Multi-level assessment of flood risk perception and flood behaviour

Responses to reviewers

Response to Reviewer #4

Dear Reviewer,

We sincerely thank you for your positive evaluation of our manuscript, especially recognizing the main findings and strengths of our work. We thank you very much for your detailed comments which helped us to improve the quality of the article.

We have provided a detailed point-by-point response to all your comments. We sincerely appreciate your guidance in helping us refine this study.

Sincerely,

The authors

Minor comments:

1) While the introduction is generally well written, a clear and explicit hypothesis statement is missing. I recommend formulating and placing the hypothesis at the end of the introduction (after line 87).

Answer: Thank you for giving us the possibility to state a research hypothesis. After line 87 we included the hypothesis: Spatial scale is crucial for understanding the relationship between risk and behaviour, as both worry and preparedness vary significantly across territories, while flood hazardousness is strongly conditioned by local factors. Previous research has examined flood risk and behaviours mainly at the local scale, such as neighbourhoods or municipalities. This article goes further by incorporating individual and household characteristics, allowing us to capture the multilevel complexity of space and its consequences for flood risk perception and adaptive behaviours. The hypothesis of this work is: "Flood behaviour varies differently with flood risk perception elements across different levels". To verify the hypothesis, the dimensions and variables that explain worry and preparedness at the different levels: individual, household, neighbourhood and municipality, and the relationships between worry and preparedness as well as the flood behaviour are analysed in four municipalities located along Chile, that represent different forms of urban agglomeration, ranging from small localities to intermediate cities within the national context.

2) Figure captions would benefit from being more descriptive. In particular, adding two to three sentences explaining what is shown in each figure and why it is relevant would improve clarity and interpretability (see detailed comments below).

Answer: Thank you. Figure captions were expanded to be more descriptive:

Figure 1. Location of the study area: a) the four municipalities in Chile, and surveyed households in (b) San Pedro de Atacama, (c) San Fernando, (d) Hualqui, and (e) Arauco was changed to:

Figure 1. Location of the study area showing in a) the four municipalities under study in Chile, and the surveyed households marked with orange dots in (b) San Pedro de Atacama, (c) San Fernando, (d) Hualqui, and (e) Arauco together with the rivers causing floods in blue.

Figure 2. Principal coordinate analysis (PCO) of worry at (a) the municipal level and at (b) the neighbourhood level. Dendrogram showing clusters based on similarity for (c) the municipal level and (d) the neighbourhood level changed to:

Figure 2. Principal Coordinate Analysis (PCO) of worry based on the significant variables from the multilevel regression models, with biplot vectors showing the direction and relative influence of each variable (a) the municipal level and (b) the neighbourhood level.

Figure 3. Principal coordinate analysis (PCO) of preparedness at (a) the municipal level and at (b) the neighbourhood level. Dendrogram showing clusters based on similarity for (c) the municipal level and (d) the neighbourhood level changed to:

Figure 3. Principal Coordinate Analysis (PCO) of preparedness based on the significant variables from the multilevel regression models, with biplot vectors showing the direction and relative influence of each variable (a) the municipal level and (b) the neighbourhood level.

Figure 4. Heatmaps with the joint distribution of worry and preparedness for (a) the whole sample, (b) the municipality level, and (c) neighbourhood level changed to:

Figure 4. Heatmaps derived from contingency tables between worry and preparedness visualizing the cross frequency of the different preparedness (0 - 3) and worry (1 – 3) levels for (a) the whole study area, (b) the municipalities, and (c) the neighbourhoods. The cross frequency can vary from 0 to 100%. A darker colour corresponds to a higher cross-frequency.

Figure 5. Maximum instantaneous discharges recorded each month between years 2000 and 2025 measured at gauge stations San Pedro@San Pedro de Atacama, Vilama@San Pedro de Atacama, Tinguiririca@San Fernando, Biobío@Hualqui, Hualqui@Hualqui, and Carampangue@Arauco changed to:

Figure 5. Maximum instantaneous discharge recorded each month between years 2000 and 2025 measured at gauge stations San Pedro@San Pedro de Atacama, Vilama@San Pedro de Atacama, Tinguiririca@San Fernando, Biobío@Hualqui, Hualqui@Hualqui, and Carampangue@Arauco. Red circles highlight events reported in the news and social media as damaging floods.

