Nhess-2020-12: Towards Resilient Vital Infrastructure Systems: Challenges, Opportunities, and Future Research Agenda

(Mehvar et al.)

Reply to the comments from Referee # 2

We thank the referee #2 for providing constructive feedback and detailed comments, which indeed are very helpful to improve the manuscript. We have responded to the comments and we modified the manuscript in accordance to the received suggestions and comments. Our responses are given in blue. For all modifications affected the manuscript, line numbers are given in our responses, referring to the revised version of the manuscript which will be submitted in the next phase of the review procedure.

Dear authors,

The paper you wrote touches upon an important subject. The paper starts with a title which attracts the attention and promises a research agenda. The authors claim to provide an overview from literature on vital infrastructure resilience, to make a conceptual framework on resilience and identify gaps and based on those come up with a research agenda. The paper partly is interesting, but it is difficult to read and not convincing. It is not clear what the authors mean by resilience and how that links to their framework. The link between the literature review, gaps and opportunities is weak. The paper could therefore also be presented as a opinion paper instead of a literature overview.

Response: In response to your general comments, we would like to highlight that the paper has been undergone considerable textual and structural changes which are explained in details in our responses to your main and detailed comments below.

Main comments:

- Provide a section on resilience definitions and then clearly explain how you define resilience of vital infrastructure systems in your paper and stick with that definition. This could be done right after the introduction. It may mean part of the conceptual challenges need to be solved, and therefore in a different structure of the paper. This means it is a significant change. However, it will increase the readability enormously.

  Response: We thank the reviewer for this important comment and we clarified this issue with following explanations and changes we have made in the paper:

  In the introduction section we added different definitions of resilience derived from the literature. These changes include:

- lines 75 – 80: adding the definition of 'system resilience'
- lines 84 – 97: Clarification on the definitions of the concepts: 'Engineering resilience' vs 'Ecological resilience', 'Resilience engineering' vs 'Engineering resilience'

  With respect to our own resilience definition in this paper and required clarifications asked by the reviewer, we added resilient infrastructure definition at the very beginning of the paper (i.e., briefly in the Abstract, line 32-34), and also in the introduction section (line 99-102).

Correspondingly, we also made a significant change in the structure of the section 3 as below:

The new section 3 starts now with definition of the VIS systems, and its resilience, including elaboration on inter/cross sectoral dependencies that exist in VIS. Then we identified different shocks & pressures affecting the infrastructures (section 3.1), followed by two distinct approaches in designing VIS (section 3.2). The latter (capacity-oriented approach) provides a foundation and basis for the main part of the section 3. Section 3.3 provides the literature-based background on the conceptualization of the resilience engineering for VIS, and then we presented our own descriptive definition grounded on the five mentioned principles required to call a system resilient. To this end, the fourth paragraph (lines 310-326) explicitly presents what the authors want to deliver as their own definition of resilience engineering concept and its application for VIS.

However, integration of the inputs from the literature review, and our own definition in this section might be the reason of this un-readability to reviewer. To avoid this, we distinguished between these two sources of inputs, by first presenting literature based materials, and then the adopted concept by the authors. This clarification has been done by the following changes:

- Line 179: Adding the paragraph ‘‘In this article, we define VIS as...’’
- Line 190-205: Editing the text ‘‘we further assert a cross-sectoral dependency ….’’
- Line 265 at the beginning of the section 3.3: Adding ‘‘Reviewing the literature shows that …’’
- Deleting the lines 275-284 and moving them further to the lines 310-319
- Line 310 – 326: Adding the descriptive definition of the resilience concept presented by the authors

In our responses to your comments for the section 4, we explained about our motivation to structure the paper in this way and to present that section as conceptual challenges, rather than inputs for the resilience definition. However, there are considerable changes we have made to the section 4 to increase readability.

- The authors conclude literature focuses on designing and conceptualising resilience, but provides little guidance for designing resilient infrastructures. Their paper, however, does the same.

  Response: As mentioned in the paper, in this study we focused on conceptualization of the resilience concept and applying it for designing resilient infrastructures. So, the study comprises of not only designing systems, but also how resilience is defined for VIS. This involves by (firstly) unravelling the current challenges in designing resilient systems (section 4), and then by providing solutions and identifying potential measures to design resilient systems (section 5). In this sense, the paper provides a coherent review of the compiled inputs (and examples of successful applications) which all contribute to designing resilient infrastructures. We believe that such linked sections provide guidelines and better insight to apply the resilience engineering concept for designing VIS, a thorough review on challenges and possible solutions which is scarce in current resilience literature.

