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.

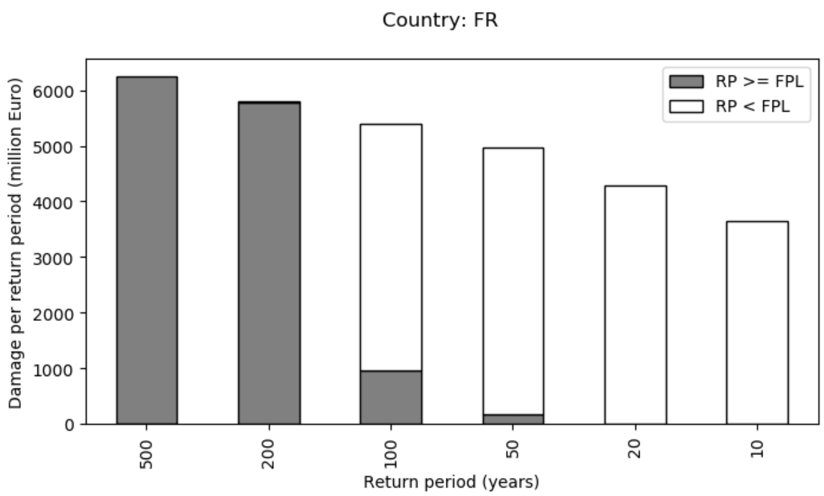

Figure S8 Damage per return period per country
White bars indicate floods with a return period smaller than the flood protection in place, meaning that these damages will not contribute to the risk (as shown in Figure S1).

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.

Response to Anonymous Referee #2

Reply by the authors on 13 august 2020.

The paper shows a methodology to calculate direct flood risk for roads on the basis of developed damage curves. This is a relevant topic and the methodology that is presented in the paper provides very useful information and contributes to advance risk knowledge particularly in the European context.

We thank the referee for the in-depth review work and for the nice comments on usefulness of the methodology and results.

My comments are as follows:

The paper indicates that a new object-based approach and new damage curves are proposed. However, I recommend to clarify what the novel contributions are *[22]*, since object-based approaches have been used before (e.g. Hackl et al, 2017). In paragraph 65 it is mentioned that Koks et al. (2019) used OMS data for a global multihazard analysis but that several assumptions were made due to data scarce regions of the world, but in the European context data is more complete and a more detailed analysis can be carried out. Does this mean that the approach in the paper is the same as in Koks et al. (2019) but with more detail?. What are the differences with the approach in Koks et al. (2019) *[22A]*? What are the differences with the approach in Bubeck et al. (2019) *[22B]*?

The novel contributions of our study are as follows:

- *Indeed, the computational core of the model is similar as what was used by Koks et al. (2019). However, we have developed new vulnerability curves (which were very stylized in Koks' study) and did an extensive literature review on road reconstruction and damage costs to support these. Also, we use road metadata/attributes on the road type, number of lanes, presence of bridges and street lighting to improve the damage estimate, which was not done in Koks study. Finally, we make an extensive comparison to grid-based approaches using the same hazard data, to gain an understanding about the differences between both approaches. Also, we present our results with high spatial detail, rather than aggregated per country. All these elements are new.*
- *The spatial extent of our study is much broader than for example the work of Hackl et al., which had a study area of 20*20 km, whereas we cover entire Europe. We will make a reference to this in the introduction.*
- *Bubeck studies the railway network, whereas we study the road network which contains much more elements and is more diverse in terms of road types.*

In the introduction, we will more clearly indicate the above novelties.

The paper will gain clarity if a clear differentiation between direct and indirect damage is established *[23]*. This will set the context to clarify the difference between an approach that analyses the physical damage to the road and one that provides a network analysis.

We thank the referee for pointing this out, because one of the largest benefits of taking an object-approach for direct damage, is that the same objects can be used to construct a network on which an analysis of indirect damage can be done. Hence, the object-based approaches enables the study of direct and indirect damage in a coherent way.

In the last lines of the first paragraph of the introduction, we will explicitly make the distinction between direct and indirect damage and indicate that the remainder of the paper will focus on improving the estimates of the direct, physical damage. In the conclusion, we readdress this issue when we illustrate the potential of the object-based approach for studying indirect damage as well.

The main objective of the paper, as stated in line 65 is to compare the results and performance of an object-based approach to the more traditional grid-based approaches. It seems to me that such comparison is problematic. Results and performance of a grid-based approach depend on scale. If the grid is too coarse results will be coarse and then limited to, for example, strategic decisions in flood risk management. If the scale is detailed the performance should be better and the decisions informed by a more detailed flood risk assessment, therefore, will be more local. Object-based approaches are intended for detailed assessment, therefore they should provide a better level of information than e.g. mesoscale analysis. I recommend to clarify in the paper the differences in scale of the methods and how they can be compared *[24A]*. For example, what is the purpose of the continental-scale analysis (what decisions can be informed? It is for hotspot identification? are hotpots better identified by the object-based approach?) is this purpose better fulfilled by the object-based approach? *[24B]*. According to the explanation on section 2.2 and figure S2 it is clear that Corine 2012 and LUISA 2018 have a coarse resolution (100 m) then it is impossible that an object with only several meters of width can be appropriately represented by this information, besides Corine 2012 even lacks the representation of the roads in some cases. Then, I recommend to elaborate the discussion on the limitations of this data sets and their purpose *[24C]*.

In line with what was also suggested by referee 1 [comment 3A], we will expand our description of how roads are represented in the grid-based based methods with CORINE and LUISA, and what the implications for our comparison are [24A, 24C].

We can partly understand the referees objections against comparing the object-based and grid-based approaches, because there are indeed large differences between both methods in terms of scale and intended purpose. However, we reasoned that these differences instead would be an interesting starting point for a comparison of the 'new' continental-scale object-based approach, to investigate if it made a significant difference on the model results. Actually, rather than interpreting our results as a 'criticism' of the grid-based approach, one could also see it is as rather strong confirmation of the validity of the grid-based approach, because we show that LUISA with the Huizinga damage curves can give reasonable estimates of the order-of-magnitude of the continental-wide damage, [as you also point out in comment 34].

There are also arguments pleading for a comparison between the both approaches. Both aim at gaining continental-scale estimates of the damage to road infrastructure. Despite the limitations of the grid-based approach, it used to support EU-scale policies (possibly even beyond the original intentions of the academia developing these models). We think the object-based approach better fulfills this purpose, because the results are directly presented at the level of road segments which more directly meets the needs of road owner or operator. Therefore, we think it is useful to compare the 'new' approach to the more common approach of assessing flood risk at the continental scale.

*We do not agree that object-based approaches are necessarily more suitable for high-resolution approaches while grid-based approaches are more suitable for low-resolution approaches. Firstly, because there are also examples of very high-resolution studies using grid-based approaches, for which it can be questioned if an object-based approach would add value. Secondly, because we show how an object-based approach can be used with a rather coarse (100*100 m) continental scale inundation model, which can help to identify flood hotspots on the continental level.*

With regard to [24B], indeed the purpose of hotspot identification indeed is better fulfilled by the object-based approach, because:

- *We have more detailed information about the location of the road (because as we earlier argued, the precise location of the road cannot be easily captured in the rasterized grid)*
- *We have more detailed information about the characteristics of the road (so we can distinguish a major highway in the European E-road network from a local motorway), which is not directly clear from a mere land use raster*
- *Because the road objects can also be studied as a network graph, the object-based approach cannot only identify flood hotspots in terms of direct damage, but also in terms of indirect damage. Arguably, this indirect perspective is very important for the EU-policy maker or road owner. After all, a road flood hotspot is not a spot with only large damage, but also with high criticality for overall network performance.*

Line 91 mentions the Huizinga infrastructure damage curves. However, no introduction of the Huizinga et al. (2017) reference is made. Since these curves are very important in the paper, consider including an introduction of these and why you chose those curves before they are mentioned in line 91 *[25]*.

We thank the referee for the insight that we introduce the Huizinga curves too late in the manuscript, whereas they are indeed important for the comparison in the paper. Therefore, in the updated manuscript, we will already introduce them in the introduction. With regard to the question why we choose the Huizinga curves the answer is simple: this is the most comprehensive set of damage curves available for Europe, and are therefore used in virtually all continental-scale studies (for examples see the enumeration in the old section 2.3.4), making them a fitting benchmark for our new curves.

Line 109 indicates that flood hazard is represented with a set of inundation maps taken from Alfieri et al. (2015), with a recent update by Dottori et al. (2020) which cover most of the European domain at a grid resolution of 100 m. The scale of the hazard maps could be considered coarse. Consider including in the paper a discussion about the impacts of the scale of the hazard maps particularly when using the object-based approach *[26]*. Are the scales commensurated?

*For continental-scale hazard modelling, a 100m*100m arguably is state-of-the-art, because comparable models (such as GLOFRIS) operate on a 1*1 km scale. The highest resolution currently available is from the Fathom model (90*90 m), Sampson et al., 2015. But we fully agree that on a lower spatial scale, much higher resolution hazard models are available, and that it would be very interesting to test the performance of the object-based models for these models. With the very high exposure data of OSM, the resolution of the hazard data on this scale indeed is currently the bottleneck in the modelling, and in that sense the scales in our models are not fully commensurated because an improvement can be made on the hazard-side now. This we already discussed in the second-last paragraph of the conclusion, in a recommendation which we will rephrase as: "The flood hazard data can be easily substituted with (small-scale) high-resolution data, to fully exploit the level of detail offered by the OSM exposure dataset. Moreover, more local scale case studies are required to validate the proposed damage curves."*

Sampson, C. C., Smith, A. M., Bates, P. D., Neal, J. C., Alfieri, L., & Freer, J. E. (2015). A high-resolution global flood hazard model. Water Resources Research, 51(9), 7358–7381. https://doi.org/10.1002/2015WR016954

Paragraph starting at line 133. Please refer to the appropriate table at the beginning of the paragraph otherwise it is difficult to understand from where the percentage of 27% is obtained. How were these percentages obtained by Blending of Huizinga (2007)? and why damage was calculated to the percentage of infrastructure in each land use class? Could it be any type of infrastructure? *[27]*

We will make reference to the table in the beginning of the paragraph. The use of the percentages "originates from Huizinga's suggestion to map the damage functions to CORINE using a land cover cross-tabulation from the EEA)" (section 3.1).

