Response to Anonymous Referee #1

Reply by the authors on 13 august 2020.

General comments:

Overall, this is a good study with a lot of detail, and it is a well-written paper. I therefore have only a few overall recommendations, as well as detailed suggestions for corrections or adjustments to the text.

We thank the referee for the careful consideration and referee work of the paper, and for the nice comments on the level of detail and writing style.

I am missing a few contextual issues: first of all, this study is looking at large scale river flooding. In many European countries, there are substantial issues with local flooding and coastal erosion, as well as flash floods damaging roads and railway lines, such as in the Alps. The paper could discuss these impacts as well, and stress the relevance of the current analysis and findings for studying these hazards and risks *[1A]*. In this context, I am also missing an integral look at costs for road owners. The study covers inundation damages, but issues like erosion, scour under bridges and impacts on secondary infrastructure seems to be omitted *[1B]*.

We will pay more attention to the context of the hazard we have investigated (large scale river flooding) in the introduction and discussion, notably on how our method could help to investigate related hazards such as local floods and flash floods. In the introduction we will clearly state on which hazard we focus. In the conclusion we have added the following recommendation on line 483: "We especially recommend the investigation of the damage caused by flash floods and rainfall-induced landslides in hilly terrain, as the flow velocities and resulting damages seem to exceed what we observed for large scale river flooding."

In relation to the 'integral look at costs for road owners', we will more clearly elaborate what we did and did not include into our damage calculations. In this study, we have primarily focused on costs for a road owner to let a contractor repair the damage to a road segment. This does include clean-up costs, asphalt and embankment repairs (also of damage resulting from erosion) and in the case of sophisticated roads, also the repair of secondary infrastructure such as electronic signaling and lighting. It however does not include damage to bridges and tunnels. This we will add to 2.3.2. The problem with bridges is that also under normal (non-flood) conditions, inundated grid cells will overlap with the infrastructure. This does not necessarily mean that there is damage to the bridge. Calculating damage to bridges (for example resulting from scour hole formation) will require a different model approach with even more detailed information about the design characteristics of the bridge objects. Therefore we decided to leave it completely out in this study.

Second, the largest losses are arguably the delays, and indirect effects caused by the disruptions. This could be discussed in the introduction *[2]*. Now the focus is heavily on the repair costs, it seems.

We agree that the largest losses could be in the delays and indirect economic effects caused by the disruptions, although these are usually not attributed to the road owner. In the introduction we will make a clear distinction between direct and indirect costs of road flooding, and emphasize that our focus is on the repair costs.

Third, roads are mentioned in this study in a rather casual way, while in fact there are many different classes of roads, with different construction and damage costs, as well as agencies responsible for their maintenance and investments. As major classes national (highways), regional roads, and local roads stand out. I would welcome some discussion in the paper (for instance in Section 2) on this in relation to 1) the data for these classes included in CORINE, LUISA, and the object-based data from OSM; *[3A]* 2) how these differences are treated in the damage modelling (different curves as described in the supplement) *[3B]*.

We agree that there are many different classes of roads, for which we accounted by distinguishing six different road classes (motorway, trunk, primary, secondary, tertiary and other roads), following the OSM conventions. Besides, we also consider different characteristics of these roads (e.g. the number of lanes, electrified or not). As such, we believe we cover a great deal in variation in possible road types. If more detailed information would become available, our method allows for incorporating that. In the method section (section 2) we will elaborate on:

1. *How well these road types are represented in CORINE and LUISA. In Corine motorways are only present when they cover more than 50% of a 100*100 m grid cell, which is not the case for normal straight motorway sections, but only incidentally at junctions (see Figure S2). This leads to an underestimation of motorways and trunk roads in CORINE. In LUISA the motorways are 'burned' into the grid, also when they cover less then 50% of a 100*100 m grid cell. This leads to an overestimation of the area of motorways and trunk roads in LUISA. In both CORINE and LUISA, all lower-level road types have no spatial reference, but some percentage of infrastructural land use is assumed in other land use classes such as residential areas. This is purely based on average occurrence of road cover in these land use classes and does not necessarily reflect the local condition.*
   We will rephrased line 126 as: "CORINE, however, overlooks most of the road network (Rosina et al., 2018), because even large motorways typically cover less than 50% of a 100x100 m grid cell, see Fig. S2." and added to line 132: "However, due to the resolution of the grid, the actual road width is overestimated in most areas (Fig. S2).
   Also we will rework lines 133-139.
2. *We will expand our description of different damage curves in section 2.3.3, with a focus how we treat motorways and trunk roads differently from the other road types.*