Figure 6. Flood behaviour according to flood recurrence and preparedness, adapted from Leong (2018). Q1: forgetting effect; Q2: proactive effect; Q3: status quo effect; Q4: learning effect changed to:

Figure 6. Flood behaviour according to flood recurrence and preparedness level, adapted from Leong (2018). The flood behaviours are Q1: forgetting effect; Q2: proactive effect; Q3: status quo effect and; Q4: learning effect. Big dots correspond to municipalities. Small dots correspond to neighbourhoods. Purple dot represent the study area, red is for Arauco, blue is for San Pedro de Atacama, black is for Hualqui and grey is for San Fernando.

3) In Section 2.2 (Survey), it would be helpful to explain the rationale behind the distribution of the survey sample across households and to clarify why the selected sample size is considered representative.

Answer: The sample distribution across municipalities was proportional to the number of households located in flood-prone areas within each municipality, ensuring adequate territorial representation. Households were selected following a spatially distributed fieldwork strategy within predefined flood-exposed zones.

The total sample size (n = 1,015; valid responses = 1,007) was calculated assuming a 95% confidence level and a maximum margin of error of 5%, using a conservative population proportion (p = 0.5) to maximize variance. Given the size of the adult population in each municipality, the achieved sample allows statistically robust estimations at the municipal level and supports multilevel modelling across individual, household, neighbourhood, and municipality scales.

4) The clustering shown in Figure 2 is informative; however, similar groupings already appear evident in the PCO plots, making the dendrograms somewhat repetitive. One potential improvement would be to include biplots (vectors indicating the direction and relative influence of the variables) within the PCO plots, which would help visualize the ordination and the “pull” of individual variables - then of course discussing those further in the discussion. The same suggestion applies to Figure 3.

Answer: Thank you for your comment. We agree that the dendrograms provided information that was largely redundant with the PCO plots. Biplots help to improve and visualize the influence of the significant variables. The figures (Fig 2 and Fig 3) have been updated according to your suggestion. The results and discussion are shown below.

Figure 2 presents the Principal Coordinate Analysis (PCO) performed using the variables that are significant in the multilevel regression for worry at municipalities and neighbourhoods. The biplots include vectors indicating the direction and relative contribution of the significant variables.