- The review message is not convincing. The list of literature considered is long, but the outcome is not clearly linked to needs or issues in resilience enhancement plans. It is not clear if the recommendations are based on an analysis of what goes wrong in designing or adapting vital infrastructure, nor is it clear when a system would be sufficiently resilient. It is not even clear what must be resilient: the technical system including its management or the functionality towards society (e.g. if there is no power but society has backup generators which can replace power networks for 2 days and the power is back on in time, the system is very resilient, isn’t it? Or not?)

Response: Thank you for highlighting these points. To develop resilience enhancement plans, first there should be a clear vision on the resilience concept for VIS, and the current issues to be addressed in designing resilient systems. This is the missing knowledge for which we presented this study to contribute to addressing the challenges of designing resilient infrastructures (also is linked to the previous reply).

The section 6.2 which includes the needed future development and suggested points, are based on the author's views and the missing knowledge revealed from the literature review (e.g., necessity of different way of resilience thinking, effective use of remote sensing data, etc). The content referred in this section is mostly embedded in different sections of this paper.

Regarding the outcome of the study and in particular, the review message, the authors indicated in different sections of the paper that the VIS resilience is a function of resilience of three interlinked sub-systems (ecological, technical, and social). This view is incorporated and embedded in the content of this paper as it is explicitly highlighted, e.g., in sections 3 (introduction); 4.3; and 6.1. It is difficult to determine a certain level of resilience for infrastructure systems to which we call a system sufficiently resilient, as the resilience is broadly perceived and depends on resilience of the technical system, the environment in which the system provides its function, and the users of provided services (e.g., society).

This also replies the question of ''what must be resilient'': indeed, the technical system, governance, and users are interlinked and integrated elements of infrastructures to providing the final services to users, and hence, we cannot make a distinction between these components as translated to our defined three sub-systems in this paper.

Having considered such an integrated system, at the time of disruption, the entire system must be indeed resilient. So in some cases the resilience is fulfilled by the social component (e.g., as society mentioned in your example) or by the technical system itself. The five different systems abilities in our definition also refers to this multi-dimensional view.

- The definition of resilience adopted in the paper and the one on risk are unclear which sometimes makes the paper confusing. In the end the aim is to enhance resilience of society to disturbances and perhaps trends. The resilience of infrastructure contributes to resilience of society. This is not always clear in the paper. It seems sometimes resilience is used as a system property which contributes to the system's ability to cope with disturbances and at other locations as an aim in itself.

  Response: Addressing your comment, we believe that society and the infrastructure system should not be separately considered. As explained in our previous reply, society itself is part of the entire system which contributes to the resilience of the infrastructures. This is the fundamental point which we aim to highlight in our paper. In the end, the aim is to enhance resilience of the entire VIS involving technical asset, the environment, and the society/users. The five abilities of a system are all need to exist for calling a system resilient. We aimed to not limit the resilience to a certain ability/characteristic of system as defined in some literature (e.g., to cope with disturbance), instead, we explicitly defined it in relation to the five required abilities/capacities (lines 310 – 326).

- The questions in chapter 2 are promising. However, the answers to the questions are not clearly provided or discussed in the paper. There is no discussion of current practice in designing vital infrastructure systems and gaps in there in relation to your resilience framework. This state of the art is crucial when promising gaps and a research agenda to fill gaps.

  Response: With respect to the questions in chapter 2 and our answers, we would like to clarify the following points:

  Answer to question 1: Section 3.1, Line 214-221: We added more explanations on the definitions of shocks and pressures with provided examples and discussions.

Answer to question 2: Providing an introduction in section 3.2, the section 3.3 descriptively explain conceptualization of resilience engineering within VIS. In this section, which has been revised considerably, we explicitly highlighted a history of this conceptualisation, followed by our own conceptualisation as included in this paper (line 310-326).

Answer to question 3: Chapter 4 extensively identifies main conceptual and practical challenges in designing resilient VIS.

