

Dear anonymous referee,

Thank you for your constructive comments which have helped improve our manuscript. We highly appreciate your time, effort and support. The point by point reply below includes our responses to your comments and how we adjusted the manuscript accordingly.

Introduction

"The study conducts an exposure assessment for unembanked areas in Rotterdam for the years 1970 to 2150 accounting for different extreme water levels. Building exposure is estimated for different scenario combinations and neighborhoods to identify the contribution of sea level rise, urban development and adaptation (i.e. construction of the Maeslant barrier and elevating new buildings) to the exposure. The study presents a comprehensive framework for local exposure assessments, integrating future development of building infrastructure and adaptation. The manuscript is written clearly and the text is supported by insightful figures. Though the idea of the exposure assessment does not present an entirely new approach and the findings are sometimes relatively obvious, the study combines many different contributing factors to future exposure and the framework is interesting for further local studies. I have some general and also more specific comments that I believe could increase the scientific and presentation quality of the manuscript. I hope the authors consider the comments useful."

Response: We are glad that you find the manuscript relevant and well written. While exposure analysis itself is not new, our contribution indeed lies in combining regional sea level rise projections with detailed local urban development data across both historical analysis and future projections. The scientific added value is the combination of these analyses to reach novel insights on developing flood risk adaptation strategies by accounting for urban development changes over time and neighborhood-level differences in exposure that would be lost in national or regional flood risk assessments.

General comments

"The discussion and conclusion could benefit from some restructuring. Right now, the discussion mostly presents the limitations of the study, whereas the conclusion discusses the implications of the results. This should also be part of the discussion and the conclusion should then only highlight on the main findings."

Response: We have restructured the conclusion and discussion as suggested. The discussion section now addresses both limitations and implications, while the conclusion contains only the main findings.

"The Methods describing the calculation of the flood hazards are not described sufficiently for readers to be able to reproduce them. How does the Hydra-NL model incorporate the results from the hydrodynamic model to calculate water level frequency lines at different locations? Which hydrodynamic model combinations have been used from the database? It would be helpful to add a short explanation to the manuscript."

Response: Thank you for your sharp observation. We have expanded our explanation of Hydra-NL for calculating water level frequency lines to assist the reproducibility of the calculations. Hydra-NL uses the entire database of hydrodynamic computations, weighing the contribution of each stochastic variable combination based on exceedance probability, sea level rise, and Maeslant barrier operation. Detailed breakdowns of contributions of hydrodynamic combinations are available in the supplementary material (<https://data.4tu.nl/datasets/d1291401-708a-4d48-9d95-8259cfd987d2>). For example: rotterdam_unembanked\5_hydranl\computations.zip\WBI2017_Benedenrijn_17-2_v04\017-02_0018_9_NM_km0995\Berekeningen\m000_exMLK\uitvoer.html. In our manuscript, we have added references to these sources as well.

"In the results, exposure between neighborhoods is expressed and compared based on the relative share of exposed housing units in each neighborhood. You state for example that Kop van Zuid-Entrepot is the most vulnerable neighborhood with 48% of the housings being exposed. However, in absolute numbers these "only" refer to 100 exposed houses. In this context for example Feyenoord would be more exposed (200 houses). From a city planning perspective, I think it might be more relevant to know about the absolute exposure in order to identify hotspots and prioritize actions in neighborhoods where many houses and thus people are affected. The absolute numbers might be especially relevant for the 1000-year event, where 100 % of the houses are exposed for almost all neighborhoods. This could also be picked upon in the discussion to reflect, that evaluating exposure is also a matter of perspective and scale."

Response: We acknowledge that from a city planner's perspective, both the absolute as well as the relative exposure are valuable. While we previously highlighted absolute exposure in Section 4.1 and relative exposure for the neighborhoods in Section 4.2, we have now also included absolute exposure figures in Section 4.2 to better represent the contributions of different neighborhoods.

"Throughout the manuscript the use of the terms exposure, risk and vulnerability is inconsistent and often erroneous. Since this is an exposure analysis, I would suggest to stick to this term and be careful when using the terms risk and especially vulnerability."