We rewrote the entire paragraph 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 S1,2). 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.".

Huizinga (2007) mentions that the curve is explicit for roads, although in practice, many studies also use them in other land use categories such as airports and railways where the curve seems to cover a share of the runways, railways etc., besides the roads that it represents in these land use categories. But the curve is intended for roads, which enables a fair comparison.

Line 148 implies that the approach in the paper was proposed by Koks et al. 2019 and that the difference with the method in the paper is the use of damage curves tailored to the European context and uses additional metadata. I recommend that this is clearly stated, particularly in the introduction and the conclusions *[28]*.

This point was also raised in comment [22]. We will stress the novelty of our approach in the introduction and conclusion as elaborated under [22].

Line 205 states that only flow depth will be used for the damage curves. However, velocity is indeed considered at least to develop two groups of curves. I recommend to review the way in which the parameters to be considered are presented *[29A]*, because it is confusing that velocity appears afterwards in the analysis. Furthermore, what consideration should be given to duration *[29B]*? Is this factor important in damage? Should it be considered somehow?

We thank the reviewer for this suggestion, the original order in which we present the parameters are presented is indeed confusing. We removed '… an approach also adopted in this study' (lines 205-206) and rewrote and restructured section 2.2 as follows.

"In general, damage curves derive flood damage from flood parameters such as water depth and flow velocity. Continental-scale models typically work with functions relating damage to water depth only (Alfieri et al., 2016a; de Moel et al., 2015; Winsemius et al., 2013). Flow velocity, however, is at least as important as water depth for explaining damage to roads (Kreibich et al., 2009; Merz et al., 2010;

Thieken et al., 2009). Under low flow velocities (< 0.2 m/s), there is hardly any structural damage to pavements, whereas under high flow velocities (> 2.0 m/s) there is most likely severe structural damage (Kreibich et al., 2009). Indeed, pictures of floods in Europe show that under very quiet flow conditions, a road can remain almost undamaged whereas under flash floods with strong currents, complete reconstruction may be required. The flood hazard maps used in this study represent floods in rivers with an upstream area >500 km^2 whereas large flow velocities are typically found in smaller water courses in steep upstream areas and locally close to dike-break locations (De Moel et al., 2009). Therefore, we assume that the predicted floods have relatively low flow velocities. We deal with the remaining uncertainty by estimating two depth-damage curves that span the uncertainty of this typical slow flow velocity; one for the low-flow estimate and one for high-flow estimate that can be reasonably expected for large river floods."

Kreibich et al. (2009) show that structural damage of road infrastructure is best explained from flow velocity/flow force and an 'intensity' indicator which is a combination of water depth and flow velocity, so we removed the reference to 'duration of the flood' (since it distracts from the narrative).

Line 217 mentions for the first time in the paper a Lisflood model. It is very unclear what was Lisflood used for. In the previous sections the source of the flood hazards is explained without any mention to Lisflood and in the methodology the use of Lisflood is not explained. I recommend to complement the methodology section explaining the use of Lisflood, what type of model was developed, what area was modeled and what information was used for the model *[30]*.

We apologize for the confusion generated here. We reformulated this sentence (lines 217-220) as well as a paragraph in lines 465-468 to better explain our reasoning. Furthermore, we now explain in Section 2.1 that the flood hazard maps used in this work were calculated with the hydrodynamic model LISFLOOD-FP, while the hydrological input was calculated by the hydrological model LISFLOOD. Alfieri et al (2014) described the complete procedure including a general description of LISFLOOD and LISFLOOD-FP, and how they were applied. Since in the present work the maps were not modified, we opted to make reference to the original papers, rather than providing again a description.

Line 220 indicates that it was assumed that the predicted floods have relatively low flow velocities. Please elaborate your explanation here *[31]*: Your study area does not cover any area where flash floods occur?, how did you carry out that identification?

Our study area covers entire Europe. In Europe flashfloods do occur. However, our study is focusing on the large scale river floods occurring in Europe. River floods typically originate from much larger catchments than flashfloods, and also have much larger timescales (inundation takes days rather than hours). The hazard maps only includes floods originating from catchments large than <500 km^2, and therefore simulate river floods rather than flash floods. Large scale river floods typically have lower flow velocities than flashfloods.

We rephrased this in the section where we also addressed the comment on flow velocity, see comment [29].

Line 225 explains that an overview of the damage curves and supporting narratives can be seen in the supplemental document. In that document, there are figures of the damage curves with a description (narrative). However, it remains unclear how the curves were constructed. Commonly, damage curves are constructed from damage data, structural models or expert judgement. What method was used here *[32]*? In case, the method is expert judgement, an explanation of procedure, experts, validation should be given.

The damage curves were constructed by comparison of the costs of road construction and repairs (as tabulated in the SI) with the repair activities required after floods of different intensities. So they are initially based on a combination of expert judgment and actual road (re)construction data. The narratives and resulting curves were discussed with flood risk and transport modelling experts and discussed with the Dutch road operator.

We will add to 2.3.3 "To construct the curves, we compiled an overview of road construction, maintenance and repair costs. These costs were compared to the road repairs needed following a river flood, derived from literature and photo imagery of river floods in Europe. The damage narratives and resulting curves were validated during an expert workshop with flood risk and transport modelling experts and with the Dutch road operator, see acknowledgements."

Line 266 mentions the use of a model is it the Lisflood model? *[33]*

Indeed, the hazard maps originate from the Lisflood and Lisflood-FP model as discussed under [30]. Here, this is of minor importance for our argument, so we will rephrase as: "We masked the 1:10 year flood hazard map (which better resembled the reported inundation than the 1:100 year flood map) over the extent of the observed inundation and calculated the damage using the object-based model."

Section 3.1 emphasizes the need of a more in depth discussion about the suitability of the comparison. Again, the question arises about what the percentage of infrastructure refers to in the CORINE and LUISA data. *[34]*

Please see our reply to comment [27]: "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 S1,2). 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.".

Figure 4. The value of the LUISA flood risk is the upper limit of the interquartile range. I believe that this result should be discussed, considering the uncertainty is LUISA less useful? In terms of hotspots is LUISA providing significantly different results? *[35]*

We were also surprised by this result, so we also think it is interesting and worth discussing. We will add to line 420: "indicating that using LUISA, a fair proxy of the total damage to road infrastructure can be obtained". The LUISA results cannot be easily visualized in a way that allows for hotspot identification for systematic comparison to our object-based approach. In general, one would always need a map of road network to compare the rasters to, for identification of flood hotspots.

Line 328. From this line on, the results refer to the object-based approach? Please clarify. *[36]*

As the caption above this subsection indicates, all results in this section refer to the object-based approach combined with the new damage curves (unless where otherwise stated, for comparison *purposes). We will rephrase line 238: "Figure 5 shows how the risk (deterministic estimate) is geographically spread over Europe." which refers back to the earlier mentioned deterministic estimate of the object-based approach with the new damage curves.*

Line 425 states that the Huizinga infrastructure function is a fair proxy for the average damage to road assets but is unsuitable for assessing damage at the individual road level. Is this to be expected? Are the Huizinga functions intended for damage at the individual road level? Here scale issues may have a role. *[37]*

This could indeed be what one expects from the original purpose of the Huizinga's damage function, which was developed for the JRC's inundation model combined with the CORINE land cover classification. It nevertheless is an interesting insight, because we have shown that the CORINE – infrastructure combination has several pitfalls (such as attributing infra damage to the wrong land use types). Moreover, CORINE is now complemented by LUISA, which is constructed in a fundamentally different way (with vector-based information data added to the grid, rather than just remote-sensed data). Also, many have used Huizinga's damage functions on scale levels beyond the original use, for example Jongman et al., 2012. Jongman suggested that the infrastructure function highly underestimated the damage, an observation that we have questioned on the basis of the results of our study. So although some might think that this is what was to be expected from Huizinga's curves, other's might have held a different view.

Direct flood risk assessment of the European road network: an object-based approach

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Abstract

River floods pose a significant threat to road transport infrastructure in Europe. This study presents a high-resolution object-based continental-scale assessment of direct flood risk ~~of~~ of the European road network for the present climate, using high-resolution exposure data from OpenStreetMap. A new set of road-specific damage functions is developed ~~and validated for an observed flood event~~. ~~We estimate the~~The median ~~annual~~ expected annual direct damage from large river floods to road infrastructure in Europe is ~~at~~ 250 million euro per year. Compared to grid-based approaches, the object-based approach is more precise and provides more action perspective for road owners, because it calculates damage directly for individual road segments, while accounting for segment-specific attributes. This enabled the identification of European hotspots, such as the Alps and roads along the Sava River. ~~A comparison with grid-based approaches suggests that these methods likely may overestimate direct flood damage to road infrastructure and might allocate infrastructural damage to the wrong land use classes.~~ A first ~~validation~~ comparison to a reference case shows that ~~our~~ the new object-based method computes realistic damage estimates, paving the way for targeted risk ~~adaptation~~ reduction strategies.