Answer to question 4: key opportunities and measures for enhancing infrastructure resilience are descriptively elaborated (one by one) as engineering and non-engineering measures in the section 5.1.

Answer to question 5: In section 5.2, we reviewed a sample of 50 (relatively) recent practices in which the measures elaborated in section 5.1 have been applied. This review is followed by a discussion on application of these measures in current practices, and highlighted: (i) the infrastructure sectors which have been commonly analysed; (ii) the most (and the least) used methods and approaches for enhancing resilience of VIS; and (iii) type of shocks and pressures included in these studies.

We would like to clarify that the gaps highlighted in our paper do not only include the gaps in current practice in designing VIS. Instead, they pertain to the three main cores of our review: (1) definition of VIS, and conceptualization of the resilience concept for designing VIS in chapter 3; (2) challenges and contrary definitions/interpretations for applying the resilience concept for VIS in chapter 4; and (3) discussions which identify the gaps in applying the measures/methods for different types of VIS in chapter 5. Therefore, we excluded more discussion and elaboration of gaps about the selected applications in section 5.2 which can itself be presented as a different review paper. Thus, answering the question 6, identifying gaps and future research agenda provided in chapter 6 are derived from our review on the three main cores of this study.

Consider literature such as:

- Pitt review: Pitt Review Lessons learned from the 2007 floods - Designing Buildings Wiki
- Resilience principles: Resilience in practice: Five principles to enable societies to cope with extreme weather events – ScienceDirect
- Literature on requirements which must be met when designing vital infrastructure or performance targets etc.
- Béné, C., Cannon, T., Gupte, J., Mehta, L., Tanner, T., 2014. Exploring the Potential and Limits of the Resilience Agenda in Rapidly Urbanising Contexts. Institute of Development Studies.
- Carpenter, S., Walker, B., Anderies, M.J., Abel, N., 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4, 765–781. doi:http:// dx.doi.org/10.1007/s10021-001-0045-9.

Response: Thank you for these literature suggestions. We have gone through them and identified helpful materials and related content which are mostly aligned with the content of our paper. We would derive inputs from these suggested literatures which certainly can add value to our paper.

Detailed comments

1. Introduction

- page 2, line 73: resilience is related to the ability to cop with performance variability? I would say the performance variability shows the system is an outcome which shows its degree of resilience? And why

is this definition of Hollnagel et al. (2006) in line with the definition of Davodi et a.l (2012) according to you?

Response: Addressing this comment, we did a major textual edition in the introduction section, and added more explanation to clarify different points of view, definitions/interpretations which have been derived from the literature. These changes include:

Lines 75-80:
''For example, Henry and Ramirez-Marquez (2012) described system resilience as ''how the system delivery function changes due to a disruptive event and how the system bounces back from such distress state into normalcy''. Hosseini et al. (2016) stated that depending on which type of domains are considered (i.e., organizational, social, economic, and engineering), system resilience traditionally concentrates on the inherent ability of systems to absorb a disruptive effect to their performances, with more recent focuses on recovery aspects.''

Lines 84-88:
''According to Holling (1996), engineering resilience concentrates on stability near an equilibrium steady state, in which resistance to disturbances and speed of return to the equilibrium are centred in this definition. In contrast, ecological resilience emphasizes conditions far from any equilibrium state in which a system can change into another regime of behaviour due to instability.''

Lines 91-97 (specifically addresses your comment):
''Notably, there are similar terms/concepts used in resilience studies such as ''resilience engineering'', and ''engineering resilience''. ''Resilience engineering'' focuses mainly on a system's ability to cope with performance variability (Hollnagel et al., 2006), and to bounce back to a steady state after a disturbance (Davoudi et al., 2012; Kim and Lim, 2016). In contrast, ''engineering resilience'' mainly refers to the traditional view of system safety to withstand the failure possibility (Steen and Aven, 2011; Dekker et al., 2008).''

- Page 3, line 95: confusing sentence. It says shocks and pressures affect resilience. How do you then define resilience? In my view, shocks and pressures affect the system, not its resilience. The system needs resilience or uses its resilience to cope with those shocks and pressures.

Response: Indeed! We also meant your point as we explained it in the section 3.1. This paragraph has been already removed from the paper in addressing the other reviewer's comment.

