Comments by Reviewer n. 2 and Replies by Authors

General comments

This manuscript presents a probabilistic assessment of fluvial flood risk for the countries in the region of Central Asia. My opinion is that the work is a relevant contribution to improve flood risk knowledge in Central Asia, providing a consistent transboundary risk assessment for all the region.

The overall methodology is appropriate for the task and makes use of well-established models and datasets, integrating where possible global-scale a local-scale data. The inclusion of several risk parameters in the analysis (e.g. damage for different economic sectors) is appreciable

Having said that, I think that the manuscript needs to be improved in some parts. The descriptions of some components of the methodology are rather short or incomplete and should be expanded. Similarly, the presentation of results should provide a more detailed overview of the different outcomes.

R: Thank you for your assessment of our manuscript. We appreciate your acknowledgment of its relevance in improving flood risk knowledge in the region, particularly through the provision of a consistent transboundary risk assessment.

We're glad to hear that you find the overall methodology appropriate.

We take your suggestions for improvement seriously. We recognize the need to expand upon certain components of the methodology that may be lacking in detail and to provide a more comprehensive overview of the results. Your feedback will guide our revisions to ensure the manuscript meets the standards of clarity and completeness expected by readers.

Specific comments

Abstract: it is not well structured as it is now. Background information (lines 22-36) should be reduced or moved in the introduction (for instance, the work done in the project on pluvial flood and seismic risk). At the same time a short summary of the main elements of the methodology and main results should be added.

R: Thank you for your feedback on the abstract. We will restructure it to reduce background information and potentially move it to the introduction. Additionally, we will include a concise summary of the main elements of the methodology and key results to improve clarity and organization.

Figure 1: please add country names and, if possible, other details such as the location of main rivers (in particular those mentioned later in the text) and/or main urban areas

R: Thank you for your suggestion regarding Figure 1. We will incorporate country names and, if possible, include additional details such as the location of main rivers and major urban areas.

Page 4 L135-137: can you please explain how you used observed data from the KNMI Climate Explorer to correct ERA5-Land extreme precipitation estimates?

R: Regrettably, the bias correction of ERA5-Land precipitation using raingauge data is not relevant to the present paper and should not have been placed in the draft originally submitted. The original study carried out fluvial and pluvial flood risk assessments, but the present paper only shows fluvial risk assessment. This bias correction mentioned here was not carried out for the fluvial risk assessment, only for the pluvial risk assessment, and therefore is not relevant here. We apologise for the confusion. We will remove all references to pluvial flood and ERA5-Land bias correction from the paper.

Figure 2 is not relevant within the description, so I suggest removing it

R: Noted.

Figures 3 and 4: I think they can be merged

R: We agree with the reviewer and will merge the two figures.

Page 5: please provide a reference for the GlobeLand30 dataset. Is it based on static or dynamic-over-time land use information?

R: GlobeLand30, developed by the National Geomatics Center of China, is a global land cover dataset that categorizes the earth's land into 10 classes worldwide, including water bodies, wetlands, artificial surfaces, cultivated land, forests, shrublands, grasslands, bare land, tundra, and permanent snow & ice. This dataset offers a resolution of 30 meters and it provides information for two time points (2000 and 2010) for comparison. The dataset has been independently assessed to be 83% accurate (Dong, et al. 2015). The data is available for non-profit use, and it was contributed to the UN in September 2014 (https://www.un-spider.org/links-and-resources/data-sources/land-cover-map-globeland-30-ngcc).

In the revised manuscript we will include a reference and a brief description of the dataset.

Page 5 L 144 "This dataset has been made accessible to the United Nations (UN) through the UN-ESCAP Statistics Division and the UN_ESCAP ICT and Disaster Risk and Reduction Division": please move this detail in the Data Availability section.

R: Thanks for the suggestion, we will move it accordingly.

Page 5 L 150 the reference for the original MERIT DEM should be Yamazaki et al (2017)

R: Noted.