Commented [KvG1]: Comment [20]

Commented [KvG2]: Comment [7]

1 Introduction

River flooding is among the most damaging natural hazards in Europe. Following disruptive and costly European floods in the year 2000 and between 2009 and 2014, significant advances in continental (and global) scale flood risk modelling have been made (Dankers and Feyen, 2008; Hirabayashi et al., 2013; Kundzewicz et al., 2017; Ward et al., 2013). Although these models ~~give~~ provide good estimates of total damage to all land use types, they do not accurately represent damage to transport infrastructure (Jongman et al., 2012, Bubeck et al., 2019~~, Koks et al. 2019~~). Flood damage to road infrastructure is still an underexplored, yet important issue (Doll et al., 2014; Merz et al., 2010, Koks et al. 2019). Previous studies have shown that transport infrastructure significantly contributes to direct tangible flood losses, usually in the order of 5-10% but in exceptional cases up to 50-60% (Bubeck et al., 2019; Jongman et al., 2012). 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). This study focusses on improving the estimates of direct physical damage to road infrastructure, but also paves the way for assessment of indirect effects.

Existing continental-scale river flood risk studies do not accurately represent damage to road networks for several reasons. First, these studies are typically grid-based. Damage in a grid cell is determined using a depth-damage curve based on the land use and flood depth in each grid cell. In these grid-based approaches, infrastructure damage is typically determined using the (potential) percentage of infrastructural land use in a cell. However, transport network infrastructure such as roads and railways are (relative narrow) line elements and take up only a small percentage within a typical grid size for continental-scale modelling~~,~~ (e.g. 100~~ ~~*~~ ~~100 m^2 in Europe). As these (assumed) percentages are often applied uniformly among the same land-use type, this may result in an overestimation of infrastructure damage when there in reality is no infrastructure, but an underestimation if the infrastructure is there but not enough to be the dominant land-use type. Second, little progress has been made in research on transport-specific damage functions (Hackl et al., 2016). One reason is that damage to road infrastructure does not contribute much to the overall flood damage. Also, there is limited reported data on road damage from flooding. Many studies have pointed out that research on flood vulnerability is underdeveloped (Dottori et al., 2018a), with high associated uncertainty (de Moel and Aerts, 2011) stressing the need for improved vulnerability methods (Winsemius et al., 2013), especially for infrastructure (Jongman et al., 2012).~~.~~ To date, virtually all European-wide flood risk studies (Bouwer et al., 2018, Dottori et al., 2020, Lincke et al., 2019) still rely on the comprehensive set of damage curves proposed by Huizinga (2007), which were developed for (coarse) grid-based assessments, but lack detail for accurate assessment of damage to road networks (Jongman et al., 2012).

Previously, the grid-based approach could be justified by incomplete object-based exposure datasets, and insufficient computational power for a more detailed approach. Object-based transport infrastructure datasets such as OpenStreetMap are now nearly complete (Barrington-Leigh and Millard-Ball, 2017), and computational power is no longer a limiting factor, allowing for high-resolution damage modelling approaches (Koks et al. 2019). Object-based damage models have

Commented [KvG3]: Comment [2,23]

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substantial benefits compared to grid-based approaches. First, the geometric representations have a higher resolution, allowing for more accurate intersects between the exposed roads and the hazard data. Second, object-specific ~~metadata~~ attributes can be used to make more accurate damage estimates (Merz et al., 2010). For example, for an intersect between the road network and an inundation map, it is crucial to differentiate an inundated road from a bridge over the water. The ~~metadata~~ attributes also enable~~s~~ the development of different damage curves for different road types (e.g. motorway or rural road), which may have very different characteristics (e.g. number of lanes, width, quality and maintenance standards). Third, the network properties of roads, enabling graph representations, can be maintained in an object-based approach (Gil and Steinbach, 2008). This enables the study of direct infrastructural flood damage in coherence with other sources of impacts, such as travel delay times from road closures and detours, as well as indirect economic losses from passenger or freight delays.

Commented [KvG9]: Comment [16]

Commented [KvG10]: Comment [16]

Koks et al. (2019) proposed a method to study the impacts of climate hazards to road (and rail) infrastructure on the global scale, using data from OSM ~~and taking advantage of parallel processing techniques~~. The analysis in this global, multi-hazard study used highly stylized damage functions and had to take several assumptions due to information gaps in data-scarce parts of the world. In Europe, object attribute data availability is more complete, allowing for a more detailed approach in this study. Based on an extensive review of road (re)construction costs in Europe, we developed new damage curves ~~which use~~ by utilizing the available data on road type, number of lanes and the presence of street lighting. Also, we benefit from the higher resolution of flood protection and GDP data in Europe. The increased level of detail allows for presenting the results on the level of individual road segments for hotspot identification. ~~In particular, it could not benefit from specific types of metadata, which are missing for large parts of the world. However, on the European scale, object data availability is more complete, allowing for a more detailed approach.~~ This meets the need of European road owners for GIS-aided vulnerability assessments, for which guidelines have been provided in the ROADAPT project (Bles et al., 2016) but where actual modelling has so far focussed on small spatial scales (e.g. Hackl et al., 2018). ~~A comparable study on the European railway network has been done by Bubeck et al. (2019), using OpenRailwayMap data and a highly stylized damage function implemented in the RAIL model.~~

Commented [KvG11]: Comment [22, 28]

Commented [KvG12]: Comment [4] and [22] and [28].

This study introduces an object-~~explicit~~based, continental-scale ~~river flood risk~~ assessment of large-scale river flood risk of the European road network for the present climate. ~~Our main objective is to~~We ~~compare the results and performance of an~~introduce new damage functions for the object-based approach ~~to~~ and compare it to~~the more traditional~~ a grid-based approach~~es~~. ~~Moreover, we introduce a new set of object-specific damage functions, which make optimal use of the available metadata in OpenStreetMap and thereby improve the damage estimates. This will also provide insights in the uncertainty around the estimates.~~ To illustrate the richness of the object-based approach, flood hotspots will be identified within the European motorway network. ~~and validated using damage reported~~The model results are compared to damage reported for a real flood event near Deggendorf, Germany.~~.~~ ~~Finally, the discussion and conclusion sections reflect on the differences between both approaches and give suggestions for further research.~~

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2 Method

Flood risk is commonly defined as a function of flood hazard, exposure and vulnerability (Kron, 2005; Peduzzi et al., 2009). In this study, these components are modelled in three blocks (Fig. 1~~Figure 1~~). Hazard ~~Flood hazard~~ data are taken from the Joint Research Centre'~~'~~s inundation maps of large river floods~~s flood inundation maps~~ ~~for~~ in Europe (Fig. 1, left). The hazard maps are inputs to two approaches that model exposure and vulnerability: the traditional grid-based approach (Fig. 1, top) and the new object-based approach (Fig. 1, bottom). In total, four combinations of exposure and vulnerability are used to calculate the risk.

Commented [KvG14]: Comment [11].

Grid-based:

1. CORINE land cover + Huizinga infrastructure damage curve
2. LUISA land cover + Huizinga infrastructure damage curve

Object-based:

3. OpenStreetMap + object representation of Huizinga infrastructure damage curve
4. OpenStreetMap + new object-based damage curves

These four combinations are selected to enable a comparison between the grid-based and object-based approach, for (1) a land cover grid with poor representation of the road network, (2) a land cover grid with the road network explicitly added to the grid, (3) an object-based approach with the damage curves from the grid-based approach, and (4) an object-based approach with new damage curves. In the remainder of this section, we introduce the flood hazard maps (Sect. 2.1), the grid-based approach (2.2), the object-based approach including the development of new damage curves (2.3), and the ~~validation procedure~~reference case (2.4).

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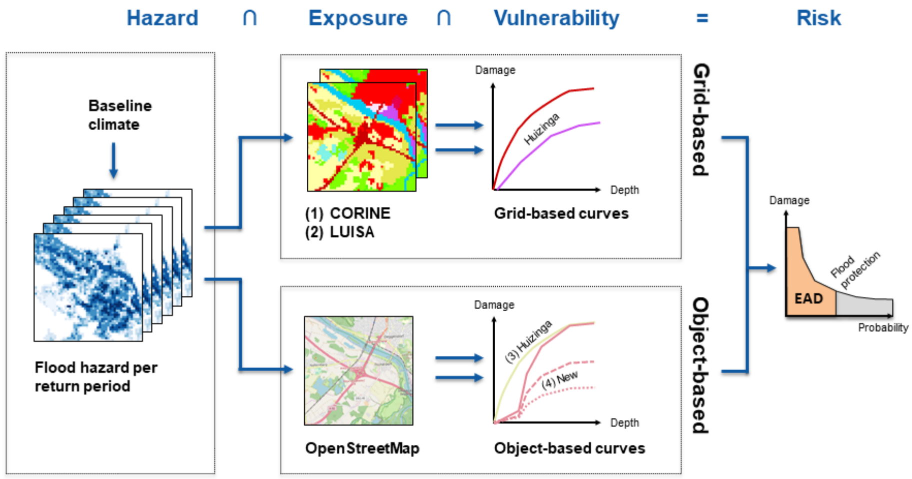

Figure 1 Graphical representation of the risk assessment using the grid-based approach (top-row) with the (1) CORINE and (2) LUISA land cover grids and the object-based approach (bottom-row) with OpenStreetMap and (3) the Huizinga and (4) a set of new damage curves © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License

2.1 Flood hazard

Flood hazard is represented with a set of inundation maps taken from Alfieri et al. (2015), with a recent update by Dottori et al. (2020) which cover most of the European domain at a grid resolution of 100 m. The dataset consists of six inundation maps corresponding to flood return periods of 10, 20, 50, 100, 200 and 500 years, assuming no flood protection in place. These maps represent the inundation depth and extent in all river sections with upstream area larger than 500 km^2. They do not include the effect of pluvial flooding, coastal flooding, as well as river and flash flooding in the most upstream catchments. Inundation maps were produced by merging the results of thousands of 2D hydraulic simulations along the European river network, based on the hydrodynamic model LISFLOOD-FP (Bates et al., 2010). The input hydrographs of flood simulations were defined consistently with the peak discharges and flow duration curves of a 25-year long simulation taken from the European Flood Awareness System (Thielen et al., 2009) and based on the hydrological model LISFLOOD (Van der Knijff et al., 2010). Additional details on the methods and models used to produce the maps are described in Alfieri et al. (2014; 2015), together with some skill assessment of the simulated maps versus official regional inundation maps for the United Kingdom and Germany.~~Inundation maps were produced by merging the results of thousands of 2D hydraulic simulations along the European river network, where the input hydrographs were defined consistently with the flow duration curve of a 25-year long simulation taken from the European Flood Awareness System (Thielen et al., 2009). Additional details on the methods and models used to produce the maps are described in Alfieri et al. (2014), together with some skill assessment of the simulated maps versus official regional inundation maps for the United Kingdom and Germany.~~