2. Method and materials

- Page 3 --? Line 110 --? Again: what types of shocks and pressures affect infrastructure resilience? What do you mean by resilience in that question? Isn't it a systems property which enables systems or societies to cope with shocks and pressures?

Response: We removed the word 'resilience' in this line and corrected it as: ''… affect infrastructures?'' For clarification, we defined resilience as the ability of a system to monitor and anticipate, absorb, adapt/transform, recover …. to the disturbances induced by shocks and pressures. So, yes, indeed! To be able to cope with those shocks/pressures.

- Page 3: line 112, question 2: this is a question for literature review. Based on the outcome you define resilience in the paper, right? It is strange to ask how you define it in the paper. You should know…rephrase.

Response: In response to this comment, we removed the second part of this question. So, the question is now rephrased as: ''(2) How is resilience engineering within VIS conceptualized?''

Chapter 3: current approaches in designing VIS

- the title suggests that current approaches are discussed. I would expect some description on the design standards, or performance targets where the design is made for, requirements taken into account, life span of the design or other aspects related to resilience. However, this chapter is not on design but on definitions again.

  Response: Given the large extent of the paper covering many definitions/concepts, in the section 3.2 we mainly aimed to provide an introduction to the resilience concept which is defined in the next section. To do this, we explored the literature to identify the common approaches in designing VIS and to identify the root of the resilience concept (from the capacity-oriented approach). Therefore, the two distinguished approaches are identified and briefly defined according to different literature, and more discussions and description on them are excluded because of being out of the scope of this study.

- Chapter 3.2: why do you take the capacity-oriented approach and not the performance-based approach? Is it really the dominant approach in critical infrastructure resilience literature? What is resilience then in this approach.

  Response: The reason has been mentioned in the previous reply. The resilience is defined under the capacity-oriented approach with wide range of definitions as presented in the following section 3.3, highlighting the link with section 3.2.

- The definitions mentioned in 3.3 are not all linked to vital infrastructure systems, some are linked to e.g. socio-ecological systems such as the one at line 193. What do you mean with absorb changes and keep the same functioning in the context of vital infrastructure systems? How would a critical infrastructure absorb change? Clarify.

  Response: Definitions of resilience engineering are widely presented in the literature. One of the challenges is that there is no unique definition for a resilient VIS. This wide range of definitions/interpretations is also seen for defining the infrastructure system itself. While some of the literature consider infrastructures as socio-ecological systems, some others define them as socio-technical, or mostly technical. The word 'socio-ecological' refers to the infrastructure systems in this line. Regarding the second comment, absorption capacity and keeping the same functionality refers to the ability of infrastructure to absorb a shock/pressure with no destruction in its physical form (this is different than adapting to changes or transforming to a new structure). Suppose coastal protection structures (e.g., dike) that can absorb wave pressure and withstand its impact with no disintegration.

- In line 211 and further the example on flood protection is mentioned. Resilience of a flood protection system is unclear if it is based on resilience of the embankments only. It is about resilience of society to floods. Embankments help to protect the more vulnerable parts of the system, which enable the whole valley or basin to cope with high discharges more easily: only the less vulnerable parts with lower protection standards are flooded and may suffer from adverse impacts. The area as a whole (including society along the rivers) recovers faster then. Here, in this paper it seems that resilience is linked to adaptive capacity which provides a different angle. It is then about resilience to climate change, or resilience if societal preferences change? I think the paper would be much clearer if in examples like that a few words are added explaining where you are talking about: resilience of what precisely (the embankments, or society in the riverine area) to what (high discharge waves coming down the river, or climate change or ?)

  Response: Here again the issue is about how we define an infrastructure system. As already replied to your 4th main comment about 'the definition of resilience' in page 3, VIS and in particular, flood protection structures as the example presented here are considered as interdependent socio-technical

systems. So, resilience here refers to the resilience of the entire system in which social and physical characteristic of the structure both play important roles in enhancing the system's resilience.

In particular, in this example we explicitly indicated that the resilience of dikes or embankments relies on: (i) the degree to which a system is able to be self-organizing (referring to the social component of VIS represented by e.g., governance issues such as maintenance activities and monitoring systems operated by system managers/controllers), and (ii) the adaptation capacity pertaining to the physical characteristic of the system to disturbances. Therefore, in this example we pointed out the social component which is indeed part of the system, contributing to its resilience.