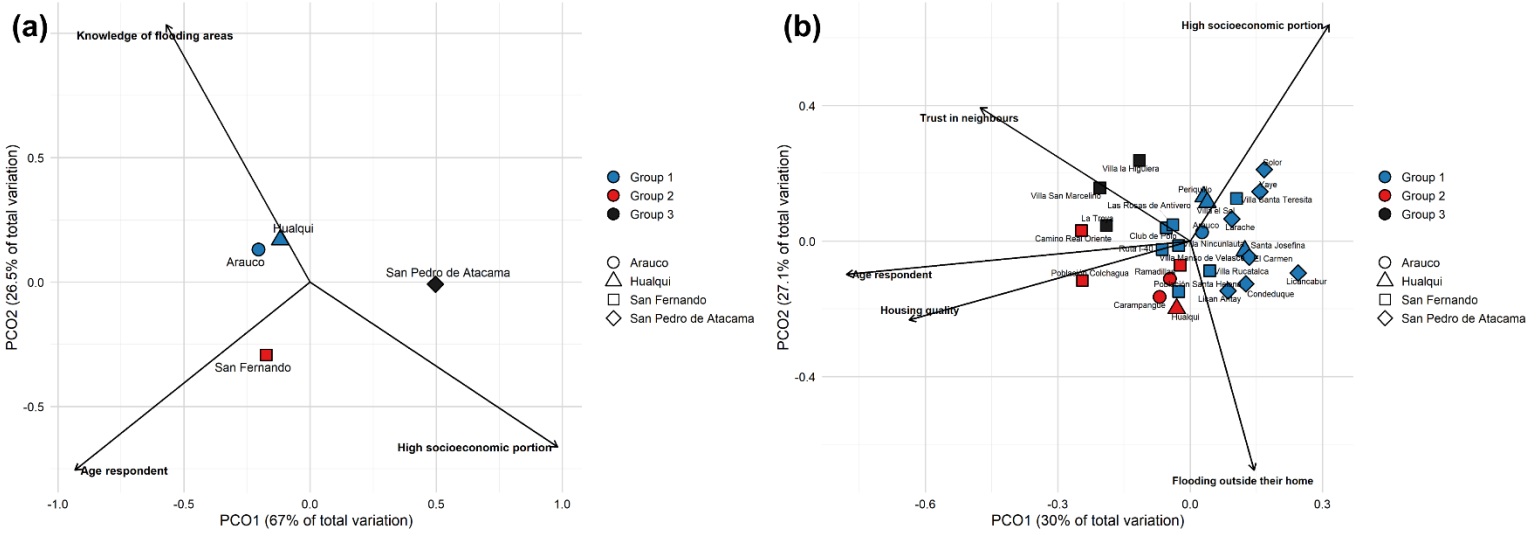


Figure 2. Principal Coordinate Analysis (PCO) of worry based on the significant variables from the multilevel regression models, with biplot vectors showing the direction and relative influence of each variable for (a) the municipal level and (b) the neighbourhood level.

At the municipal level both axes capture 67.0% and 26.5% of the total variation of worry, explaining 93.5% of the variability in the data. The biplot shows that three variables capture worry, namely age respondent, knowledge of flooding areas, and high socioeconomic proportion. Figure 2a shows that the municipalities are grouped into 3 groups. Hualqui and Arauco group together, showing similar characteristics of worry. Both municipalities are aligned with the vectors for age respondent and knowledge of flooding areas, indicating that worry in these municipalities is mainly associated with older respondents and greater awareness of flood-prone zones. San Fernando forms a separate group, although it is not completely distant from Hualqui and Arauco, as it also shares the influence of age respondent. However, it is less associated with knowledge of flooding areas, and by the contrary it is associated with socioeconomic factors. San Pedro de Atacama appears clearly separated from the other municipalities and is primarily associated with high socioeconomic proportion, indicating that worry in this municipality is linked to socioeconomic characteristics.

At the neighbourhood level (Fig 2b), the PCO shows that both axes capture 30.0% and 27.1% of the total variation of worry, explaining 57.1% of the variability in the data. The biplot shows that five variables capture worry: Age of respondent, trust in neighbours, housing quality, flooding outside their home, and high socioeconomic portion. Three different groups are formed. Group 1 is made up of neighborhoods from all municipalities, showing that neighbourhoods from different municipalities can share similar worry-related characteristics. One part of the group is associated with high socioeconomic portion. The other part of the group is mostly associated with the variable flooding outside their home, indicating that worry in these neighbourhoods is associated with direct experience with floods. Group 2 comprises neighbourhoods in San Fernando, Hualqui, and Arauco. Worry in these neighbourhoods is related to flooding outside their homes, meaning they have experienced flooding; housing quality; and the age of the residents. Group 3 consists of neighbourhoods located only in San Fernando. In this group, worry is mainly associated with trust in neighbours and age of respondent. There is also an association with high socioeconomic portion, suggesting that socioeconomic characteristics play a secondary role in terms of the worry for this group.

Neighbourhoods located near the centre of the plot are not strongly related to any specific variable. This central position indicates that worry is related to a combination of factors, without one dominant variable structuring their pattern.

Figure 3 presents the Principal Coordinate Analysis (PCO) performed using the variables that are significant in the multilevel regression for preparedness at municipalities and neighbourhoods. The biplots include vectors indicating the direction and relative contribution of the significant variables.