Fourth, and moreover, this study on damages stands in contrast to more broad vulnerability assessments approaches that have been developed over the past years. Surprisingly, no references is made to the ROADAPT project, that has done extensive work on flooding and other climate-related threats, including vulnerability modelling for highway infrastructure. This work also has had a major impact on public policy related to road infrastructure with national highway authorities. Here, in particular the vulnerability assessment in part C (Falema et al. 2014) is relevant:

https://www.cedr.eu/download/other_public_files/research_programme/call_2012/climate_change/roadapt/ROADAPT__guidelines_on_vulnerability_assessment_method.pdf

I would expect the authors to place their work in the broader context of risk assessments for roads, and how this adds/complements to methods such as ROADAPT VA. *[4]*

We thank the referee for this suggestion, we found that most national road operators in Europe are indeed familiar with ROADAPT, so that it is helpful to clarify how our study relates to it. The ROADAPT project provided guidelines for how a semi-quantitative vulnerability assessment for roads can be done. It is a description of a method/approach, rather than an actual modelling study. Therefore, our study can be seen as new step in this field: we move beyond describing how it can be done and provide an actual tool and quantitative results for the European continent. Also, we calculate actual damages rather than just mapping vulnerability factors.

In the introduction, we replaced the reference to the study of Bubeck (which referred to railway and was a source of confusion, see comment 22) in line 71-73 with: "This meets the need of European road operators for GIS-aided vulnerability assessments, for which guidelines have been provided in the ROADAPT project (Bles et al., 2016) but actual modelling has focussed on small spatial scales (e.g. Hackl et al., 2018)."

We referred to Bles et al. rather than Falema et al., because the Bles study is reviewed and gives a good overview of the entire ROADAPT project.

Finally, I really appreciate the large image at the end of the Supplement with exposed road segments. However, it would be even better (also in the context of the EU funding of the work) if the authors would make this and other data available digitally in a repository. *[5]* I would urge the authors to include a section on data and code availability. *[6]*

We will make the image at the end of the supplement available as a shapefile. We will include a section with data and code availability, including:

- *The shapefile with the model results*
- *A reference to the model code on GitHub*
- *A statement that the high-level model results (including tertiary and other road types – i.e. beyond the level of detail included in the shapefile) can be obtained for individual NUTS-3 regions upon reasonable request*

Below, I provide several further questions and textual suggestions, which I hope are useful for improving the manuscript.

Specific comments:

Page 1, Line 24: please replace "risk adaptation" either by "risk reduction" or "adaptation". *[7]*

We will replace it by "risk reduction".

Page 1, Lines 31-32: Please explain why it is an important issue, also keeping in mind my general remarks, above. *[8]*

Besides the reason we gave directly following these lines (the significant contribution of road infrastructure to direct damage), we will elaborate on the traffic and trade disruptions, as well as the indirect economic damage resulting from road disruptions. We hope this also reflects your general comment on delays and indirect effects [2]. "At the same time, transport disruptions are an important source of indirect economic effects through passenger and cargo delay costs, which may exceed the direct costs (Pregnolato et al., 2017). Furthermore, the accessibility of the road network during flood events is of crucial importance to evacuations and therefore in avoiding casualties (Sohn, 2006). Vehicle-related drowning is the most frequent cause of death during flood disasters (Jonkman and Kelman, 2005)."

Page 2, Line 37-42: It is unclear here what the implication is. In principle, when surface area is correctly accounted for, a grid of 100x100 meter could contain accurate information on the share and characteristics of line-shaped infrastructure. In general, infrastructure damage is often overestimated in course grids, but this is rather due to the overestimation flood water depth and extent at the location of the infrastructure, which is often located at higher grounds. Please provide a more detailed discussion of the issues here, as now it is unclear what you mean *[9]*.

This indeed is an important point. In the manuscript, we will add the following sentence: 'As these percentages are often applied uniformly among the same land-use type, this may result in an overestimation of infrastructure damage when there is in reality no infrastructure, but an underestimation if the infrastructure is there but not enough to be the dominant land-use type'.