We also would like to clarify that throughout our paper, we do not limit the sources of disturbance to only long term pressures (e.g., climate change; urbanisation). Adaptation to the disturbances caused by these types of pressures is only one of the abilities (out of the five highlighted ones) needed for a VIS to call it a resilient system.

- Line 231: "resilience to disturbances". Change to "resilience to disturbances and trends" in order to make it consistent with figure 1, where this line refers to.

Response: The suggested change has been done accordingly, in line 181.

Chapter 4

- You state that conceptual tensions are a challenge for designing critical infrastructure. Are they really? What if in applications it is just stated what is meant by resilience, robustness etc. without claiming that the definition applied is the best for everyone? There are also many papers out there which conquered those challenges: bouncing back is often replaced by "continuing to develop similarly as before the disturbance" and in a way bouncing forward maybe seen as an advantage/opportunity instead of a challenge for design. I think you have to focus on the other type of challenges and solve part of the conceptual challenges in your framework and defintions to make the paper readable.

Response: Thank you for highlighting this important point. The authors believe that to design resilient VIS, there should be first clear definitions of the fundamental concepts related to the resilience engineering and what basically applying this concept means for infrastructures. Having a thorough literature review, we believe that this is a missing knowledge in resilience-related literature where there are many contrary definitions and debates regarding application of resilience concept for designing VIS.

Indeed, we call them as challenges that slow down the design of resilient systems, since there is no concrete agreement and straightforward method to design resilient systems in different sectors. Therefore, we identified these challenges and provided a wide range of (literature-based) contrary/similar interpretations of resilience concept to unravel them and provide a better insight for designing resilient VIS which do not need to be necessarily *case-specific* and *application-based* (referring to your question). Notably the content of section 4 is based on common definitions and different discussions in the literature and as we indicated in the paper it presents different ways of thinking and broad interpretations (e.g.., bouncing back versus bouncing forward) over the highlighted issues which we selected and described in our paper. More elaboration is excluded due to the large extent of the content in our paper.

- Line 289-301: are those relevant? The figure 3 on technical and social and ecological aspects is not convincing. Most challenges are in the centre (thus link to all three aspects). All challenges are linked to the social system. It is not clear why the distinction between the 3 aspects is made or how it is used in the remainder of the paper (it is used? Why do you mention it?)

Response: The main idea behind making this figure is that we aimed to link the section 4 with the section 3 in which we stated that resilience of VIS depends on the resilience of each sub system (component).

This figure also shows the importance of interdependent socio-ecological-technical systems for which we need to address the related challenges pertaining to the components. We believe that the figure provides a clear visual representation of such a relevance which shows that most of the challenges relate to the three system's components. The distinction between three aspects is referred to as the main conceptual framework of resilience engineering concept for VIS as described in section 3 and figure 1. The figure also provides a clear vision for readers to relate the discussed tensions and challenges to each component of VIS.

- Line 325: the "resilience goal of promoting justice". Since when is this "the resilience goal". It was not mentioned in your definitions before. How does that link to your definition of resilience? Is resilience a goal or a means? I thought the goal was to enable systems/societies to cope with shocks and trends. Social justice might help there, but that is another topic outside the scope of your paper. Resilience was never an aim in itself. In line 330 you suggest it is and also that it is narrowly defined.

  Response: As you know, the resilience concept is a very broad topic which experts in different fields of expertise state their own interpretations about the concept. In our paper, we clearly defined it in the section 3, and in the section 4 we included inputs in agreement/contradiction to our own definition. We aimed to cover many different ideas and statements to provide a comprehensive review on this extensive research topic. Therefore, the specific topic of justice and resilience which is related mostly to the social component of VIS is derived from the cited reference (similar to many other references used in this section) and does not represent our own attitude/interpretation. The following explanation at the end of the paragraph is also derived from the cited reference by which we aimed to highlight this different view as we did the same for all the challenges included in section 4. Such contrary viewpoints are indeed what we call 'tensions' in this paper.