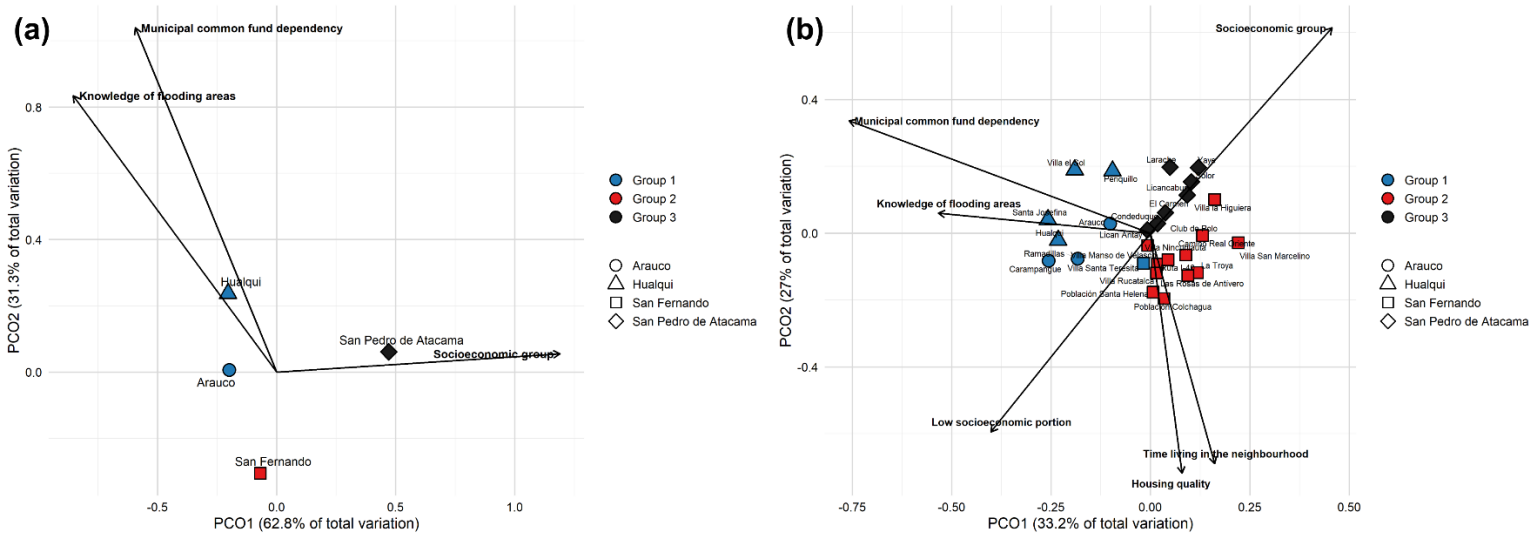


Figure 3. Principal Coordinate Analysis (PCO) of preparedness based on the significant variables from the multilevel regression models, with biplot vectors showing the direction and relative influence of each variable for (a) the municipal level and (b) the neighbourhood level.

At the municipal level the first and second PCO axis explain 62.8% and 31.3% respectively, explaining 94.1% of the variability in the data. The biplot shows that three variables capture preparedness: Knowledge of flooding areas, socioeconomic group, and municipal common fund dependency. Figure 3a shows that the municipalities are grouped into three groups. Hualqui and Arauco group together, showing similar characteristics of preparedness. Both municipalities are aligned with the knowledge of flooding areas and municipal common fund dependency, indicating that preparedness in these municipalities is mainly associated with a greater understanding of the flood-prone areas in the municipality and the economic dependence on the municipal common fund.

At the neighbourhood level (Fig 3b), the PCO shows that both axes capture 33.2% and 27.0% of the total variation of preparedness, explaining 60.2% of the variability in the data. Six variables characterize the preparedness at the neighbourhoods: Knowledge of flooding areas, time living in the neighbourhood, housing quality, socioeconomic group, low socioeconomic portion and municipal common fund dependency. The neighbourhoods are grouped into three groups. Group 1 consists of neighbourhoods from Hualqui and Arauco, and one from San Fernando. Preparedness in these neighbourhoods is mainly related to the knowledge of flooding areas and to the municipal common fund dependency. Their proximity to the vectors socioeconomic group and low socioeconomic portion indicates that preparedness in this group is also structured by socioeconomic factors. Group 2 includes only neighbourhoods from San Pedro de Atacama. This group is primarily determined by socioeconomic status, demonstrating that preparedness in the neighbourhoods of San Pedro de Atacama depends mainly on their socioeconomic condition. Group 3 is composed of neighbourhoods from San Fernando and is mainly characterised by housing quality and time living in the neighbourhood. This indicates that preparedness in these neighbourhoods is due to better housing quality and longer residence time in the neighbourhood.