Page 5 L 163-168: I think that the details on the method applied to combined local-scale information on flood defences with the FLOPROS, WorldPOP and Landsat HBASE datasets (now in page 11 L333-348) should be moved here.

R: We agree. Thank you.

Page 9: the description of the CA2D model is perhaps too long compared to the description of the other models

R: Thank you for your observation. We will review the description of the CA2D model and ensure it is balanced with the descriptions of the other models for consistency.

Pagge 9 L250-254: I suggest moving this description in Section 3.2. Also, can you provide more information on the exposure database? For instance, does it include building-scale or aggregated information? Which infrastructures are considered? In the following sections you name different types of infrastructures, they should be described here

R: All the details related to the developed exposure model and the assets at risk included in the model can be found in two companion papers (Scaini et al., 2023 – for population and residential buildings; Scaini et al., 2024 – for non-residential buildings, transportation infrastructure and cropland).

Page 11 L301: Generalized Extreme Value

R: Ok. Thank you.

Section 4.1 is quite long. Consider splitting it into two or more subsections (e.g. hydrological modeling, hydraulic modelling and stochastic analysis)

Figure 5 is not much useful so it could be deleted.

R: Thank you for your suggestion. In order to address both your and the other reviewer's comments, we will revise Section 4.1 and reorganize it into subsections corresponding to the 5 steps. Since each step will correspond to a specific portion of Figure 5, retaining the figure will aid in streamlining the discussion.

Page 11: did you undertake any calibration of the CA2D model (e.g. the roughness parameters)? Also, how did you identify the river sections mentioned in the description?

R: Thank you for your inquiry. The calibration of the CA2D model primarily focused on reproducing historical event hydrographs in terms of volume and peak timing. Specifically, our calibration efforts centered on adjusting configurations to best replicate historical event hydrographs, with the final assumption of a triangular hydrograph reaching the flood peak at 2/3 of the concentration time and returning to zero at twice the concentration time.

We did not calibrate roughness parameters. Instead, we relied on roughness coefficients obtained from literature sources (Arcement, et al., 1989).

Page 11 L333-348: see my previous comment about the opportunity of moving this description to Section 3.1. Besides that, how did you implement flood protections in the risk modeling framework? Did you explicitly include flood protections in CA2D simulations (e.g. by modifying the DEM) or only in the risk analysis (i.e. assume that the all floods below the design level would cause no damage)?

R: Thank you for your feedback. We will relocate the description to Section 3.1 as suggested.

In our risk modeling framework, flood protections were not explicitly accounted for in CA2D simulations. Instead, we adjusted water depth maps to reflect the presence of flood protections. Specifically, we assumed that areas with water depths below the designated level of protection would not incur any losses.

Page 12 L375-383: there is little information on the climate scenarios. Could you please describe the underlying models that were used to define these scenarios (GCMs. RCMs) and provide references? How did you downscale future climate scenarios to match ERA5-land data resolution?

R: The climate scenarios we employed are described in Ozturk et al. (2017). In that stud, the Regional Climate Model (RCM), RegCM4.3.5 of the International Centre for Theoretical Physics (ICTP) was driven by two different CMIP5 Global Climate Models (GCMs), the HadGEM2-ES GCM of the UK Met Office Hadley Centre and the MPI-ESM-MR GCM of the German Max Planck Institute for Meteorology, under two emission scenarios (RCP4.5 and RCP8.5). Based on its predictive skills, we selected the MPI-ESM-MR GCM. We selected the RCP4.5 over the RCP8.5 as it is more in line with the current emission pathway and the future pledges for emission reduction (Roger Pielke Jr *et al* 2022). The model was run over CORDEX's (Giorgi et al., 2009) Central Asia domain (with the corner points at 54.76°N - 11.05°E, 56.48°N - 139.13°E, 18.34°N - 42.41°E, and 19.39°N - 108.44°E).