- Resilience versus robustness: that is a matter of wording. Sometimes as by Mens who you refer to, resilience and resistance together are seen as robustness. Resistance is then referred to as the ability to prevent damage from disturbances and systems need that to cope with more frequent disturbances (otherwise they would be in a state of ar ecovery all the time). Resilience is for the more frequent event that do cause damage or disruption and is the systems ability to limit impacts/damages and recover fast. Together resilience and resistance then relate to the system's ability to cope with disturbances. Sometimes resistance is considered as part of resilience and then the word resistance can also be replaced by robustness (especially in infrastructure related literature and relates to the threshold at which damages occurs). Resistance/robustness is then the ability to prevent damage. This is not really a challenge for defining resilient infrastructures, but a matter of wording, isn't it? As long as it is considered that some disturbances must be resisted, others must be coped with by allowing little damage and fast recovery, a system will function. It does not matter which words you use for those system's ability.

  Response: We fully agree with your explanation regarding the available definitions of the words resilience and resistance/robustness. Such different interpretations are exactly what we aim to identify which we indeed believe that make the concept of resilience unclear when it relates to the infrastructure systems. We see this as a challenge that needs to be addressed by clarifying what resilience means, what robustness means and how we can relate or contradict these two words before applying the resilience concept for designing VIS. You mentioned that this can be a matter of wording, but we see this more complex than the matter of wording, as we believe that for readers, the meaning of resilience should not be misunderstood with common related words such as robustness and resistance ability, recovery, adaptation to changes, or prevention from damage, being proactive, etc. Therefore, these wide ranges of definitions need to be identified and distinguished. This clarification is crucial before designing VIS, as we aimed to do so by elaborating these words and their distinct definitions in the literature.

- Line 358: new definition of resilience. Why? Move it to the beginning of the paper and define what you mean by resilience of critical infrastructure systems. Why would you now define resilience as the adaptive capacity of a system? The discussion on definitions is described in section 3.2? How would you relate that definition to critical infrastructure systems anyway?

  Response: In response to this comment, again we would like to clarify that the content of section 4 is a collection of different interpretations and definitions derived from the literature. Here we included definitions related to the adaptability of systems versus transformability. Our aim is to unravel these issues as what we call conceptual debates and tensions in our paper. We explicitly stated our own definition of resilience in the newly structured chapter 3 (lines 310-326).

- Risk versus resilience: (line 392): how do you define risk? Risk is usually defined as a combination of probabilities and consequences, or as a combination of hazard, (exposure), and vulnerability and expressed in units like euros/per year or number of fatalities per year or expected annual damage. In your text I think you define it as probability? You state it depends on the hazard type and its magnitude and that is an exponent of resilience but it is not completely clear. In line 407 I lost track when you discuss hazard impacts and hazard risks. What do you mean by hazard impacts or hazard risks? Is that equal to risk? Why introduce a new concept then.

  Response: Addressing your comment, we added our definition of risk to clarify what we mean by the word 'risk' (line 495-498) as below:

  ''Risk is widely defined within the literature as a combination of the occurrence of a disturbance, the exposure and vulnerability of a system within different context (e.g., Ness et al., 2007; Covello and Merkhoher, 2013; Oppenheimer et al., 2014). In this article, the concept of risk is defined as probability of occurrence of a disturbance (hazard) to VIS, times the consequences (damages) to the system''.

  'resilience is a function of hazard type and its magnitude' refers to the abilities of systems that need to cope with the disturbances/shocked induced by the hazards. The more sever the hazard magnitude and resulting impacts are, the better systems need to be prepared to absorb, adapt/transform, recover, etc. In this sense, risk is related to the resilience.
  Clarifying your last point, in line 512 we replaced the word hazard 'impact' by hazard 'consequences' to make it consistent with our definition of risk. Also we removed the word hazard from 'hazard risks', and only stated 'risks' as we meant so.

- In line 411 you say embankments may result in a risk increase and then you discuss the wellknow spiral of embankment raising and economic growth. I think you should describe that more carefully. It is not the embankment which increases the risk, in fact, it reduces risk. It is the economic development. That development is in many cases a positive thing which is enabled by the reduced flood frequency.

  Response: Addressing your comment, we did a textual edit to clarify this point in line 513-518 as below:

  ''For example, investments in flood protection structures (e.g., dikes, seawalls) in vulnerable coastal areas may help to reduce risks (by reducing hazard impacts), via raising embankment heights that can reduce the flood frequency. However, protective measures may also be counterproductive since they may allude people to move and live closer to the sea, increase economic development, and thus increase potential consequences (damages) and exposure areas to flooding, which will result in increasing the risk.''