*We agree that, in theory, all the object-based information could be attributed to rasters, by either (1) having a unique mix of underlying land use types per raster cell (the data of which would need to be stored in something like a multidimensional raster) or (2) working with a high resolution raster like 5*5 m. However, in practice, such high-resolution rasters are not available on the continental scale. Moreover, for the assessment of road networks, arguably the traffic delays and indirect economic impacts from network disruptions are at least as interesting and important as the direct damages. For indirect assessments, road networks need to be described in network graphs, which can only be done from an object-based approach. Therefore, we think it is also preferable to take an object-based approach to the assessment of direct damage, so that both can be studied in a coherent way. Moreover, we can now make benefit of the object-specific metadata such as road type, street lighting, electric signaling, number of lanes, etc. Of course, all this information can be rasterized as well, but that would take away the computational advantage of the rasterized approach, so one could as well directly take an object-based approach, in which all the book-keeping is done on the level of road objects rather than on the level of individual grid cells. For an interpretation of a raster-based study, the road owner will need to compare the raster with an (object-based) map of the road network, so we prefer to directly assign all the flood information to the road objects.*

We correct for the overestimation of the flood water depth by assuming that motorways and trunk roads are elevated with respect to the inundation grid (represented by a concave section in the damage curve), we have expanded the description of this in 2.3.3 (also see your comment 3B).

Page 2, Lines 53-54: This sentence should be rewritten. What I think is meant here, is not the gridded damage model, but the gridded exposure data, which is only one component. This should be made clear here, and also in other places, as the distinction does not go further (as far as I can assess). And then still, in many of the available models, objects are transferred to grids, to simplify computation, which performs equally well as vector-based computations. So what is probably meant here, is vector information on exposed infrastructure versus remote sensing or other gridded data on infrastructure, and their detail or accuracy. *[10]*

*We have rephrased the first sentence of the paragraph as: 'justified by incomplete object-based <u>exposure</u> datasets'. What we mean with an object-based approach is an approach where the inundation, damage, and risk **bookkeeping** is done for individual road assets, rather than for raster cells. So rather than storing all the metadata of the objects in a grid (which indeed is possible but cumbersome when many different attributes are used, such as we do, see our previous reply), we attribute the flood depth from the inundation grid as an additional attribute to the vectorized road object, and then do the damage calculations for all road objects. We think we have given three valid arguments in the paragraph (and in the previous comment) as to why we prefer the object-based approach over a grid-based approach when it comes to the assessment of road networks.*

Page 3, Lines 85-87: Please explain that flood risk here means: large scale river flooding only. *[11]*

We rephrased as: "Hazard data are taken from the Joint Research Centre's inundation maps of large scale river floods in Europe"

Page 4, Line 126: Maybe you can briefly add why this is overlooked. Is this because the roads are not resolved or sufficiently classified as roads from remote sensing data, or because in the production of CORINE such information from member states is not included? *[12]*

*We will add: "because even large motorways typically cover less than 50% of a 100*100 m grid cell, and the land cover of the entire grid cell is attributed to the dominant land use type, see Fig. S2."*

*In general, the road width of any type of road is well below 50 m, so from remote sensing data the roads are not distinguished on a 100*100 m grid cell. In most cells, even those containing large motorways, will be dominantly covered with other land use types (such as 'grass land'), and are therefore not identified in CORINE. There are a few exceptions to this, such as the case of large motorway junctions; Figure S2 shows that the Deggendorf junction is the one of the few parts of the motorway network that can be clearly recognized in CORINE.*

For road types other than motorways and trunks, there existence is implied by assuming some percentage of infrastructural land use in other land use types such as urban fabric. These however are fixed percentages for entire Europe, and therefore there is no guarantee that they refer to some existing road, at least there is not explicit spatial reference to existing road objects. We will further explain this in our next comment.

Page 5, Lines 133-136: This sentence is unclear to me: who has assumed these percentages? The producers of the CORINE dataset, or you? I would imagine, based on Tables S1 and S2 these are intrinsic to the data, but please explain this to the reader. *[13]*

This assumption is used in many flood risk studies, and follows from Huizinga's (2007, p. 2-22) suggestion to map the damage functions to CORINE using a land cover cross-tabulation from the EEA (2006). So they are not intrinsic to the flood hazard or exposure data, but to Huizinga's vulnerability functions. We will elaborate on this point at this place in the text.