Bias-correcting climate projections before using them in hydrological modelling is standard practice and should always be carried out to avoid propagating the climate model biases into the hydrological model results (Shrestha et al., 2017; Teutschbein and Seibert, 2012). The methodology we used here belongs to the "delta change" family cited by Teutschbein and Seibert (2012), The literature on this methodology and its implications on hydrological model outputs is very extensive and well documented, here we cite only a few examples (Räty et al., 2014; Mudbhatkal and Mahesha, 2017; Räty et al., 2018; Fang et al., 2015). It is simpler than other techniques, since it does not require to bias-correct the baseline climatology (which is still the observed climatology), although it has the disadvantage that some properties of the variable to be corrected still remain unadjusted (for example, if the precipitation from a certain climate projection is simply multiplied by a factor in order to reproduce the annual average of the reference dataset, the distribution of the original reference dataset will be maintained and only the mean values will be corrected – this is also called "constant scaling"). However, the approach used in this paper, which adjust the whole distribution of precipitation and temperature, not only the mean or the standard deviation, limits this disadvantage. Räty et al (2014), among others, have discussed the advantage and disadvantages of such technique, which blends the simplicity of the delta factor methodologies with the robustness of the quantile mapping methodologies.

Section 4.2: some comments here: 1) there seems to be no description of how you applied SSP scenarios in the risk analysis, please provide details. 2) provide a complete list or table of all the risk parameters (impact for different economic sectors, population affected, mortality etc.). 3) put the description of calibration/validation in a dedicated subsection 4) it is sometimes difficult to understand which data were used for calibration and validation of the model (here and in Section 5 too), please try to make it clear.

R: Thank you for these comments. All the details related to the considered SSPs and their application in the exposure model development and therefore in the risk analysis can be found in the paper Scaini et al., 2023.

Page 13 L430: you mention a list of historical events and reported losses, can you provide a reference for this information, is it coming from local governments?

R: The list of historical reported losses is sourced from local governments/agencies and was obtained as part of our project's objective of regional cooperation and capacity building. In the revised manuscript, we will explicitly mention the data source to provide proper credit and transparency.

Section 5.1.1: change section name to "hydrological model"

R: Noted.

Figure 7: make sure that the Y axis for precipitation and temperature data is readable in all panels. Also, the small maps on the top left side of each graph are difficult to interpret (is it the river basin?). Perhaps it could be useful to put a separate map to locate the different river sections in the region.

R: Thank you for your feedback. In response to other reviewer suggestions, we plan to enhance this section by providing more detailed information on the hydrological model calibrated parameters and incorporating relevant metrics from the stochastic evaluation.

To improve clarity, the figures will be moved to the supplementary material, and we will take measures to enhance their readability as suggested.

Figure 8: the trend lines should be more visible

R: Noted.

Section 5. 1.2: please put in dedicated sections the calibration of vulnerability curves and the validation of flood extent maps (they should be presented before the validation of modelled risk estimates).

R: Thank you for your suggestion. This section currently lacks clarity and will be reorganized to distinguish between calibration and validation procedures and results.

Section 5.1.2: Here you mention vulnerability functions for infrastructures and crops, they should be described in Section 4 (I undestsnf they are taken from previous studies but you should specify, for instance, if you used separated functions for each country).

R: The assets covered are buildings, infrastructure (roads and airport) and crops. More information can be found in a companion paper (Scaini et al., 2023, 2024).

Flood vulnerability for buildings was derived using a component-based flood vulnerability model, called INSYDE (Dottori et al., 2016). This model account for different measures of the event intensity (water depth, but also flow velocity, flood duration, sediment load, water quality, etc.) and different components of the building (structural, non-structural, finishing, doors/windows, systems, basement, etc.) to derive a large set of curves for each component of the damage. These curves are then combined depending on the characteristics of the building categories.