- In line 415 you state that the concept of risk changes more rapidly than climate. That sounds like a weird comparison. Rephrase.

Response: We addressed this comment by removing this comparison as below:

‘‘ …. the concept of risk that is currently accepted by people may potentially changes rapidly’’.

- Challenge g to j are clear. Challenge k must be better formulated. Since it is not easy to quantify resilience, it si more difficult to take decisions or to evaluate alternatives aiming to increase resilience. This makes decision makers more relunctant to take resilience into their decisionmaking processes.

Response: Addressing your comment, we included this point in the challenge k (now is changed to challenge - j – in the revised version) in lines 604-607 as below:

‘‘ ….. However, because of the difficulty in quantifying resilience-related metrics, decision makers face a challenge to either take decisions or to evaluate alternatives in resilience enhancement plans. Hence, they may become reluctant to take resilience into account in their decision making processes...’’.

- Line 512: raising dikes decreases the system’s resilience. Why? What do you mean?? Line 512-523 are not clear at all. Why does raising decrease resilience and why would multi-functionaliry increase resilience. Resilience to what then?

Response: This paragraph refers to the two different attitudes; one in favour, and another one against multi-functionality of infrastructures in increasing resilience of systems. The key point here is how ‘adaptability’ of VIS might be changed due to multi-functions of a systems. We included the word ‘‘may’’ in lines 616, and 619, to not state these attitudes as a verified fact, but rather as the two contrary opinions that exist. However, there are successful examples as included in the paper (e.g., MFFD) showing that multi-functionality can also increase the resilience of VIS since a multi-functional VIS may adapt to changes while providing different functions.

As mentioned in the line 616, multi-functionality may decrease resilience of a system, since it may decrease the *adaptability of the system to changes* because of difficulty of multiple functions to change in a long run (systems with higher number of functions are less likely to adapt to changes as the system should still provide similar number of functions while adapting to changes). This is in line with our presented resilience definitions, in which adaptability of infrastructures is one of the key five abilities required for a resilient VIS. Therefore, lower adaptability would lead to lower resilience.

The example of rising dikes also indicates this point that by re-building (increasing crest height) and strengthening these flood protection structures, we increase the robustness, and therefore, higher robustness would lead to lower adaptability, and resilience to flood-induced consequences (linked to the challenge b: Resilient *vs* robust systems). This has been already mentioned in the paper, challenge b.

‘‘From a different perspective, robustness (referring to resistance capacity) may not similarly be interpreted and equated with resilience. Martinez et al. (2017) point out that resistance is the ability of systems to hold a pressure without modification, while resilience is the ability of adapting to disturbances and returning to the original status.’’

- Line 525-538: long time-scales play a role when planning measures. Perhaps you should point out is therefore important to be pro-active instead of reactive?

Response: Indeed! This point has been included in the line 644-645:
‘‘Therefore, the long time-scale of resilience enhancement schemes should be considered when planning measures. Hence, being pro-active is a better strategy than being reactive.’’

- Line 562: costs are mentioned as a limitation. Perhaps move that sentence to the challenge of balancing resilience and efficiency?

Response: We do not have such a challenge entitled: ‘‘balancing resilience and efficiency’’. If you mean the long time scale and efficiency of resilience enhancement plans, we believe that the cost/benefit of the adaptive alternative/options may not be a well fit therein. So, we think this sentence might be better to be under this separate sub-section.

5. Toward resilient VIS

- Figure 4 does not explain the link at all. It just summarizes the opportunities you identified and the resilience framework and puts a line between the two. The link between them is not clear at all. Explain how the opportunities identified are linked with the 5 aspects in the framework. (the framework itself is also not explained well: I still do not understand what you mean by absorb changes, respond etc. in the context of infrastructure systems….