2.2 Grid-based exposure and vulnerability

In the grid-based approach, two different land cover maps are used: CORINE-2012 (version 18.5) and LUISA (version 2~~), both at a 100x100 m resolution.~~). They indicate the dominant land use type in each 100*100 m^2 grid cell. The CORINE land cover map (Büttner et al., 2014) and its predecessors have been used in many European flood risk studies (e.g. Alfieri et al., 2018; Lugeri et al., 2010; Serinaldi and Kilsby, 2017). ~~These~~CORINE, however, overlooks most of the road network (Rosina et al., 2018), because even large motorways typically cover less than 50% of a 100*100 m^2 grid cell, see Fig. S2. ~~-~~Therefore, roads have been manually added to the land cover map in some studies (e.g. Jongman et al., 2012; cf. Meneses et al., 2019). The LUISA land cover map is a spatial and thematic refinement of CORINE-2012 using various additional data sources, such as rasterized object datasets (Rosina et al., 2018). ~~As a result, many~~Therefore, motorways and trunk roads that were absent in CORINE are now present in LUISA as coarse grid representations of the original lines. However, due to the resolution of the grid, the actual road width is overestimated in most areas (Fig. S2).

To correct for the underrepresentation of infrastructural land use (and other land use types) in CORINE and LUISA, they assume for each land use class some percentage of infrastructure ~~is assumed~~ (Table S1, 2). This assumption follows from Huizinga's suggestion (2007, p. 2-22) to map ~~his~~the damage functions to CORINE using a cross-tabulation by the EEA (2006), which then became the~~ir~~ default implementation method. To enable a comparison with the object-based approach, we ~~maintained~~only considere~~d~~ the percentage of infrastructure per land ~~cover~~use class, whereas the contributions of the other damage curves are ignored (Table S1, 2). An implication of these percentages is that, although motorways and trunk roads 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

Commented [KvG16]: Comment [12]

Commented [KvG17]: Comment [12]

Commented [KvG18]: Comment [3A]

Commented [KvG19]: Comment [13,27,34] land use types. ~~Note~~ Also, note that in the land cover category ‘road and rail networks and associated land’, only a 27% infrastructural land use is assumed (Table S1, 2), which to some extents corrects the overestimation of the actual road widths in LUISA. In summary, the grid-based land cover category ‘Road and rail networks and associated land’ roughly corresponds to the object-based road types ‘motorway’ and ‘trunk road’, and the infrastructure percentages in the other grid-based land cover categories roughly correspond to the object-based road types ‘primary’, ‘secondary’, ‘tertiary’ and ‘other road’.~~Also note, that some percentage of infrastructural land cover is assumed in many other land use categories. To enable a comparison with the object-based approach, we calculated damage for the percentage of infrastructure in each land-use class; i.e. the original infrastructure percentages are maintained for all land use cover classes whereas all the other damage curve contributions are assumed 0 (Table S1, 2).~~

2.3 Object-based exposure and vulnerability

This section details the set-up of the object based model (2.3.1); the estimation of the value of the exposed roads (2.3.2); the ~~shaping~~ development of the new damage curves (2.3.3); the application of the Huizinga reference curve (2.3.4); and the sampling from the uncertainty spanned by the new damage curves (2.3.5).

2.3.1 Model set-up

In the object-based approach, all individual OSM road segments in Europe are intersected with the flood hazard data, followed by a damage and risk calculation per inundated segment (Fig. 2).~~(Figure 2). This approach is developed by Koks et al. (2019), but our implementation has damage curves tailored to the European context and uses additional metadata.~~ To perform this analysis using parallel processing (Fig. 2), the continental OSM ‘planet’ file is subdivided into 1498 regions[1], based on the European NUTS-3 division. Per region, every road segment is intersected with the flood hazard maps per return period, to determine the inundated length and average depth over the inundated part of the segment. Then, the damage to the road segment is calculated for the applicable damage curves. In the post-processing step, the expected annual damage (EAD) is calculated using the trapezoidal rule (Olsen et al., 2015), accounting for flood protection (Fig. S1). 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. ~~Flood protection data is derived from Dottori et al. (2020) which is an updated version of the flood protection levels estimations by Jongman et al. (2014).~~ In this step, the maximum damage per segment is corrected by linearly scaling the national to the former EU-28 average real GDP per capita (Eurostat, 2019).

[1] For hydrological reasons, our analysis includes the European Union (EU) 27 member states except Cyprus and Malta; it includes the United Kingdom and the adjacent European Free Trade Association countries Liechtenstein, Norway and Switzerland (not Iceland); and includes the (potential) candidate countries Albania, Montenegro, North Macedonia and Serbia (not Turkey). We excluded the EU’s remote overseas areas such as the Azores, Canary Islands, Guadeloupe as well as small Islands.

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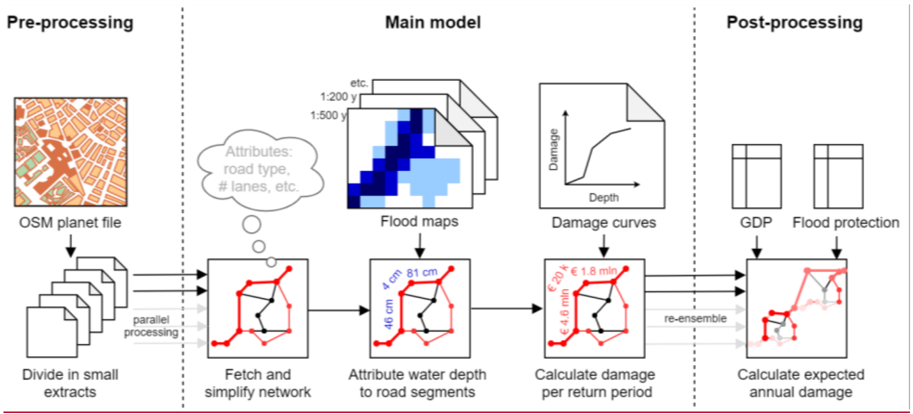

Figure 2 Stylized overview of the object-based approach

Where available, OSM attributes ~~road metadata~~ on road type, number of lanes, bridges and lighting is used to improve the damage estimates. Six road types are distinguished following the OSM tagging convention[2]: motorway, trunk, primary, secondary, tertiary and other roads (Table S3). Lane data is available for 90% of the motorways, 60% of trunks, 48% of primary, 23% of secondary, and less than 5% for tertiary and other roads; where unavailable, the countries' median number of lanes per road type ~~was~~ is used. For road-water intersections tagged as bridges, no damage to the road is calculated. We acknowledge that bridge failure can be an important source of flood damage (Lamb et al., 2019; Pregnolato, 2019; Vennapusa et al., 2013). Bridge damage, however, does not usually originate from the inundation of the roadway, but rather from scour hole formation to bridge piles and its foundation (Lamb et al., 2019), which cannot be accurately represented in our model.

2.3.2 ~~Estimating the value of exposed roads~~Overview of road construction costs

To construct the new damage curves, we compile~~d~~ an overview of road construction, maintenance and repair costs. These costs ~~were~~are related to the road repairs needed following a river flood, derived from literature and photo imagery of river floods in Europe. The damage narratives and resulting curves ~~were~~are validated during an expert workshop with flood risk and transport modelling experts and with the Dutch road operator, see acknowledgements. An overview of the damage curves and supporting narratives (reasoning from the road construction and maintenance costs presented below) is given in Fig. S3, 4 and Table S9, 10. The damage curves cover what it would cost for 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, repairs of road embankments, 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.

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[2] Key: highway. (6 February, 2019). In *OpenStreetMap Wiki*. Retrieved April 18, 2019, from https://wiki.openstreetmap.org/wiki/Key:highway

All costs mentioned in this and the following subsection are linearly scaled using national real GDP per capita (Eurostat, 2019) to represent former EU-28 average, 2015 price-levels in euro (€). The model inverses this operation when doing the damage calculation, to tailor the damage to the local context. This is common practice in pan-European flood risk studies (e.g. Alfieri et al., 2016b; Arnell and Gosling, 2016; Ward et al., 2013) and enables comparison ~~with~~ with existing studies. Besides GDP, the cost of constructing a new road depends on many factors, such as: road design; accessories like lighting and electronic signalling systems; soil conditions; noise reduction elements; and presence of tunnels and bridges (e.g. Blanc-Brude et al., 2006). For *motorways*, the European Court of Auditors (ECA, 2013) estimates the EU average construction costs at 11.4 million €/km. The cheapest 2x2 lane motorways with fairly simple road designs are about 3.5 million €/km, the most expensive roads with tunnels, bridges or noise barriers cost about 35 million €/km (ECA, 2013). Other studies report values well within this bandwidth (Carruthers, 2013; Federal Ministry of Transport and Digital Infrastructure, 2016; Heralova et al., 2014; Nijland et al., 2010; Pryzluski et al., 2012), as presented in Table S6. For costs of other road types see Table 1, which is based on literature tabulated in the SI (Table S5-7). For roads with more (less) than the default number of lanes, we added (subtracted) 25% of costs for each lane, based on Table S5.

