide effects on the network itself, but also difficult to repair because of the impacts on another interconnected network, i.e. the road network.

- Line 393: "The third recommendation is to enhance the system redundancy for those municipalities totally reliant on a single main system, with e.g. emergency water storage tanks." I agree but by adding new infrastructures maybe we add new externalities to the urban area? What are the immaterial costs of building new water storage tanks in Florence? This paper might be interesting Chelleri and Baravikovab (2021) "Understandings of urban resilience meanings and principles across Europe".

Reply. We agree with this observation and we will be more cautious with the recommendation, i.e. by saying to evaluate increasing the redundancy with respect to considering other factors such as costs, environmental impact in a sustainable perspective.

- Conclusion part, line 444: "Results showed that the impact of flooding to the two systems differs in both spatial (up to 5 affected municipalities per WSS, 37 for the road system) and temporal scale (60 minutes before first pressure drop, 30 minutes to reach critical depths on roads).” I cannot find in the result part where you reported or discussed the 30 minutes to reach the critical depths on roads. Please, write this result in the main result section.

Reply. We will amend the text to keep results in the main result section.

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