Response: We agree with you that the link is not shown in the figure in details. The reason is that with this figure we mainly aimed to visually show the linkage between the measures and the five abilities of a resilient system. Visualisation of each linkage to a specific ability makes the figure a bit messy and unclear as there are many measures and different systems abilities. This is why we already indicated the linkage to the certain abilities in the text as some examples are mentioned below:

- Line 711: systems thinking and its linkage to e.g., anticipating and absorbing disturbances
- Line 726: Early warning system and its role in anticipation of disturbances
- Line 750: Remote sensing technique and linkage to post-disaster functional recovery
- Line 771: Nature-based solutions and adaptive coastal ecosystems to climate change (adaptation) and for natural storm recovery of flood protections (line 785)
- Line 830: Diversification and its contribution to resilience through enhancing the recovery speed
- Line 876: Risk assessment (e.g., fault tree) and linkage with monitoring/anticipating failures
- Line 909: Cognitive approach and linkage to the fifth ability (i.e., learn from the previous failures)

With respect to the second comment, we already explained what we mean by absorb changes in the previous replies.

- the motivation of why nature based solutions are leading to more resilient systems is not clear. Do they absorb changes better, or monitor, or respond differently? Explain that in the text.

Response: This point has been already described in the text indicating that the NBS mainly increase the resilience by promoting the absorption, adaptation and recovery characteristics of the system. This has been included in the text as below:

Line 769-772: Promoting the adaptability:

‘‘Green infrastructure thus plays an important role in enhancing the resilience of the system, through for instance, limiting extreme temperatures in urban areas, or increasing the capability of the coastal communities to withstand sea level rise through adaptive coastal ecosystems (EC, 2015).’’

Line 782-785: Promoting the recovery capacity:

‘‘Such nature-based solutions may involve restoration plans of degraded ecosystem services (Sapkota et al., 2018; Mostert et al., 2018) and also enhancement of healthy ecosystem services, such as supporting the natural storm recovery potential of dunes that function as flood protection (Keijsers et al., 2015).’’

Line 789-797: Promoting the absorption, adaptation, and recovery capacities:

‘‘As an example, the “Sand-motor” mega nourishment (Stive et al., 2013; de Schipper et al., 2016), located near the most densely populated region in the Netherlands is an innovative way to promote resilience of the coastal communities to climate change-driven hazards, by not only increasing the area available for recreation and creating new opportunities for the beach tourism industry, but also by improving coastal safety in the long term due to increased dune growth. Such a solution improves the system’s ability to absorb storm events, as wider beaches dissipate more wave energy, hence reduce erosion of the dunes (natural flood defense), and support recovery of the dunes by windblown sand transport (Galiforni Silva et al., 2019). At the longer time scale it allows the flood defense system to flexibly adapt to changes in rates of sea level rise.’’

Line 799-802: Promoting the absorption, and adaptability capacities:

“Room for rivers” (Klijn et al., 2018) represents another form of “building with nature” suggesting to lower and broaden the flood plain and create river diversions, widen the conveyance channels, and provide temporary water storage area, so there would be more room for embanked river systems to absorb high discharge events.’’

Line 809-813: Promoting the absorption capacity:

‘‘Vegetated foreshore presents another example of nature-based solutions by which wave loads on coastal dikes can be reduced considerably (see Vuik et al., 2016). Such combined green and grey systems are also used to reinforce coastal protection structures while inundation occurs during storms. Within a similar approach, ecosystem engineering species (e.g., mussel and oyster beds, willow floodplains and marram grass) can also trap sediment and damp waves (Borsje et al., 2011).’’

6. Conclusions

they are interesting, but there do not deliver what the title promised

Response: We already explained the main message of this paper, and what the authors aim to cover in this study in addressing of the current gaps which are reflected in the concluded points (specifically highlighted in our responses to your 2nd and 3rd main comments.

With respect to the future research agenda, we believe that section 6 reveals where the research in this field should be heading to. For example, these directions include:

- Further assessment of the integration between socio-ecological-technical aspects of infrastructures
- Understanding the complex cascading effects of failures and disturbances among the network of infrastructures
- Development of integrated approaches (e.g., system of system) for improving resilience of the large scale VIS
- More emphasis on the recovery process in designing and decision making procedures and understanding the most significant responsible parameters to inform the success of recovery
- More emphasis on the role of regular maintenance and understanding the performance of the current infrastructure systems
- Emphasis on how to make the obtained data useful in identifying the factors that create different recovery characteristics, e g., by developing couple image-based recovery assessment with macro-economic agent-based modelling