~~Besides construction costs, road maintenance costs are also indicative for estimating flood damage (Table S8). Clean-up and small repair works are in the order of a few percent of construction costs; larger scale road improvement and resurfacing in the order of 10% of construction costs; and major asphalt works and road reconstruction in the order of 30-40% of construction costs (Carruthers et al., 2013; Archondo-Callao, 2000).~~

~~**Table 1 Road construction costs and maximum damage per road type, differentiated between low flow (low flow velocities) and high flow (high flow velocities). The values present the average for the former EU-28, in million 2015-euro per km.**~~

~~Road type~~	~~Lanes~~	~~Construction cost range~~	~~Max damage (low flow)~~	~~Max damage (high flow)~~	~~Max damage (low flow)~~	~~Max damage (high flow)~~	~~Huizinga max damage[A]~~
			~~Relative to constr. costs~~		~~Absolute values~~		
~~**Motorway**~~	~~2*2~~	~~3.5 - 35~~	~~20% (a)[B] 4% (s)[B]~~	~~22% (a)[B] 35% (s)[B]~~	~~3.9-7.0 (a)[C] 0.1-0.8 (s)[C]~~	~~4.2-7.7 (a)[C] 1.2-6.7 (s)[C]~~	~~0.90~~
~~**Trunk**~~	~~2*2~~	~~2.5 - 7.5~~	~~20% (a)[B] 4% (s)[B]~~	~~22% (a)[B] 35% (s)[B]~~	~~1.0-1.5 (a)[C] 0.10-0.20 (s)[C]~~	~~1.1-1.7 (a)[C] 0.88-1.75 (s)[C]~~	~~0.60~~
~~**Primary**~~	~~2*1~~	~~1.0 - 3.0~~	~~5%~~	~~35%~~	~~0.050-0.150~~	~~0.350-1.050~~	~~0.25~~
~~**Secondary**~~	~~2*1~~	~~0.50 - 1.5~~	~~5%~~	~~35%~~	~~0.025-0.075~~	~~0.175-0.525~~	~~0.225~~
~~**Tertiary**~~	~~2*1~~	~~0.20 - 0.60~~	~~5%~~	~~35%~~	~~0.010-0.030~~	~~0.070-0.210~~	~~0.175~~
~~**Other**~~	~~1~~	~~0.10 - 0.30~~	~~5%~~	~~35%~~	~~0.005-0.015~~	~~0.035-0.105~~	~~0.075~~

~~Notes:~~

~~A) Huizinga max damage costs are obtained by multiplying the m^2 costs with typical road widths per road type (Table S4).~~

~~B) a = road with accessories such as street lighting and electronic signalling; s = simple road, without accessories~~

~~C) For accessories roads: 50-100% of the construction costs range, for simple roads: 0-50% of the construction costs range~~

2.3.3 Estimating the shape of the damage curves

~~In general, damage curves derive flood damage from flood parameters such as water depth, flow velocity and flood duration.~~ Continental-scale models typically work with functions relating damage to water depth only (Alfieri et al., 2016a; de Moel et al., 2015; Winsemius et al., 2013~~), an approach also adopted in this study. Although damage predictions may significantly improve from more complex damage models under some conditions (Schröter et al., 2014), the inclusion of more parameters does not necessarily give better results, especially not when data availability is scarce~~

(Amadio et al., 2019). Therefore, we follow the recommendation of Schröter et al. (2014) to quantify the uncertainty around our estimates, which is mainly determined by uncertainty about the flow velocity.).

Flow velocity, however, is at least as important as water depth for explaining damage to roads (Kreibich et al., 2009; Merz et al., 2010; Thieken et al., 2009). Under low flow velocities (< 0.2 m/s), there is hardly any structural damage to pavements, whereas under high flow velocities (> 2.0 m/s) there is most likely severe structural damage (Kreibich et al., 2009). Indeed, pictures of floods in Europe show that under very quiet flow conditions, a road can remain almost undamaged whereas under flash floods with strong currents, complete reconstruction may be required. The flood hazard maps used in this study represent floods in rivers with an upstream area >500 km^2 whereas large flow velocities are typically found in smaller water courses in steep upstream areas and locally, close to dike-break locations (De Moel et al., 2009). Therefore, we assume that the predicted floods have relatively low flow velocities. The Lisflood hydrological model used in this study is developed for river floods in large river basins (Van Der Knijff et al., 2010). Because large flow velocities are typically found in steep upstream areas and next to dike-break locations (De Moel et al., 2009), we assume that the predicted floods have relatively low flow velocities. We deal with the remaining uncertainty by estimating two depth-damage curves that span the uncertainty of this typical slow flow velocity; one for the low-flow estimate and one for high-flow estimate that can be reasonably expected for large river floods.

We developed six newly shaped depth-damage curves, by differentiating along three dimensions: road type, road accessories and flow velocity (). An overview of the damage curves and supporting narratives (reasoning from the road construction and maintenance costs presented in the previous section) is given in Fig. S3, 4 and Table S9, 10.The six new depth-damage curves differentiate between three dimensions: road type, road accessories and flow velocity (Figure 3). Concerning road type, motorways and trunk roads are distinguished from other roads because of higher driving speeds and maintenance standards, reflected in higher reconstruction costs. and Also, these arebeing often located build on top of embankments, so that relatively little damage occurs when the top of the road embankment is not yet reached, represented by a concave section in the beginning of curve C1-C4. The other road categories (primary, secondary, tertiary and other roads) are usually not located onbuild on top of embankments, and their curves (C5,C6) therefore do not have such a concave section. Next, motorways and trunk roads with sophisticated accessories such as electronic traffic management systems, lighting and noise barriers (C1,C2) are differentiated from simple roads without these accessories (C3,C4). This represents the large spread in construction costs between simple and sophisticated motorways and trunk roads (Table S6) and the corresponding extra damage that may occur to the electronic signalling and lighting of sophisticated roads, even under low-flow conditions.. Finally, low-flow conditions (C1,C3,C5) are distinguished from high-flow conditions (C2,C4,C6).

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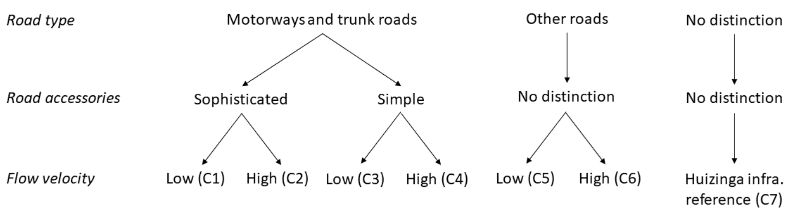

Figure 3 Dimensions used for differentiating the new damage curves (C1-C6) and the reference curve (C7)

Road maintenance and repair costs (Table S8) are used for estimating flood damage under various flood depth and velocity conditions. These are expressed as a percentage of the construction costs of the corresponding road type. For example, for roads without embankments, clean-up and small repair works are in the order of a few percent of construction costs (Reese, 2003, Archondo-Callao, 2000) and are required for small flood depths (<50 cm) with low velocity. Larger scale road improvement and resurfacing is in the order of 10% of construction costs and is required for small flood depths with high velocity (Carruthers et al., 2013, Archondo-Callao, 2000). Major asphalt works and road reconstruction is in the order of 30-40% of construction costs (Carruthers et al., 2013; Archondo-Callao, 2000), and is required for larger flood depths and higher flow velocity (Table S9, S10).

Table 1 Road construction costs and maximum damage per road type, differentiated between low flow (low flow velocities) and high flow (high flow velocities). The values present the average for the former EU-28, in million 2015-euro per km.

Road type	Lanes	Construction cost range	Max damage (low flow)	Max damage (high flow)	Max damage (low flow)	Max damage (high flow)	Huizinga max dam.[A]
	[-]	[10^6 €/km]	[-]	[-]	[10^6 €/km]	[10^6 €/km]	[10^6 €/km]
			Relative to constr. costs		Absolute values		
Motorway	2*2	3.5 - 35	20% (a)[B] 4% (s)[B]	22% (a)[B] 35% (s)[B]	3.9-7.0 (a)[C] 0.1-0.8 (s)[C]	4.2-7.7 (a)[C] 1.2-6.7 (s)[C]	0.90
Trunk	2*2	2.5 - 7.5	20% (a)[B] 4% (s)[B]	22% (a)[B] 35% (s)[B]	1.0-1.5 (a)[C] 0.10-0.20 (s)[C]	1.1-1.7 (a)[C] 0.88-1.75 (s)[C]	0.60
Primary	2*1	1.0 - 3.0	5%	35%	0.050-0.150	0.350-1.050	0.25
Secondary	2*1	0.50 - 1.5	5%	35%	0.025-0.075	0.175-0.525	0.225
Tertiary	2*1	0.20 - 0.60	5%	35%	0.010-0.030	0.070-0.210	0.175
Other	1	0.10 - 0.30	5%	35%	0.005-0.015	0.035-0.105	0.075

Notes:
A) Huizinga max damage costs [€/km] are obtained by multiplying the m² costs with typical road widths per road type (Table S4).
B) a = road with accessories such as street lighting and electronic signalling; s = simple road, without accessories
C) For accessories roads: 50-100% of the construction costs range, for simple roads: 0-50% of the construction costs range

2.3.4 The Huizinga reference curve

A comprehensive set of depth-damage curves has been proposed by Huizinga et al. (Huizinga, 2007; Huizinga et al., 2017), which has been applied in many studies (e.g. Albano et al., 2017; Amadio et al., 20169, ~~2016~~2019; Carisi et al., 2018; Dottori et al., 2018b; Jongman et al., 2012; Prahl et al., 2018). We use~~d~~ the 'EU-average curve' for road infrastructures (Huizinga, 2007) to compare to our new curves. In this study, the curve is used in both the grid-based approach and the object-based approach, where the per m² damage was multiplied by typical widths of roads in Europe (Table S4).