INSYDE is a very flexible vulnerability model, suitable for both data-rich and data-poor scenarios. In this study, a specific vulnerability function relating water depth and level of damage was set up for each of the taxonomy categories: Residential (Unreinforced masonry, Unreinforced masonry concrete floors, Confined masonry, Reinforced masonry, low rise, Reinforced masonry, medium rise, Reinforced concrete frame without earthquake-resistant design, Reinforced concrete frame with moderate earthquake-resistant design, Reinforced concrete frame with high level of earthquake-resistant design, Reinforced concrete walls without earthquake-resistant design, Reinforced concrete walls with moderate level of earthquake-resistant design, Reinforced concrete) walls with high level of earthquake-resistant design, Adobe, Timber structure, Timber structure, Steel structure, Other structure), Schools, Hospitals, Commercial, Industrial (Scaini et al., 2023, 2024). Note that the categorisation is, in some cases, done based on criteria that are not relevant to flood risk (e.g., earthquake-resistant design does no affect flood damage). This was done in order to ensure compatibility with a companion earthquake risk model.

Some flood-relevant parameters were not explicitly considered in the categorisation, due to lack of spatialised data, for example the presence of a basement, the number of storeys or the height of the ground level over the surrounding terrain. These parameters were treated in a statistical way. For example, if, within a certain category, the percentage of buildings with one storey is 40% and the percentage of buildings with two storeys is 60%, the final vulnerability curve was obtained as the weighted average of two curves, one considering a one-storey building, the other considering a two-storey building. The distributions of such parameters were obtained from the available literature (Pittore et al., 2011; Pittore et al., 2020; The World Bank, 2017; Wieland et al., 2015), from local institutions (for example, the Kazakh Research and Design Institute of Construction and Architecture –

KazNIISA), from local surveys (for example, in Dushanbe, Tajikistan, from Pittore et al., 2020) and from polls and consultations with local experts carried out during several workshops in 2021 an 2022 and organised by the World Bank.

The component-based approach also requires unit costs for each component. These are the costs per unit (usually per m, m2 or m3) of cleaning/removing/replacing each of the component. These costs have been collected onsite by local advisors and engineers through inquiries with engineers and architects involved in the design and pricing of buildings and from engineering manuals or real estate catalogues (for example, the ENiR - Uniform norms and prices for construction, installation and repairing works).

Local knowledge was key in the construction of vulnerability curves for buildings, in terms of defining unit costs of the components, archetype buildings, materials, etc. This knowledge, together with the literature cited above and the collaboration with local institutions and experts led to produce vulnerability curves that are highly suitable for the local context, as opposed to the common practice of transferring curves developed elsewhere without considering the local context. This approach also allowed producing separate curves for each country.

The infrastructure vulnerability (e.g., roads, power plants, airports) was taken from the Global Flood Depth-Damage dataset developed by the European Union's Joint Research Centre (Huizinga et al., 2017) and from from HAZUS (HAZard United States) (FEMA, 2018), the natural hazard analysis tool developed and freely distributed by the US Federal Emergency Management Agency (FEMA).

Flood vulnerability for the two prevalent crops, cotton and wheat, were derived from the literature. The cotton curve was derived from Qian et al. (2020). The wheat curve was derived from similar crops (no specific wheat curves were found for Central Asia, or Asia in general, but vulnerability curves for other cereals in Asia exist) (Baky et al., 2020; Hendrawan et al., 2021; Kwak et al., 2015; Molinari et al., 2019; Win et al., 2018).

Section 5.1.2: Can you describe how the observed flood extent for the 2005 event was derived? Did you carry out a quantitative comparison of observed and modelled flood extent model? It would be useful to calculate some performance metrics (see Alfieri et al 2014 for instance) and check if the observed underestimation of impacts might depend on underestimation of flood extent. Also, please include the reported the flood footprint in the map in Figure 9.

R: The 2005 Hamadoni flood is the only event for which reported losses, flood footprints and river flow time series are available.