We rephrased as:

"To correct for the underrepresentation of infrastructural land use (and other land use types) in CORINE, for each land use class some percentage of infrastructure is assumed (Table S1, S2). This follows from Huizinga's suggestion (2007, p. 2-22) to map his damage functions to CORINE using a cross-tabulation by the EEA (2006), which became their default implementation method. To enable a comparison with the object-based approach, we maintained the percentage of infrastructure per land cover class, whereas the contributions of the other damage curves were ignored (Table S1, 2). An implication of these percentages is that, although motorways and trunk are mostly missing in CORINE, damage for (local) roads in urban and industrial areas (amongst others) is still calculated, albeit without any explicit spatial reference to the actual road position, but based on their average presence in these urban and industrial land use types. Also, note that in the land cover category 'road and rail networks and associated land', a uniform share of 27% infrastructural land use is assumed, which to some extent corrects the overestimation of the actual road widths in LUISA.".

These apparently well-chosen percentages could explain why (when aggregated on the EU-scale: Fig 4), the order of magnitude of the results of LUISA are comparable with the results of the object-based approach, also see comment 35 of referee 2.

We will also add this clarification to the tables S1 and S2 in the SI.

Page 5, Lines 155-156: But the study by Dottori et al. (2020) refers to the study by Ward et al. (2017, in Nature Climate Change) where e.g. the 100-year protection level associated with the corresponding water level is assumed. However, where does the data on current protection levels per country or river segment comes from, as stated in these lines? That is not clear to me. *[14]*

Dottori et al. (2020) developed a new dataset of flood protection standards for Europe. The dataset integrates the available information on design standards of flood protection (e.g. through technical reports) with modelled protection standards calculated by Jongman et al. (2014) and Scussolini et al. (2016), selected according to observed and simulated historical flood loss data. The text has been revised accordingly to clarify this point.

Revised text (to replace lines 155-157)" Flood protection data is derived from the dataset developed by Dottori et al. (2020). The dataset integrates the available information on design standards of flood protection (e.g. through technical reports) with modelled protection standards calculated by Jongman et al. (2014) and Scussolini et al. (2016). Modelled data is selected according to observed and simulated historical flood loss data."

Page 5, Footnote: Guadeloupe seems to be misspelled. *[15]*

This will be corrected in the manuscript.

Page 6, Figure: What does the cm indicate in the main model panel? Are these inundation depths? But these vary across the sections, correct? I assume that per flooded grid cell, the length of road is exposed to a single inundation value over that length; perhaps this can be explained in the text. Now it seems as if some average is used, which would not work with non-linear damage functions. Also, I think what is called “metadata” in the figure are actually attributes of the vector files. Attributes is a common term in GIS, and I would propose to use this instead. *[16]*

Indeed, the numbers with the unit ‘cm’ indicate inundation depths, we will add a label to clarify this. Indeed, these may vary across the sections. Per road segment, we summarized the inundation data with ‘inundated length and average depth over the inundated part of the segment’ (line 153). Since the OSM road segments are typically short, and the hazard data is relatively coarse, we assumed this is a fair approximation. We will alter the manuscript on two points:

1. *The figure is (falsely) suggesting that each road only exists of one road segment, whereas in OSM, multiple shorter road segments (linestrings) might have been used to described one road stretch. We will update the figure to clarify this.*
2. *The referee is right that this assumption may have an impact on the results, but mainly when the hazard data has a higher resolution. Therefore, we will add this as a suggestion for further research in the conclusion (line 487-493). Currently, roads are inundated by only a few grid cells, with limited variation in inundation depth. We expect that the uncertainty introduced here is well below the uncertainty that is already incorporated in the damage calculations, which are much more sensitive parameters.*

Page 7, Table 1: For Footnote A, I would also expect an adjustment for the Huizinga exposed values from m2 to road length, so accounting for both width and length, and only length is mentioned here. *[17]*

We assume the referee means: ‘only width is mentioned here’, because that is what the footnote reads. The table heading indicates that the table values represent ‘(…) euro per km’, so the required outcome unit is euro per unit of road length [€/km]. The Huizinga max damage costs are expressed in [€/m^2], so to arrive at [€/km] we only need to multiply by width [m] (and a factor 1000 to convert *from m to km [-]). Multiplication by the length of the inundated part of the road segment is done in the model, but should not be done is this table, because this shows the costs per unit of road length.*

To clarify we will add the units to the column headings.