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2.3.5 Sampling the uncertainty space

The damage estimates come with considerable uncertainty, which primarily originates from the bandwidth of the maximum damage estimates and the space between the upper and lower estimate of the flow velocity. This uncertainty space is sampled to obtain (1) a deterministic estimate of the expected annual damage, as well as (2) a probability distribution around a median estimate. Motorways and trunk roads with street lighting tags in OSM are assumed to have sophisticated road accessories; damage curves C1 and C2 are applied (Fig. 3) in combination with a max damage sample from 50-100% of the max damage range (Table 1, note C), and 75% in the deterministic sample. For motorway and trunk roads without street lighting tags, simple ~~motorway~~ road designs are assumed; damage curves C3 and C4 are applied in combination with a sample from 0-50% of the max damage range, and 25% in the deterministic sample. Concerning the uncertainty in flow velocity, we assume~~d~~ a normal distribution with the low flow curve at -2 standard deviations and the max flow curve at +2 standard deviations from the mean flow damage, and the average of the min and max flow curve in the deterministic estimate.

2.4 ~~Deggendorf flood event~~Comparison to reference case

~~To validate our approach~~As a reference, we compare our model to road repair data reported by the Bavarian Government (Table S17). On 4 and 5 June 2013, an approximately 1:100 year flood caused a dike breach near the confluence of the River Danube and its tributary: the River Isar, close to the town of Deggendorf. The inundated area spanned the cloverleaf junction of the motorways A92 and A3, as well as 6.6 km of the A3 and 2.8 km of the A92 (Fig. 7). Both roads have 2*2 lanes + 2 safety lanes and are 30 m and 26 m wide, respectively. The roads are located on embankments and have a fairly simple road design, i.e. no lighting or electronic signalling. We estimate ~~Water~~ water depths and damage to these roads and surrounding area ~~are estimated~~ from reports (Rogowsky, 2016), video's, photos and satellite imagery (Table S17). ~~We masked the~~We then mask the 1:10 year flood hazard map ~~of the model~~ (which better resembled the reported inundation than the 1:100 year flood map) over the extent of the observed inundation and calculate~~d~~ the damage using the object-based model.

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3 Results

This section presents the flood risk ~~of~~ of the European road network. Firstly, the new object-based approach is compared to the grid-based approach, using the same damage curves in both approaches (Sect. 3.1). Secondly, the new damage curves are used in the object-based approach, to give more precise estimates of the aggregated road damage in Europe and to give insight into the uncertainty surrounding these estimates (3.2). Thirdly, these results are presented on the road segment level to identify flood hotspots in the European highway network (3.3). Fourthly, the model results are validated by comparison with the damage reported for the Deggendorf flood event (3.4).

3.1 Grid-based vs. object-based damage for Huizinga damage curve

The grid-based approach estimates the total expected annual damage (EAD) for the CORINE and LUISA land cover map at 536 and 301 million €/y respectively (Fig. 4a), whereas only 228 million €/y is estimated by the object-based approach (Fig. 4b). Both approaches use the same hazard data and both use the Huizinga vulnerability curve, so that the differences are mainly attributable to the exposure data. A surprising observation concerning the exposure data is the large amount of infrastructural damage (65%) attributed to the CORINE land cover type 'water'. This peculiarity originates from Huizinga's suggestion (Huizinga, 2007, p. 2-22) to map the damage functions to CORINE using a land cover cross-tabulation from the European Environment Agency (EEA, 2006, cf. Table S1). The EEA shows that some cells that contain 'water bodies' in CORINE contain 'infrastructure' in a reference map. Consequently, some percentage of infrastructure is assumed for all CORINE water bodies, for which large damage is calculated, because sometimes large 'inundation depths' are modelled for water bodies. This peculiarity was manually removed in the model implementation of LUISA (Table S2), such as in the recent PESETA-IV study (Dottori et al., 2020). Another difference between CORINE and LUISA is the strong increase in damage to 'Road and rail networks and associated land', from 15 to 144 million €/y respectively, resulting from integrating the motorway network into the LUISA land cover grid (Rosina et al., 2018).

It should be noted that the object-based approach only reports damage to road infrastructure, whereas the grid-based approach also reports damage to rail infrastructure. However, since railways are very narrow line elements and have not been explicitly integrated in the LUISA grid (Rosina et al., 2018), their contribution to the LUISA damage is negligiblesmall. Therefore, we assume that LUISA class 'Road and rail networks and associated land' corresponds to the motorway network and that the other LUISA land use classes correspond to the underlying road network. Accordingly, in the grid-based approach, motorways contribute 48% and the underlying road network 52% to the total road infrastructure damage (Fig. 4a). In the object-based approach, motorways contribute 9%, trunk roads 7%, and the underlying road network 85% (Fig. 4b). This relatively minor contribution of motorways in the object-based approach results from the way in which the Huizinga curve is implemented: damage per square meter is multiplied by the road width. Motorways, however, are more expensive than is to be expected from merely their width. Therefore, the damage to motorways is underestimated in Figure 4b. The other way around, the other road types are less expensive than is to be expected from their width. Therefore, damage to the underlying road network is underestimated in Figure 4b. This emphasizes the need for damage curves that correct for road characteristics beyond only the road width, as used in the next section.Motorways, however, are disproportionally more expensive than roads in the underlying network (when merely looking at their width), which emphasizes the need for damage curves that correct for road characteristics beyond only the road width, as used in the next section.

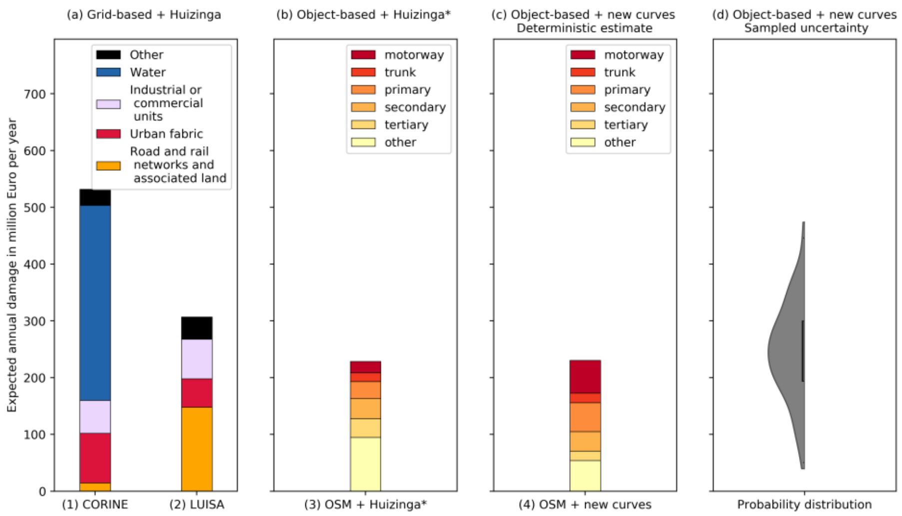

Figure 4 Flood risk ~~of~~ of the European road network according to the grid-based and the object-based approach
(a) Grid-based approach with (1) CORINE and (2) LUISA + the Huizinga damage curves, per land cover type
(b) Object-based approach + *object translation of Huizinga damage curves (3), per road type
(c) Object-based approach + new damage damage curves (4), deterministic estimate per road type
(d) As (4) with probability density around the deterministic estimate of panel c, black line indicating the interquartile range

3.2 Object-based damage using new damage curves

With the new depth-damage curves the EAD is estimated at 229 million €/y (Fig. 4c), which is again below the grid-based LUISA estimate (301 million €/y, Fig. 4a). The total damage with the new curves (229 million €/y, Fig. 4c) is almost the same as the object-based implementation of the Huizinga damage curve (228 million €/y, Fig. 4b), but the contribution per road type is substantially different. Notably, the contribution of motorways (25%) has become much larger. The other contributions are 7% for trunk, 22% for primary, 15% for secondary, 7% for tertiary and 24% for other roads (Fig. 4c)

The object-based approach also gives insight into the uncertainty surrounding the deterministic estimate of 229 million €/y. Fig. 4d shows the bandwidth derived from the sampling procedure (Sect. 2.3.5). The median of the stochastically generated samples is 250 million €/y, which is above the deterministic estimate of 229 million €/y, because on the upper bound, outliers in high flow velocities cause large damage, which is not compensated at the lower bound because the damage per segment cannot be lower than zero. The interquartile range (containing 50% of the samples) is 195 to 301 million €/y, and the 90% range is 115 to 385 million €/y.

Figure 5a shows how the object-based risk (deterministic estimate) is geographically spread over Europe. Germany, France, and Italy are exposed to the highest flood risk (respectively 45, 43, and 23 million €/y, see Fig. S6,7). In these countries, the risk is concentrated around the rivers that rise in the Alps and then flow through regions with dense road networks, such as the Danube and Rhine flowing through Southern Germany; the Rhone flowing through south-eastern France; and the Po flowing through northern Italy. These three countries have additional flood hotspots in the Elbe,

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Garonne, and Tiber River basins respectively. Of the top-10 NUTS-2 regions with the largest damage, five are in France and two in Italy (Table S16~~0~~).

Another concentration of high flood risk is found on the Scandinavian peninsula. This can be partly explained by the high GDP per capita and the relatively large NUTS-regions. However, also when correcting for these factors, we find that the sparse road networks in these countries indeed have the potential to be inundated with large water depths, causing large damage. The regions Pohjois-ja Itä-Suomi (Finland) and Hedmark og Oppland (Norway) are in the top-10 of NUTS-2 regions with the largest risk (Table S16).

Because the value of the exposed assets is scaled to the national GDP per capita, the risk is relatively high in high-income countries. Without this GDP-correction, other high-risk countries emerge: the Central- European countries Czech Republic, Slovakia, and Hungary, but also Croatia and Latvia (Fig. 5~~, right-hand panel~~a). Although these countries contribute little to the total damage in Europe, the relative impact of road disruptions in these countries is large. These regional risk aggregations are influenced by the size of the regions in the NUTS classification; smaller regions show relatively smaller risk in Figure 5a. Therefore, aggregation at different levels reveals slightly different spatial patterns (Fig. S7, Table S14,15,16).