Response: Thank you for your observation. The terms exposure, risk and vulnerability each have their own meaning and purpose. However, we understand that this may raise confusion for readers from different domains. Hence, we have carefully revised our use of terminology throughout the manuscript, maintaining focus on 'exposure' and limiting references to 'risk' and 'vulnerability' only where specifically applicable. For situations related to the increase in exposure, we now use the term susceptibility rather than vulnerability. We also explicitly added the definitions of these terms where we introduced them.

Specific comments:

"Page 3, line 74-86: I find it unusual to refer to the findings already in the introduction. I would suggest to only describe the four-step process here without any interpretation of the results yet."

Response: We have chosen to share some of the findings in the introduction as they provide readers with a clearer expectation of the article content, which we believe increases readability for a broader audience. In the revised manuscript, we have framed these findings as research questions rather than explicit results.

"Page 4, line 91-101: The first paragraph of the Methods and data section reads more like part of the introduction. Perhaps, try to reduce this paragraph and/or include it in the introduction."

Response: We have shortened the first paragraph of the method section and moved the relevant content to the introduction.

"Page 4, line 109: Maybe mention that altering the design flood elevation is a scenario accounting for adaptation/accommodation."

Response: We have clarified that adjusting the design flood elevation is part of an adaptation/accommodation flood risk adaptation strategy.

"Page 7, line 178: Why did the authors choose a scenario which involves elevating the design flood level by just 20 cm? Are there concrete actions/plans considering this as a new design height? To me it doesn't sound like too much of a difference to the reference scenario and I am wondering why the authors didn't choose a higher design level? Also, the authors could consider to elaborate other adaptation options in their discussion, like e.g. household-level adaptation, which might eliminate exposure in cases of lower water levels."

Response: Indeed, the 20 cm elevation increment reflects concrete, though not yet approved, proposals from Rotterdam municipality. This might seem a minor adaptation measure, but it would already involve costs approximating tens of millions of euros while significantly reducing/delaying exposure. Household-level adaptation, and the trade-off between household-level adaptation and system-scale adaptation, is interesting and is one of the topics to include in next studies. For the current manuscript we focused on investigating on system scale adaptation measures (storm surge barriers and land-raising of new building lots).

"Page 8, line 189-191: To quantify exposure, the authors calculate the difference between water levels and the elevation of the housing unit. It appears that they are not accounting for hydrological connectivity here. This means housings behind structures higher than the water level are eventually not flooded. It would be good to mention this as a limitation. A similar issue is mentioned in the discussion about the missing seawall information."

Response: Thank you. We have expanded our discussion on missing seawall information to include how buildings affect hydrological connectivity. To be brief, there are seawalls that prevent water from initially flooding particular sections. However, these structures are relatively low (compared to the water depths), and our analysis and discussions with the municipality revealed that there are no internal structures that would limit flood propagation within neighborhoods.

"Page 15, line 341-343: "Hence the comparative subplots show that stopping urban development after 2020 could ultimately prevent exposure to 1000-year events of all 22,600 housing units planned for construction." I find this finding a bit too obvious. Perhaps there is no need to write this."

Response: We have retained this sentence as it also serves as a reference point for our subsequent exposure findings related to lower return periods (line 343-347).

"Page 20, line 421-427: Is the height information of the flood-proofing measures not reflected in the DTM? Referring to my earlier comment, if elevation information from the DTM is accurate for protection measures it might be valuable to assess exposed areas based on hydrological connectivity rather than comparing the water level to each housing elevation."

Response: While 2D modeling, or accounting for hydrological connectivity in another way, would improve accuracy for current conditions, we learned that the benefits are marginal for the entire period between 1970–2150 as uncertainties in land use changes and digital terrain models across this period are dominant. Of course, uncertainties regarding hydrological connectivity over time can be mitigated as well, but that would require many additional calculations and calculation time.

"Page 21, line 441-450: The authors compare their estimates to the results of other exposure studies. Though from what they write it sounds like these studies assess exposure as monetary value. How is the comparison of these studies with the estimates of relative exposure of housing units from this study justified?"