The flood in Hamadoni, was the subject of the PhD Thesis of one of the local partners, as well as the focus of a report from JICA (Study on Natural Disaster Prevention in Pyanj River, 2007, https://openjicareport.jica.go.jp/pdf/11870748_01.pdf). The observed flood extent as well as the inlet discharge data were extracted from the JICA report.

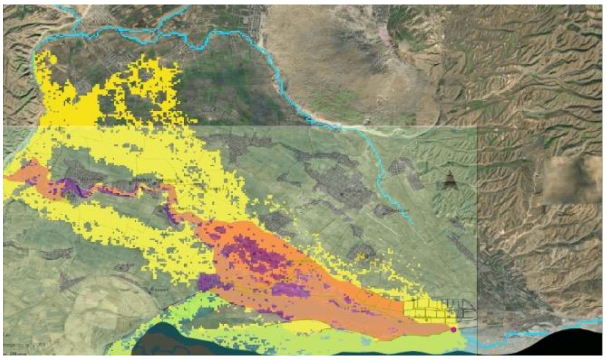
The flood event was quite long and involved a dyke breach and extensive damage to the nearby villages The JICA study provides both a probable inundation area that was estimated from satellite data, and a flood footprint that was simulated. The following factors contribute to the uncertainty in both the JICA results and ours:

- Satellite data from SPOT and ASTER are only available before and significantly after the peak. This probably explains the satellite estimated flood map underestimation of the flood extent.
- The inlet discharge was estimated from the data recorded at a different station which is located at 80 km upstream, by the peak discharge ratio.
- The simulated water depth values are not available from the JICA study, we only have a figure that we superimposed over our flood footprint for a visual comparison.
- We did not simulate the dyke breach as information on its location and the nature of the damage was not available.

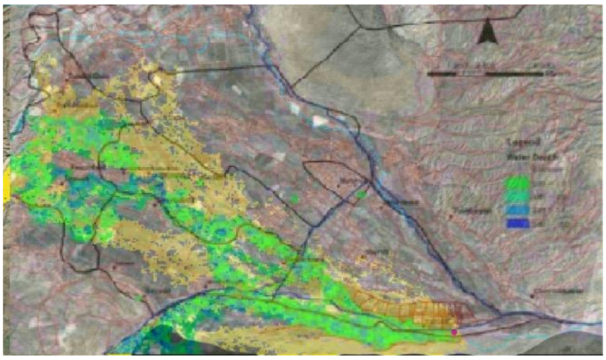
We built our hydrograph by taking the data estimated by JICA and used it as input to the CA2D model to get the flood footprint for the event.

In the revised manuscript we will provide both reference to the original study and the figures of the visual comparison.

Comparison with the satellite estimated flood map



Comparison with the JICA flood map



The graphs in Figure 10 are not useful because there's only one point for each graph. I would replace them with a table or directly include the numbers in the text. In case the event is reported in global loss datasets (for instance, in the International Disaster Database EM DAT, https://www.emdat.be/) this could be used as an additional reference for comparison.

R: Agreed, we will provide the numbers in the text and provide a reference.

Page 19 L595: do you mean that you have calibrated the loss model based on this comparison? Or are you referring to the calibration done on the vulnerability functions mentioned before?

R: Thank you for bringing this to our attention. We apologize for any confusion caused by the lack of clarity in this section regarding calibration and validation. Indeed, the reported losses were utilized for both the validation of the entire modeling chain and the calibration of the vulnerability functions.

In the revised version of the manuscript, we will reorganize this section to clearly distinguish between calibration and validation processes for the various model components. This will ensure better clarity and accuracy in describing our methodology.

Page 20 Possible explanations for underestimated impacts are that pluvial flooding impacts were not considered, as well as impacts ng in the minor drainage network not included in hydraulic modelling.