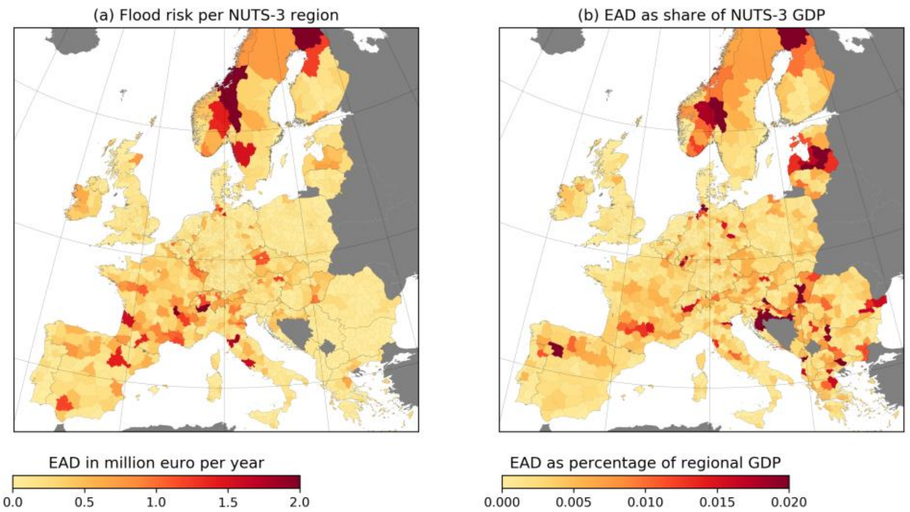

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Figure 5 Expected annual damage (EAD) to road infrastructure aggregated by NUTS-3 region. The left-hand panel presents the absolute values, the right-hand panel expresses the EAD as percentage of the GDP per NUTS-3 region.

3.3 Current flood hotspots in the EU transport network

The flood risk of all motorways and trunks in the EU road network is now presented on a high-resolution map, see Fig. ~~S8~~S9. To illustrate how this map can be used to ~~gain insight into the flood risk~~identify flood hotspots ~~to~~ in the EU road network, we highlight three notable regions (Fig. 6).

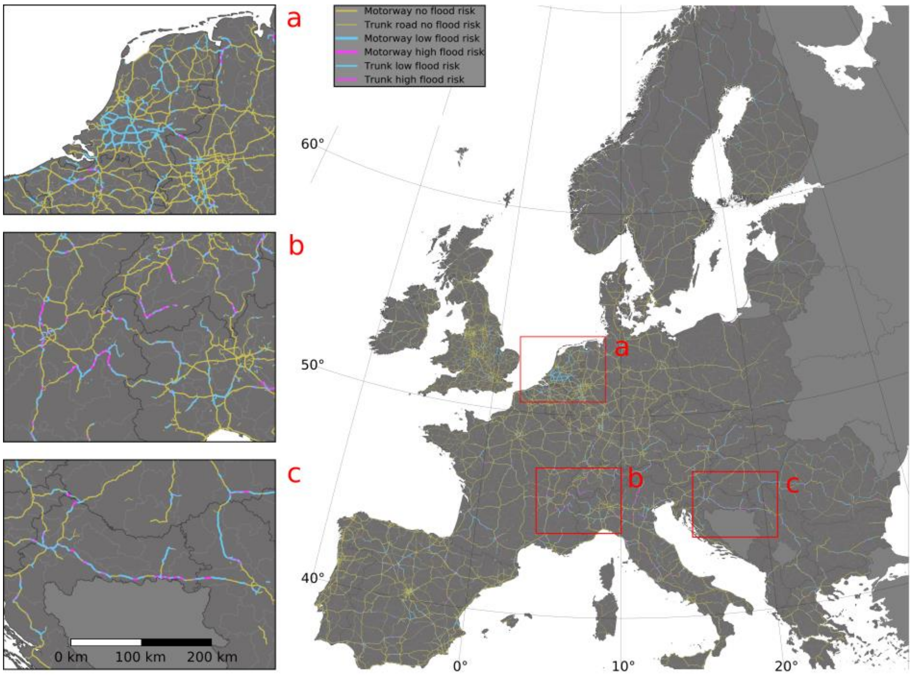

Figure 6 Flood risk of motorways and trunk roads in the European main road network, see Figure ~~S8~~ S9 for a high-resolution version. Road geometries © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.

The Netherlands stands out in Fig. ~~6A~~6a, because many of its motorways have the potential to be inundated, although at the same time, the aggregated flood risk is among the lower countries in Europe (Fig. ~~S3~~S6). This can be explained by the very high river flood protection standards in the country (return period of 1:1000 year or higher in most places), which make the likelihood of flood events very small. However, if dikes did breach, many roads would be inundated with large water depths, causing large damage. Also, this could severely hinder the possibilities for evacuation, especially in the centre of the country.

The Alps are ~~also~~ identified as a high-risk region. For example, in France, the model predicts large EAD for the A41 from Grenoble to Chambéry, and the A43 from Chambéry to Sain-Jean-de-Maurienne (Fig. ~~6B~~6b). Both motorways are located in narrow flood plain valleys along rivers. This exposes them to large flood hazards, which is also recognized in local flood risk studies (e.g. Strappazzon and Pierlot, 2017). Similar exposure of motorways can be found in other Alpine regions, such as the A9 from Sion to Montreux (Switzerland), the A22 from Lake Garda to Bolzano (Italy), and the A12 from Landeck via Innsbruck to Kufstein (Austria).

In the Balkans, the E70 motorway from Zagreb (Croatia) to Belgrade (Serbia) is subject to large flood risk (Fig. ~~6C~~6c). This road follows the course of the Sava River for about 400 km. The flood plains of the Sava River were struck by a large flood in 2014 (International Sava River Basin Commission, 2014). According to our model, the flood waters could hit the motorway at several locations. For some road segments the EAD is notably high. This is primarily the result of a large flood hazard rather than a large value of exposed assets, because the GDP of Croatia and Serbia is below the (former) EU-28 average.

3.4 ~~Validation of results for Deggendorf case~~Deggendorf reference case

As described in Sect. 2.4, the Deggendorf flood event is used to validate the damage estimates of the model (Fig. 7). During the flood event, the pavement of the A3 was submerged over 6.6 km because the road embankment was lower than the water level in the surrounding area, resulting in water depth of 0.5 m above the road pavement, on average. After the flood, the A3 was covered with debris (a gas tank, hay bags covered in plastic, wooden logs, plastic bags, pallets), sand, and mud, requiring a major clean-up. At the cloverleaf, there were rifts in the asphalt, requiring small asphalt works. Small strips of asphalt (but not the entire road) were milled and resurfaced. The embankment of the A92 was higher than the embankment of the A3, so that its pavement remained dry over the entire 2.8 km, except a small depression at an underpass with a local road (see Table S17).

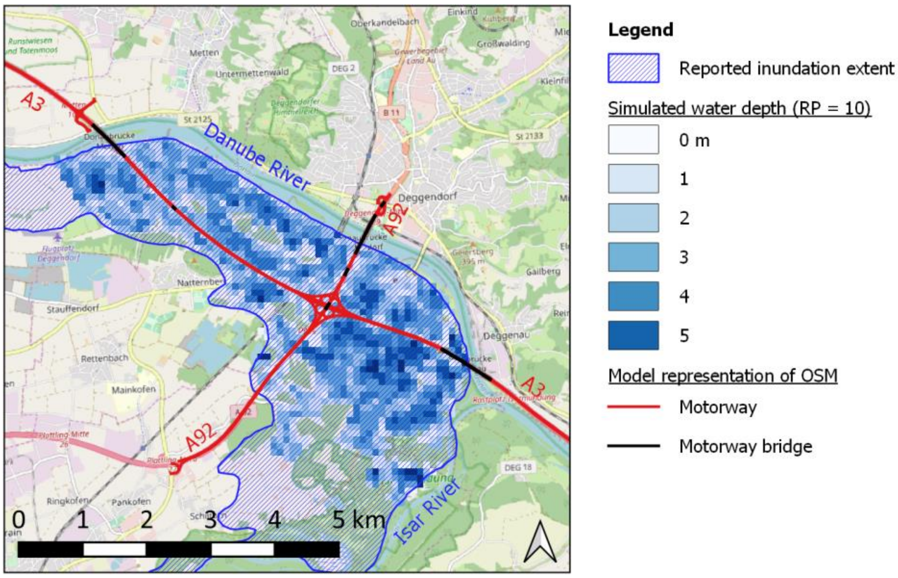

Figure 7 Observed and simulated flood in Deggendorf. Simulated map according to the cropped Return Period (RP) = 10 year flood map (Alfieri et al., 2015), background map © OpenStreetMap contributors 2019. Distributed under a Creative Commons BY-SA License.

The Bavarian State Ministry was granted 3.8 million euro for rehabilitating the Deggendorf cloverleaf junction (Table S17). The model calculates damage of 3.4 million for the low-flow curve (C3) and 28.6 million for the high-flow curve (C4)~~ respectively~~. The video imagery and the limited asphalt damage (Table S17) suggest that flow velocities were relatively low, so that one expects the damage more towards our low-flow than the high-flow damage curve, which is indeed the case.

When interpreting these results, one should consider that German motorways are relatively cheap compared to those in other EU countries (after scaling for GDP, see Table S6); which could imply that rehabilitation works are also relatively cheap (cf. ECA, 2013). Additionally, most damage seems to have occurred to the cloverleaf itself, rather than the straight sections of the two highways. Finally, it is likely that the road ~~operator~~ owner made additional repair costs beyond what was funded using the 3.8 million euro grant.

