

Disparities in exposure to hydrogeomorphic hazards in Bangladesh

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Here, authors aggregated different models which are mainly developed by other communities and applied a few statistical tests to figure out exposure biases. Authors successfully identified research gaps, but their potential contribution to bridging these gaps is limited to generating a few percentages and mapping only a few spatial datasets. I find no novelty in this.

Due to lack of local experts' consultations and/or local field knowledge/validation, misinterpretation of deep learning model (in)outputs are also observed. Figure 2, which represented geographic hotspots generated by geographical hazards, is misinterpreted. Discarding changes in Land Use Land Coverage affected its results the most. I assume the authors mixed up flood water with other water pixels.

For example, in Figure 2, the Southwest region is represented as a high hotspot area with increasing erosion or waterlogging. But, intentionally created shrimp cultivation ponds in the dry season are mostly (approximately more than 60% area) marked here as waterlogged points compared to what really exists in the field as this is a solely remote sense-based model. Also, rainwater harvesting in the rice field (which are flood free in general) during October-November for Southwest Region can be misinterpreted as waterlogged by authors as this paper took October-March as their dry season. Instead, I suggest considering Dec-Mar imageries to avoid such confusion.

Similarly, in Figure 2, a large portion of northwestern Sylhet Haor area that the paper identified as drying or accreting, in reality, has recently been practicing dry-season Boro (rice) cultivation intentionally drying up mid-portion of those natural wetlands. It is true that sedimentation has been happening in the Sylhet region but not in areas marked by authors, here in this paper.

Authors may consider avoiding the term 'subsidence' from this study. The paper linking subsidence directly to all waterlogging and drying cases for southwest polders and Sylhet Haor region, respectively, in lines 190-198, may be considered as another gross mistake for the Bangladesh study region.

It would add value if authors could have mentioned the exact proportion of permanent vs. temporary relocation/migration. If people permanently migrate from geomorphological hazard zones, the question might arise: how will the total population in hazardous zones keep rising?

A further explanation of CRV and how it works would make reading easy.

Reviewer #2

(Remarks to the Author)

I want to thank the authors for this interesting work. Please find my general and detailed comments below:

Introduction:

The introduction is well written; however, a crucial part is missing. As the study claims (Lines 10 and 65) that this is the first spatial study assessing the exposure to geomorphic hazards across populations and poverty groups, it is important to set the context of previous hazards-related work related to fluvially-induced landscape changes (Lines 37-38). For example, there has been previous work by Dewan et al., 2006 on flood hazards, Islam et al., 2016 on coastal multi-hazard vulnerability assessment, and others. Although these studies did not explicitly touch on poverty and population groups, it is important for the authors to establish the research gap with relevance to past works.

Also, it is a generally well-established knowledge that people living near or under the poverty line is more vulnerable to most hazard types (such as geomorphic). Hence given this knowledge, what novel contribution this study 'can' make to existing literature should be mentioned.

Methods:

Section 2.1: Lines 103 and 112:

a) The methods outline that one composite image has been created from all the images for every 35 years, again, it has been mentioned that a metric was developed to track changes in channel morphodynamics over space and time. Further clarification is required on how temporal change assessment has been done once the composite image has been created. Otherwise, please mention composites of how many images were processed in this part.

b) The authors previously mentioned that geomorphic processes involving fluvially induced landscape changes will be considered in this study. It is important to outline how only the morphometric analyses of channels can cover this hazard type.

Section 2.3: Lines 154-162: How the population distribution was adjusted prior to assessing the vulnerability of the poverty-stricken population towards geomorphic hazards needs to be clarified. For example, the central part of the country (intersected by Jamuna, Ganges, and Padma) has highly active fluvial processes and also houses more people compared to the other parts of the country. Therefore, any of the high-population density central divisions (Line 132) could cause a majority bias during the significance test. In other words, due to the high number of poverty-stricken people (proportional to the population) in these regions, the results of tests comparing against the whole population of the country could become biased. Please mention how this was adjusted.

Section 2.4: Lines 174 to 178: This could be a major limitation of the study. Please clearly outline in the discussion how this might affect the interpretation of the results of this study.