Page 7, Lines 202-2011: It would be good to have a discussion at this point about what kind of costs are included in the function. Are these repair costs, or also clean-up and other costs? Also, which repairs are estimated, only from the road surface or also other including erosion and adjacent infrastructure? Here, flow velocity also becomes an important point, in relation to what is said about the high and low estimates, on Pages 7 and 8 (Lines 212-223). *[18]*

Thank you for pointing out that this was not described clearly in the manuscript.

In line with your comments [1B] we added the following clarification: "The damage curves cover what it would cost the road operator to have the road cleaned and repaired by a contractor. It includes clean-up costs, resurfacing of top and deeper asphalt layers as well as road embankment repairs, and where applicable also the repair of electronic signalling and lighting. It does not include structural damage to bridges and tunnels, nor emergency response costs such as the placement of sand bags or signposting of diversions." Does this cover all potential sources of confusion?

Page 12, Figure 5: What I would like to see is which NUTS areas have a high flood risk; that is, in which locations do you see many damages at low return periods. At the moment, it is not clear in this overall risk graph, which locations suffer from frequent small losses (e.g. Austria and Germany), and which locations have a very high loss only for very rare events (e.g. Netherlands, Belgium etc.). One additional figure at a well-chosen return period (e.g. 20 or 50 years), or a bar chart per country with losses per return period, would help in this regard *[19]*.

We will add a bar chart per country with losses per return period in the SI. Below is one example, for France. White bars indicate floods with a return period smaller than the flood protection in place, meaning that these damages will not be included in the risk calculation as shown in Figure S1.

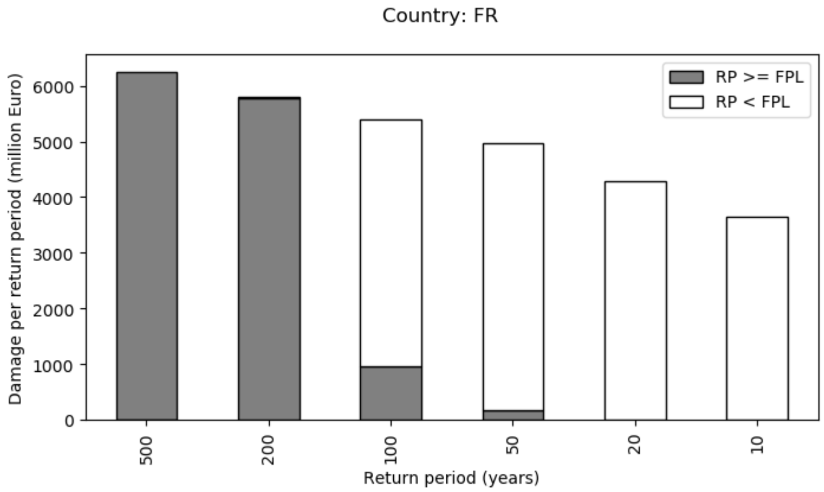

Figure S8 Damage per return period per country
White bars indicate floods with a return period smaller than the flood protection in place, meaning that these damages will not contribute to the risk (as shown in Figure S1).

Pages 14-15, Lines 381-409: I find the validation case not convincing. As you state, it cannot be expected that the Bavarian government had costs of only 3.8 million, as it is unlikely that the EU funded the repair costs in full. Until you have a good handle on the actual costs, you cannot really validate this case, and the conclusion that your model overestimates is not so well-supported. Are there not any better numbers on this case? Perhaps an additional sentence here would be useful *[20]*.

We understand the reviewer's reservations regarding the 'validation' case. We have spent a lot of time on trying to find better validation cases, but without success. In general, road operators seem not to report costs for road reports separately from regular maintenance costs, so that good validation data is very scarce (line 44-45). We have requested the Bavarian State Authority to provide more data on the case, but did not receive further response. In the conclusion we have emphasized the need for more systematic inventory of river flood road damage data: "Currently, very little road flood damage case studies are described in the literature, collection of such data by road operators and academia should be a research priority because the absence of damage data hampers the validation of the models."

We agree that the case study does not provide a decisive answer to the question whether our model estimates the right cost. However, at least it helps to get a feeling about the order of magnitude of the damage. We suggest to reframe the description of the case as a 'reference case' rather than a validation case, and present it as such in the article. Would the referee welcome this alteration?

We will nuance the statement that our model is overestimating the costs.

Page 16, Lines 456-457: But you do not know the actual total costs; so I suggest to replace with "the estimated size of total damage costs for the validation event" *[21]*.

We thank the reviewer for this suggestion, we rephrased the text accordingly.