5) The results clearly identify which population groups and spatial units are most relevant for improving flood preparedness. However, these findings are not sufficiently discussed. The manuscript would benefit from a more explicit discussion on how the identified parameters can inform targeted and repeated interventions, and how such interventions could ultimately reduce flood damage and save lives. In Table 5 and Table 6 you provided a lot of interpretation very nicely, please provide a thorough explanation within the discussion. What are these in your specific cases in your selected locations and what can we learn from them?

Answer: Thank you for giving us the opportunity to expand the discussion. An additional point was added as follows:

4.4 Improving preparedness against floods

The obtained results allowed us to identify which population groups and spatial units are most relevant for improving flood preparedness. As evidenced in Tables 5 and 6, the correlation between worry and preparedness is not straight forward, however in Fig. 6 three out of four possible flood behaviours proposed by Leong (2018) were identified in the study area as a function of preparedness and flood recurrency, namely the *status quo*, the learning, and the proactive effects. Dispersion in the observed behavior increased when reducing the level. The variables controlling preparedness and flood behaviour in critical places were related to the knowledge of flooding areas and the economic resources available for implementation of measures to prevent flood damages. This information suggests that the neighbourhood is the appropriate spatial scale at which preparedness should be promoted in the frame of risk management. Similarly, risk communication should focus on the neighbourhood level to inform residents the precise flood prone areas, especially in neighbourhoods exhibiting a *status quo* effect such as those pertaining to San Pedro de Atacama. Aim should provide households with the necessary financial resources for improvement of the cautionary measures, especially in neighbourhoods with low preparedness, such as those in San Pedro de Atacama, Arauco and Hualqui.

Other comments:

6) Line 38: add more references

Answer: Thank you for this comment. Social vulnerability indices have been extensively used and developed for accounting risk in the natural hazards context. We added key references on SoVIs:
Cutter, S.L., Carolina, S., Boruff, B.J., Shirley, W.L., 2003. Social Vulnerability to Environmental Hazards. Soc. Sci. Quart. 84 (2) 242–261.
Cutter, S.L., Emrich, C.T., Morath, D.P., Dunning, C.M., 2013. Integrating social vulnerability into federal flood risk management planning. J. Flood Risk Manag. 6, 332–344

7) Line 48: emphasize here the importance of social vulnerability.

Answer: Thank you. The text was extended after line 48 to: “Remarkably, Scolobig et al. (2012) showed that the link between awareness and preparedness is not at all straightforward, as in the Italian Alps, residents felt both slightly worried about flood risk and slightly prepared to face an event. There was also a clear discrepancy between the actual adoption of household preparatory measures and the willingness to take self-protection actions among the studied localities, emphasizing the importance of social vulnerability on flood risk perception.”

8) Line 52: three different methods - briefly explain

Answer: Thank you for giving us the opportunity to explain each of the three methods that have been used for the analysis of the long-term interactions between the human and social systems. The text was changed to: Such interactions have been studied through three different methods (di Baldasarre et al., 2015): one of the most common methods in the social sciences is based on statistical analysis of empirical research data, such as surveys and interviews combining the strengths of qualitative and quantitative data. This method relies on extensive and robust empirical data, which can be expensive and time consuming to collect. A second method is agent-based modeling which operate by prescribing rules on how individuals and/or institutions (the agents) interact, and therefore allow heterogeneity to be included. They compute the interactions at the microlevel which leads to observed behavior at higher levels. The disadvantage of these models is that they can become extremely complex, results might be difficult to interpret, and they are often not generalizable. In a third method, a number of hypotheses about the fundamental processes and interactions driving the behavior of the system are explicitly formalized using a set of differential equations. This type of modeling has proved to be useful where empirical data are limited. Moreover, differential equations for dynamic modeling have been recognized as being appropriate for understanding complex systems and it has been widely used in neoclassic economic models.

9) Line 54-55: briefly explain levee and adaptation effect

Answer: Thank you for giving us the opportunity to explain the learning and the forgetting effects. The text was expanded as follow: In particular, the socio-hydrology of floods recognized already different flood behaviour types that emerge from the interactions between the social and the hydrological system during floods, such as the so-called "forgetting or levee effect" and the "learning or adaptation effects". The forgetting effect relates to the observation that the rare occurrence of flooding (possibly caused by protection measures, such as levees) is often associated with increasing vulnerability. In the learning effect, the frequent occurrence of flooding is often associated with decreasing vulnerability. It can be attributed to enhanced coping or adaptation capacities gained by individuals and communities during their flood experience. (di Baldasarre 2017).