Results:

The results section contains some explanations and interpretations that are better appropriate in the discussion section (e.g., Lines 192-198 and Lines 213- 217)

Lines 223-225: This part clearly demonstrates the possible population artifact or effect of population distribution on the statistical test that I mentioned earlier. The exposure assessed in this study could be affected either by the locational changes of the geomorphic hazard hotspots or the population size in different regions.

Lines 248-250: Could be an oversimplification of the process. Alternatively, it is possible that the growth rate is lower compared to the whole country due to migration.

Figure 4: There could be a problem with the legend. It does not seem to cover the color range depicted on the map. Also, please consider using a contrasting color scheme that vividly captures the higher exposure.

Figure 5: Does the '0' in the Wealth Index have any meaning?

Figure 2 vs Figure 6: The normalized CRV values suggest that both the increases and decreases are high in the Khulna and Sylhet divisions. The background spatial poverty distribution (WI) also visually indicates that the poverty levels are higher in these regions compared to Rangpur or Mymensingh. Any reason why still the proportional percentage of the population in geomorphic hotspots are lower for Khulna and Sylhet compared to the other two divisions?

Discussion:

As the findings deal with geomorphic processes and future population exposure to geomorphic hazards, the effect of climate change on exacerbating future exposure should be discussed. Climate change is likely to cause severe loss of livelihoods and thus, shifting both the size and location of the poverty-stricken population. Additionally, it is likely to intensify the geomorphic processes, which include fluvial processes, and cause a change in the size of the hotspots identified in this study. Hence, mobility of poverty-stricken communities in geomorphic regions may become more restrictive due to surrounding areas, where resettlement typically occurs (as mentioned in Line 314), becoming environmentally unsuitable for relocation. This climate change-related discussion could be a new dimension included with the property-related discussion the authors have already provided to explain the results.

Reviewer #3

(Remarks to the Author)

Key Result: The key message of this paper is that the exposure to geomorphic hazards have been mostly ignored (a claim I dispute, see references). Using several decades of satellite imagery, the authors calculate a riverine geomorphic variability index, which they overlay over maps of the spatial distribution of population and poverty. The authors calculate that over 22 million people live within geomorphically hazardous regions, a figure that has increased by 5 million in the last 20 years with a strong exposure bias towards poorer demographics.

Validity: I broadly support the conclusions from the data presented, but I do have some questions:

- a) While I recognise that geomorphic hazards is an accepted terminology, I think you should be more specific about the hazards you are addressing the exposure to here. Clearly the main ones are riverbank erosion and growth are of most concern here. I am not sure subsidence is covered by the data, at least not to the extent you are implying. The data over the Sylhet region shows the historical presence/absence of water not subsidence.
- b) I am also surprised at how little change has occurred along the coastlines of Bangladesh. Could you please comment on this?
- c) I am not too sure of the definitions of poverty you are using here. Can you define them more clearly? How do they compare to the UN \$1.9 per day at PPP? Although I note, with appreciation, your section on multi-dimensional poverty.

Significance:

- a) The results are clearly important, but I am unsure as to how significant they are. Perhaps a discussion around a comparison of this number with the Bangladeshi government targets and plans would help clarify.
- b) Lines 248-250: Or could it be that wealthy people chose not to live in these regions and move out?
- c) Overall, I think the discussion is lacking. This should be a place for you to discuss the significance of “your results” and “put this” into a broader context. You talk about a lot of things in there that would probably be better placed in the introduction. For example the Charlands discussion is interesting, but how and why your results are relevant to this is unclear. Same for the land ownership section.
- i. In line 290, you mention that geomorphic change can be episodic or chronic. Is there a way to separate these out in your data analysis? You could at least expand on this point in the discussion, especially since you mention that the majority of migration happens due to seasonal changes. If this is mostly just due to annual flooding is this a relevant statistic here? What are the implications of this to your assessments of exposed populations?
- ii. Please discuss to what extent your exposure maps are entirely negative. Could those exposed to dry lands actually be in a position of new fertile land opportunity? How might this affect your final numbers?
- iii. Lines 332-345: This is interesting but please elaborate how this is relevant to the results from this study
- d) In contrast, I think the first part of your conclusion is nice! I'm not entirely sure the third paragraph is needed though.

Data and methodology: The data used in this study broadly support the conclusions. However:

- a) Is the CRV measurement something that can be done on an annual basis? Could you then do this for every year from 2000 and measure the actual number of people affected each year?
- b) Also, how do you account for periods/areas of floods in your data?