R: Thank you for raising these points. It is indeed possible that the underestimated impacts could be attributed to several factors, including the exclusion of pluvial flooding impacts and impacts within the minor drainage network not covered in the hydraulic modeling. Additionally, the consideration of landslides could further contribute to the estimated impacts. Furthermore, it's important to acknowledge the significant uncertainty inherent in the process of actualizing damages to current monetary values.

Figure 14: the graphs in this figure are not much informative because water depth changes in each pixel of the model; instead, showing flood extent graphs over an area (a country or a river basin) would be more useful.

R: Thank you for your feedback. Figure 14 should provide a comparison in risk profile for 5 representative sites (one for each country), while Figure 12 displays flood extent and intensity over Uzbekistan. We agree that Figure 12 has very small details, in the revised manuscript we could provide a different example of fluvial flood hazard map that includes a smaller area.

Section 5.3.2: The Global Assessment Report on Disaster Risk Reduction 2015 (GAR2015) produced risk profiles for all countries in the world for different natural hazards including floods. I think it would be interesting for the reader to see how GAR estimates compare with those of the manuscript (country profiles are available at https://www.preventionweb.net/english/hyogo/gar/2015/en/home/data.html).

R: Thank you for your suggestion. While comparing our flood risk estimates with those from the Global Assessment Report on Disaster Risk Reduction 2015 (GAR2015) could offer valuable insights for readers, it falls outside the scope of the paper. Nonetheless, we appreciate the idea and will keep it in mind for future research or supplementary analyses.

Section 5.3.2: Table 4 and figure 15 show more or less the same information so I would keep the figure in the text and perhaps move Table 4 in a supplement. The same applies for Table 5 and figure 16.

R: Thank you for the feedback, we will only keep the tables in the revised manuscript.

Table 6: Comparing Tables 4, 5, 6 it seems that the absolute losses decrease in the 2080-SSP1 scenario, whereas relative losses increase. Can you explain this behavior? Did you observe a similar behaviour in other future scenarios? You might also want to check if your results are consistent or disagree with existing global studies (e.g. Dottori et al 2018, with apologies for the self-citation).

R: The increase in the absolute values of losses is mainly driven by an increase in exposed value. It is widely accepted that increases in exposed value are the main driver of increased losses from natural disasters globally (Pielke, 2021), and this region of the World shows a similar behaviour. The decrease in the relative value of losses is driven by a decrease in flood hazard, caused by climate change. This is mainly due to a reduction in snow cover during winter and, subsequently, a reduction in snow melt in spring and summer, which is one of the drivers of floods in this region. It should be noted that the patterns of climate change-driven effects on flood hazard are highly variable in space, with even some increase in flood hazard in the driest parts of the area, where an increase in precipitation intensity should increase flood hazard. It should also be noted that the uncertainty in such forecasts is very large, and, for a proper assessment of the impacts of climate change at such a distant horizon, other scenarios/models should be used. This was not done within the framework of this study, as it was not the main aim of the project, but it is definitely worthwhile as a follow-up activity.

Section 5.3.2. Currently this section only shows results for overall economic damage. I would recommend to provide an overview of all the results produced by the analysis (e.g. human fatalities, breakdown of damage per each economic sector considered, impact on infrastructures etc.). This information would be useful because it is rarely reported in similar studies in literature. Also, you should include in the discussion the results for future scenarios other than 2080-SSP1 (if deemed important, additional results could be added in a Supplement).

R: Thank you for this suggestion. We will introduce more results in the revised version of the manuscript.

Data availability: Please provide here the details for accessing all the datasets used in the study (or explain why they are restricted). For instance, several global datasets are freely available (Table 1),

R: All the datasets belong to the World Bank group. However, the Bank has in plan to share the collected data as well as the computed results via a website where all the information can be download by any user.

Section 7: you could include a short summary of the main outcomes (e.g. countries with higher relative impacts, risk hotsposts).

R: The revised manuscript will include a short summary of the main outcomes in the conclusion section.

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