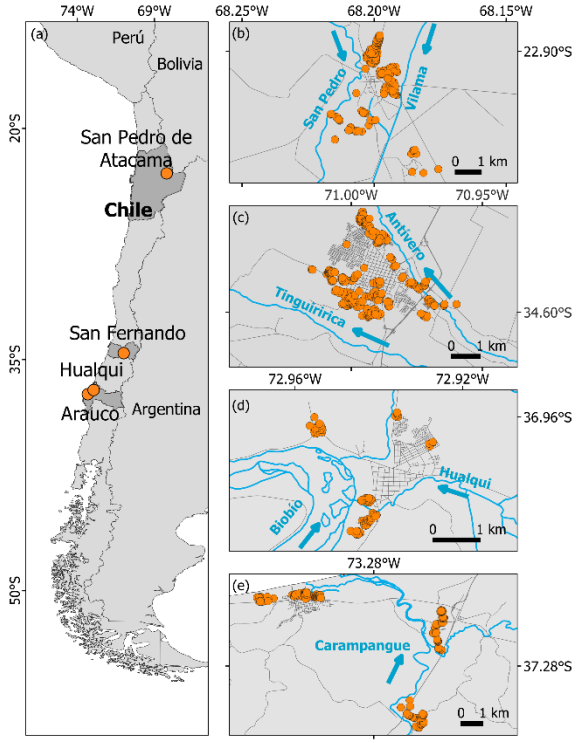
10) Line 93-95: combine these sentences and consider rephrasing it

Answer: Thank you. Please see also the Ans. to your comment 1). Line 93-95 were modified according to your suggestion:

Spatial scale is crucial for understanding the relationship between risk and behaviour, as both worry and preparedness vary significantly across territories, while flood hazardousness is strongly conditioned by local factors. Previous research has examined flood risk and behaviours mainly at the local scale, such as neighbourhoods or municipalities. This article goes further by incorporating individual and household characteristics, allowing us to capture the multilevel complexity of space and its consequences for flood risk perception and adaptive behaviours. The hypothesis of this work is: "Flood behaviour varies differently with flood risk perception elements across different levels". To verify the hypothesis, the dimensions and variables that explain worry and preparedness at the different levels: individual, household, neighbourhood and municipality, and the relationships between worry and preparedness as well as the flood behaviour are analyzed in four municipalities located along Chile, that represent different forms of urban agglomeration, ranging from small localities to intermediate cities within the national context. The next section describes the study area, and statistical analysis. Section 3 presents the obtained results on variables explaining worry and preparedness, their correlations and distribution among the neighbourhoods and municipalities.

11) Line 95-96: the word "discussed" is used twice
Answer: Thank you. The text was corrected accordingly.

12) Figure 1: explain the rationale in 2 sentences about the selected households. Also, can you mark flow directions on maps b-e?
Answer: Thank you for your comment. The explanation of the selection of household was added in the Section 2.2. of the manuscript: Across the study areas, zones for survey application were pre-selected based on their flood exposure within the four municipalities. The household was defined as the unit of analysis. Surveyors selected households where an adult resident agreed to participate, typically following a non-consecutive pattern of household. Additionally, flow directions were added in the Figure 1 (b) (c) (d) (e):



13) Line 113: …which reduces temperature extremes…. - need reference
Answer: The description of the specific climate classes was taken from Sarricolea et al. (2017). The reference was included in the text after Line 113.

14) Line 115: National Weather Agency -put a link of your source
Answer: Thank you, done!

15) Line 115-120: round all precipitation numbers
Answer: Thank you, done!

16) Line 124: Census Data - need reference
Answer: Thank you. The reference is: Chilean National Institute of Statistics (INE). Population and Housing Census 2002, 2017 and 2024. Instituto Nacional de Estadísticas, Chile.