Analytical approach:

- a) While I don't see anything particularly wrong with the methodology I am unsure of the 'novelty' the analytical approach. It seems the authors have applied an existing methodology to a stack of satellite data over Bangladesh and overlain the results over existing population datasets. Similar work has been conducted elsewhere, e.g. [1] - [2].
- b) Similarly for the exposure bias, which emulates the work detailed in Winsemius et al, 2018. However, in that study the authors weight the ratio of exposed poor/total poor with a factor that reflects the representativeness of the households to all other households. Could you explain why you didn't include this factor in your work? Also, as you mentioned the DHSWI is a household level estimate. Can you explain how you got from this to population counts?
- c) Perhaps I am misunderstanding it, but could you also explain the Steele et al, 2017 dataset in more detail. Were the DHSWI created on an annual basis? From their paper it seems that they used several Bangladeshi datasets from the years 2011-2014 to estimate the DHSWI. How relevant then is using this data to estimate your poverty exposure bias in 2020?
- d) Section 3.2: Could you discuss what might have caused the rate of increase in the fraction of people exposed to these hazards to decrease between 2008-2018?
- e) Lines 156-157: Can you clarify what you mean by interpolating between wealth index levels. Interpolate what? I'm also not entirely sure what you mean by “normalised to the highest-level frequency population group”. If this interpolation is what results in Figure 5. Please also include on that figure the actual measurement points.
- f) A discussion around the uncertainties in your results is lacking. How might the uncertainties in the various datasets propagate to the uncertainty of your final numbers?
- g) I don't understand Figure 4. Shouldn't the population exposed be zero in areas with no geomorphic activity?
- h) Figure 5: It's interesting that Mymensingh, Rajshahi and Kulna don't show the poverty offset like Dhaka and Sylhet despite having large CRV. Could you comment on why?

Suggested improvements: I've suggested some other, mostly minor, improvements below:

Line 9: Not entirely true, e.g. see [2]-[3] references below

Line 15: How is poverty defined here?

Line 51: Please define the poverty line

Lines 151-153: Where does extreme poverty sit on this line and how does that compare to the income definition (1.9 per day)?

Line 185: How does this compare to the total land surface area?

Lines 186-187: Are these calculated as total amount of area with a non-zero CRV?

Figure 2: In the table please put the value you used to delimit the High CRV and Low CRV

Figure 3: I am not sure about this colour scheme. Where are the yellow and green colours coming from?

Figure 4 Caption: Please specify the time period over which the percentage change applies

Lines 231-232: Are these accepted definitions for poverty and extreme poverty? If not please define and relate to accepted definitions.

Figure 6 caption: Please state clearly that redder background colours represent higher levels of poverty

Line 288: "vast" is too vague language, please be specific.

References noted in review:

[1] Winsemius, H.C., Jongman, B., Veldkamp, T.I., Hallegatte, S., Bangalore, M. and Ward, P.J., 2018. Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, 23(3), pp.328-348. [this has already been cited in manuscript]

[2] Tha, T., Piman, T., Bhatpuria, D. and Ruangrassamee, P., 2022. Assessment of Riverbank Erosion Hotspots along the Mekong River in Cambodia Using Remote Sensing and Hazard Exposure Mapping. *Water*, 14(13), p.1981.

[3] Bhuiyan, M.A.H., Islam, S.M. and Azam, G., 2017. Exploring impacts and livelihood vulnerability of riverbank erosion hazard among rural household along the river Padma of Bangladesh. *Environmental Systems Research*, 6(1), pp.1-15.

Other references worth reading/including:

[1] Kabir, M.E. and Kamruzzaman, P., 2022. Exploring the drivers of vulnerability among disadvantaged internal migrants in riverbank erosion prone areas in north-west Bangladesh. *Journal of South Asian Development*, 17(1), pp.57-83.

[2] Islam, M.F. and Rashid, A.B., 2011. Riverbank erosion displacees in Bangladesh: need for institutional response and policy intervention. *Bangladesh Journal of Bioethics*, 2(2), pp.4-19.

[3] Islam, T., Azman, A., Singh, P., Ali, I., Akhtar, T., Rafatullah, M., Ismail, N. and Hossain, K., 2019. Socio-economic vulnerability of riverbank erosion of displacees: Case study of coastal villages in Bangladesh. *Indian Journal of Ecology*, 46(1), pp.34-38.