Response: Thank for bringing this up. We agree that it would be better to compare our exposure figures to exposure figures from other studies. However, exposure figures are not explicitly mentioned in these studies as they only included Expected Annual Damage (EAD). The outcomes of these studies are still considered relevant as they elaborate on the same greater Rotterdam region.

Hence, we have included these studies and compared the results, but now with an explicit acknowledgment that comparing exposure results (our study) to risk results – from de Moel et al. (2014) and Veerbeek et al. (2010) – comes with limitations.

"Page 23, line 525: Is there a reference for port relocation in Hamburg? In the introduction this is only mentioned for Houston, Copenhagen and Rotterdam."

Response: We have added Hamburg to the introduction, making it consistent with the discussion section where Hamburg is already mentioned.

"Temporal line plots: I think it could be beneficial to explain the time line differences of the x-axis scales in each line plot caption in case readers are just looking into the figures."

Response: We have added brief explanations of the time scale differences in each figure caption.

Technical comments:

We have implemented almost all suggested technical corrections:

"Page 1, line 15-18: "Temporal variations in exposure rates are attributed [...] and urban development." The two sentences mean the same and one of them could be removed here."

Response: we understand your confusion. The sentences are not meant to have the same content, as the second sentence provides information about the magnitude of the attribution. We revised the sentences to better clarify their intended meaning.

"Page 5, Figure 1: Maybe write in the "exposure"-box that the data for urban development plans only reaches until 2040 to make sure it does not cover the full period of investigation."

Response: We have updated Figure 1 to clarify the urban development data horizon.

"Page 5, line 120: It should be Table 1 here, not Table 2."

Respond. We apologize and corrected the table reference on page 5.

"Page 7, line 161: I suggest to mention all tested return periods here instead of writing "from 10 to 1000 years"."

Response: We listed all return periods explicitly.

"Page 7, line 169: "These footprints were combined with elevation data from the Digital Terrain Model of the Netherlands (AHN3, 0.5-meter resolution raster) [to assign elevation values to each housing unit]. By assigning specific elevation values to each housing unit, we can accurately assess their potential exposure given various climate scenarios." I would suggest the authors to remove the words in [...] to avoid repetition and add a full stop at the end of the second sentence."

Response: We removed repetitive phrasing about elevation data.

"Page 7, line 183: "The Design Flood Elevation is one the important components ..." Look into the grammar here."

Response: We fixed the grammar in this sentence.

"Page 7, line 183 – page 8, line 188: Paragraph is formatted like the subsequent heading."

Response: We fixed the paragraph formatting issues.

"Chapter 3: Chapter 3 appears to be a bit detached from the rest of the text. I would propose to put chapter "3 Case Study: Rotterdam's unembanked areas" at the beginning of the Methods section as

a description of the study site. Chapter 3.1. and 3.2 can be included in the Results, as they describe the findings of your flood hazard calculation and data processing."

Response: We intend to have a distinct chapter to introduce the Rotterdam case. This approach allows us to provide not only data but also background on why Rotterdam is developing in a particular manner and how the current water system and policies came into place. We have included both urban development data and extreme water level data in this chapter so that we can focus on the results of the exposure analysis in the results section.

"Page 9, line 203: Should it be "have been constructed on building lots situated below the NAP+3.6 m elevation", as this is the design flood elevation?"

Response: In this case, it does not specifically refer to the design flood elevation of 3.6 m+NAP. Therefore, we have kept the original reference of 3.5 m+NAP and clarified the text to make this more explicit.

"Page 11, line 242: "3.2 Urban development between 1970-2050" Should it rather be 2040 as this is the time span of the urban development plans?"

Response: We revised the urban development timeline from "1970-2050" to "1970-2040".

"Page 17, Figure 5: The reference scenario should be mentioned in the legend."

Response. The reference is included in the vertical axis which represents the scenario minus reference.

Thank you again for your constructive and sharp comments. We hope our responses adequately address your comments.

Kind regards,

Cees Oerlemans on behalf of the co-authors.