~~Overall, the validation event suggests that the object-based model is more likely to overestimate than to underestimate the reported damage. This is a surprising result, because the object-based approach already gives lower values than the grid-based approach. More research is required to further validate the damage curves and maximum damage estimates.~~

4 Discussion

In this work, the object-based approach resulted in lower damage estimates than the grid-based approach. This contrasts with findings of previous studies. For example Jongman et al. (2012) found that "even with the complementary infrastructure data added to CORINE (by adding the road network to the grid), all damage models that include this class *strongly underestimate* the corresponding losses" (2012, p. 3744, brackets and emphasis by us) and that this "is in line with results from earlier studies" (p. 3748). Instead, our findings suggest that grid-based studies using CORINE may *overestimate* infrastructural damage by allocating infrastructural damage to water bodies. However, since the infrastructure contribution to the total damage in these approaches is limited, the estimate of total damage (beyond infrastructure) could still be reliable despite the misallocation in some land cover categories. The grid-based approach using LUISA provided an estimate close~~r~~ to the object-based assessment, indicating that with LUISA, a fair proxy of the total damage to road infrastructure can be obtained. ~~.~~

Commented [KvG39]: Comment [35]

Within the object-based approach, replacing the Huizinga damage curve with a new set of damage curves resulted in a comparable estimate of the total road damage but distributed a larger share of the damage to motorways and trunk roads. This indicates that the Huizinga infrastructure function is a fair proxy for the average damage to road assets but is unsuitable for assessing damage at the individual road level. The Deggendorf ~~validation~~ reference case showed that the low-flow curve best resembled the reported flood damage. The new curves also compare reasonably well to damage reported for a Missouri River flood in in Iowa, United States of America (Vennapusa et al., 2013). In order to compare our curves to the damage reported in this study, let us assume a motorway construction costs of 5 million €/km, given that the road design in Iowa is fairly 'simple' (Table 1). Vennapusa et al. report the following motorway damage (Table S18): for clean-up costs: 18,000-65,000 €/km, which is in the order 1% (of 5 million €); for minor up till major repair works: 54,000-388,000 €/km, which is in the order of 1-10%; and for complete reconstruction of a motorway: 5.8 million €/km, which is in the order of 100% of construction costs.

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European flood risk studies estimate the total river flood risk aggregated over all land cover types at 4-6 billion €/y (Alfieri et al., 2016b; Jongman et al., 2014), which resembles the reported damage (Paprotny et al., 2018). Our estimate of road damage of 250 million €/y is in the order of 4.2% (of 6 billion) to 6.3% (of 4 billion) of total damage. This infrastructure share of total flood damage is usually in the order of 5-10% (e.g. Pardoe, 2011, as cited by Jongman et al., 2012). Using grid-based models, Jongman et al. find 8.9%, 2.6% and 8.9% for a flood in Carlisle, for which 11.9% was reported. In specific cases, the damage may be much higher: Jongman et al. also find values of 18%, 5%, 17% and 3% for a flood in Eilenburg, for which 50% was reported. This made Bubeck et al. (2019) suggest that infrastructural losses may amount up till 60% of total damage. Our results however, suggest that such a high value should be seen as an exception; usually the infrastructure percentage of total damage is much lower. We also perceive Bubecks et al.'s estimate for the damage to railway infrastructure (11% - 14% of overall flood losses) as being on the high side, given that we find a percentage of only 4-6% for road infrastructure (with the same hazard data) and given that rail damage is usually smaller than road damage (Doll et al., 2014).

Our estimate of 250 million €/y, and 90% confidence interval of 115-385 million €/y is lower than the 660 million €/y reported by Enei et al. (2011). They used an elasticity model linking meteorological indices to road vulnerability data derived from literature. This accounted for the aging of infrastructure, so that the costs attributed to flood damage are lower than the unit replacement costs. However, they included damage caused by landslides as well as damage to bridges, whereas we only look at the impact of floods, and excluded damage to bridges.

Considering that other studies find higher values, could we have underestimated the damage? On the one hand, this seems not to be the case. Firstly, the ~~damage reported for the validation event~~estimated size of total damage costs for the reference event is at the lower range of our damage estimate. Secondly, it can be argued that places for which our model calculates large damage could be more flood~~-~~proofed than what was incorporated in our damage curves. For example, large damage is found for roads along rivers, located in flat flood plains between mountains. In these very vulnerable places, the design standards of the roads may be higher than of the average European road; the road could be extra protected in anticipation of the flood events. Thirdly, road segments that follow a meandering river are sometimes accidently intersected by the relatively coarse flood hazard grid, whereas ~~in reality~~ they do not flood. This makes our model more likely to overestimate than to underestimate the damage.

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Commented [KvG42]: Comment [21]

On the other hand, there are reasons to think that the actual river flood damage is larger than predicted by our model. Firstly, we have limited ourselves to large river floods represented in the flood hazard maps, thereby omitting floods originating from small catchments~~we have limited ourselves to large river floods represented in the Lisflood model, thereby omitting floods originating from small catchments~~ (<500 km^2). In hilly terrain, flash floods and associated landslides in these smaller catchments can locally cause large damage to road infrastructure, not the least because the flow velocities may exceed what was anticipated in our high-flow curve. Secondly, our study omitted additional damage originating from junctions, viaducts, bridges and tunnels, whereas these could contribute significantly to overall damage. For the ~~described validation~~reference event, damage to the cloverleaf seems to have contributed most to the overall damage. Similarly, ~~the exceptionally~~a main source of the exceptionally large damage for the Eilenburg case reported by Jongman et al. (2012) ~~on the Eilenburg case was caused by~~was ~~damage to~~the collapse of a bridge.

Commented [KvG43]: Comment [30]

Commented [KvG44]: Comment [20]

5 Conclusion

This study introduced a new object-based approach to modelling the river flood risk ~~of~~ of European road infrastructure. This enabled a comparison with the commonly used grid-based approaches, which clearly have difficulties to accurately estimate damage to line infrastructure: road infrastructure may either be overlooked or overestimated by attributing infrastructural damage to the wrong land use types. Also, the study introduced a new set of damage curves which puts the frequently used Huizinga curves in perspective. The median expected annual damage from river floods to the road network is 250 million €/y, which is well below the grid-based estimates with CORINE (536 million €/y) and LUISA (301 million €/y). Additionally, we showcased how the object-based approach can be used to identify flood hotspots in the European~~U~~ road network~~.~~, for which the grid-based approach was unsuitable. ~~The median expected annual damage from river floods to the road network is 250 million €/y, which is well below the grid-based estimates with CORINE (536 million €/y) and LUISA (301 million €/y).~~ This generalized approach can also be used for other hazards such as coastal and pluvial floods ~~landslides or flash floods~~. We especially recommend the investigation of the damage caused by flash floods and associated land~~-~~slides in hilly terrain, because the flow velocities and resulting damages seem to exceed what we observed for large scale river flooding.

Commented [KvG45]: Comment [24B]

Commented [KvG46]: Comment [1B]

~~The median expected annual damage from river floods to the road network is 250 million €/y, which is well below the grid-based estimates with CORINE (536 million €/y) and LUISA (301 million €/y).~~ ~~The validation event suggests that actual flood damage might be even lower.~~

The model introduced in this study could be a starting point for further analysis. First, the flood hazard data can be easily substituted with (smaller-scale)~~,~~ high-resolution data, ~~while~~ to fully exploit the level of detail offered by ~~maintaining~~ the OSM~~vulnerability and~~ exposure dataset. In combination with higher-resolution flood hazard data, it is worth to investigate if splitting the OSM road segments in smaller subsegments can further improve the object-based approach.~~s. Such local~~Second, local scale case studies are required to validate the proposed damage curves. 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. Third~~Second~~, because road flood damage is very sensitive to uncertainty in flood velocity, accounting for this parameter could improve the predictive capacity of the model. ~~Third,~~Fourth, an object-based approach can be used to investigate potential damage to bridges, culverts, tunnels, viaducts and junctions.

Commented [KvG47]: Comment [26]

Commented [KvG48]: Comment [16]

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In the broader context of risk assessments for roads, this study offers a practical method for large (continental) scale risk assessment without compromising the resolution of the exposure data, hence suitable for hotspot identification. Both continental scale and local scale assessments can use the same framework, only the hazard data needs to be substituted with high-resolution local data. The results are presented on the level of individual road segments which meets a demand of road owners (Bles et al., 2016) by providing immediate perspective of action. This bridges the gap between detailed local-scale object-based studies (e.g. Hackl et al., 2018) and coarse continental-scale econometric (e.g. Doll et al., 2014) or grid-based studies (e.g. Dottori et al., 2020).

Commented [KvG50]: Comment [4,24]

Finally, the object-based approach offers an indispensable level of detail for two types of analysis. First, damage from network disruptions and indirect economic effects can be studied using the same road network as used in the analysis of direct damage. Network graphs can be directly constructed from the OSM road objects, which is impossible with a grid-based approach. Second, flood risk studies are increasingly used to support decision making on climate adaptation. The unique characteristics of each road segment are highly relevant for targeted climate resilient infrastructure investments and can only be captured in a road specific, object-based approach.

Supplementary information

This paper contains supplementary information with model settings, road construction and maintenance cost data, the new damage curves, and detailed descriptions of the model results. These results include a high-resolution map and shapefile of the flood risk ~~to~~ of motorways and trunk roads in the European road network.

Code and data availability

The Python code for the object-based model can be retrieved from github.com/keesvanginkel/OSdaMage. The SI contains a shapefile with the model outputs for the European highway network (motorways and trunk roads). Data for all OSM road classes per NUTS-3 region can be retrieved from the authors.

Commented [KvG51]: Comment [5,6]

The JRC flood hazard maps used in this work can be obtained upon reasonable request from Francesco Dottori (francesco.dottori@ec.europa.eu) and Luc Feyen (luc.feyen@ec.europa.eu). A previous version is available for download and reuse at the JRC Data Catalogue at this link: https://data.jrc.ec.europa.eu/collection/id-0054 .

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Author contribution

KvG prepared the manuscript with contributions from all co-authors. FD, LA and LF prepared the flood hazard maps and damage maps of the grid-based approach. EK developed the object-based approach, KvG tailored it to the European context. KvG and EK carried out the computational experiments and investigated, validated, and visualised the results. All authors approved the final publication.

Competing interests

The authors declare that they have no conflict of interest.

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