17) Line 150: GIS - what version?
Answer: Thank you. The GIS version is QGIS v3.40.0

18) Line 167: what weights?
Answer: The weights refer to the official indicator weights defined in the construction of the Multidimensional Poverty Index (MPI) used in the CASEN survey, following the Alkire and Foster (2007) methodology. These weights are predefined by the CASEN methodology and are not estimated or modified in this study.

19) Line 200: The survey answers what?
Answer: Thank you for your comment. The survey answers related to flood risk perception, preparedness, worry, and sociodemographic characteristics, together with complementary data. The sentence has been revised and clarify in the manuscript.

20) Line 267-269: it is a bit hard to follow what percentage belongs to what. Consider rephrasing it.

Answer: Thank you. We fully agree with this comment. The sentence was reformulated to: Interestingly, 57.9% of the surveyed people live closer than 750 m from the river, i.e. in areas with a high exposure to flood, 84.7% declare to know the flooding areas, and 55.4% experienced a flood passing outside the home. Overall, 96.2% of all respondents live closer than 750 m from the river, declare to know the flooding areas, and/or

experienced a flood passing outside the home. Thus, in the present study people were assumed to be aware of flood risk.

21) Line 398: "…who are not worried." - Do you have an explanation why?

Answer: Thank you for this comment. One possible explanation is that preparedness does not necessarily imply high levels of worry. Even if flood events are not highly recurrent in this neighbourhood, previous experience with flooding may have led residents to adopt certain preparedness measures, which can increase their sense of capacity to manage future events. As a result, respondents may report medium levels of preparedness while not expressing high worry, consistently with the findings by Scolobig et al. (2012).

22) Line 401-405: show flood frequency in flood/yr and not average.

Answer: Thank you for the observations. Flood occurrence has been revised as suggested. Table 8 now presents flood frequency (floods per year) and the corresponding mean recurrence interval for each municipality.

23) Line 419: Table 8 caption: These are preparedness level values not expl variables. Correct table title and give explanation and meaning in 2 sentences.

Answer: Thank you. Table 8 presents the average predicted level of preparedness for each municipality, as estimated by the multi-level ordinal regression model. The outcome variable is measured on an ordinal scale from 0 (non-preparedness) to 3 (high preparedness). The Table was corrected accordingly.

24) Line 423: "...we assumed a threshold of 7 years…" - based on what?

Answer: Thank you for giving us the possibility to justify this assumption. The 7-years threshold comes from antecedents summarized by Lechowska (2018): According to The International Commission for the Protection of the Rhine (ICPR), flood risk perception usually decreases 7 years after flooding while catastrophic disasters are remembered much longer (Egli & Wehner, 2002). The literature also suggests that the positive influence of experiences on private mitigating behaviours may disappear several years after the flood. Hence, the time of the previous flood (time of the experience) plays a major role, since it can be expected that the experience of the flood that occurred a long time ago has little influence on current risk perception and mitigating behaviours. Long floodless periods result in a decrease in the level of worry and awareness." Further, Barendrecht et al. (2019) based on Egli & Wehner (2002) and Bornschein & Pohl, 2014) adopted 7 to 10 years as the time after which awareness is halved, and related it to a so-called forgetfulness.

References added to the text:

Bornschein, A., & Pohl, R. (2014). Hochwasserbewusstsein 10 Jahre nach dem "Jahrhundertereignis" im Osterzgebirge und an der Elbe. In Vorsorgender und nachsorgender Hochwasserschutz (pp. 19–29). Wiesbaden: Springer Vieweg.

Barendrecht M. H. Viglione A. Kreibich H. Merz B. Vorogushyn S. Blöschl G. 2019 The value of empirical data for estimating the parameters of a socio-hydrological flood risk model. Water Resources Research 55, 1312–1336. https://doi.org/10.1029/2018WR024128.

Egli, T., & Wehner, K. (2002). *Non structural flood plain management: measures and their effectiveness*. International Commission for the Protection of the Rhine (ICPR), Koblenz.

25) Line 508: "exhibited" used twice in the same sentence.

Answer: Thank you. The sentence was changed to: Municipalities exhibited different flood behaviours, and flood behaviours at some neighbourhoods were different to those of the corresponding municipalities, evidencing important differences across the analysed levels, according to several urban scales.