[4] Das, T.K., Haldar, S.K., Sarkar, D., Borderon, M., Kienberger, S., Gupta, I.D., Kundu, S. and Guha-Sapir, D., 2017. Impact of riverbank erosion: A case study. *Australasian Journal of Disaster and Trauma Studies*, 21(2), pp.73-81.

[5] Hassan, A., Siddik, M.A., Akhtar, M.P. and Rahman, M.H., RIVER BANK EROSION AND ASSOCIATED IMPACTS ON LIVELIHOOD: A CASE STUDY OF HARINATPUR, BARISHAL.

[6] Majumdar, S., Das, A. and Mandal, S., 2022. River bank erosion and livelihood vulnerability of the local population at Manikchak block in West Bengal, India. *Environment, Development and Sustainability*, pp.1-38.

Reviewer #4

(Remarks to the Author)

The paper provides an interesting assessment of geomorphic hazards exposure across population and to some extent, attempted to explore the impacts on some socio-economic dimensions considering Bangladesh as a case study. Although the paper attempted to address variations in disaster risk exposure indicating coastal and riverine erosion, land subsidence and siltation of water bodies; I have found substantial lack in the approaches that had been showcased to exhibit the relationship between poverty and key development dimensions. Therefore, my major concerns are as follows:

1) The paper seems to highlight the geomorphic modeling part more compared to articulating a concrete methodology to understand the impacts on the exposed population and poverty groups, in particular. In this regard, a thorough literature review is extremely vital as recent literatures do not exhibit substantial evidences in establishing a general conclusion to showcase the relationship between poverty and natural disasters (see Karim and Noy, 2016 which have used a meta-regression technique to establish this relationship). A conceptual framework is also mandatory. The authors need to explore more on the methodological approaches and should go beyond spatial assessment, as most of the development impacts provide evidences using micro-household data where spatial assessment would likely going to provide only a proportion of the scenario. Moreover, there could be major differences in the findings using these two approaches; although self-reported data is expected to provide more accurate picture compared to geospatial data (See Karim, 2018 on the comparison between self-reported and geospatial data on exposed populations in Bangladesh).

2) The paper utilizes poverty maps developed by Steele et al. which have used the 2011 DHS data to construct the wealth index. The DHS is a publicly available dataset and recent versions are available with more coverage and updated data. Importantly, literatures have shown that income patterns are more generalized followed by consumption despite trade-offs with longer term outcomes. Perhaps, it would be crucial to explore the impacts on poverty using some income-based indices too in the context of geomorphic hazards in the global context.

3) The conclusion needs to be validated in a generalized form across other disaster-prone nations with more diversification in approaches and thereby development dimensions and data. The title also needs to be more specific e.g., risk exposure.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

Thanks to the authors for their response and reviewing the manuscript based on the comments.

Reviewer #4

(Remarks to the Author)

Review Report

Disparities in exposure to hydrogeomorphic hazards in Bangladesh

Despite selected issues had been addressed in the revised manuscript, some major concerns still remain. They are as follows:

Major Concern(s):

1. The authors must include a theoretical/conceptual framework and showcase the pathway towards contribution/advancement to the literature.
2. Detailed clarification(s) on distinctions between hydrogeomorphic processes (aggregated) and specific natural hazards (in isolation) in exhibiting various estimates (and also the correlations) needs to be articulated.
3. Line 202: Why these particular years?
4. A limitations section needs to be separately added.
5. Line(s) 237, 239: These lines need to be edited.
6. An online appendix (following the journal protocol) could be added including step-by-step details on the construction/procedures of the map(s) and the indices (e.g., wealth index).
7. Question to clarify: Is there any evidence that the rest of the country (besides the identified hydrogeomorphic hazard prone areas) is not unstable/vulnerable to these hydrogeomorphic hazards?
8. The DeepWaterMap had been done based on a 35-year dataset. A hotspot analysis with future projections of hydrogeomorphic changes (due to climate change and others) should apprehend at least double this timeline.
9. Discussion section: More clarification regarding persistent hydrogeomorphic changes is required as it has been stated that these changes include both depletion and accretion. Therefore, a cut-off point analysis reflecting the areas of exploration highlighted in this study needs to be included.
10. Line 385: Check whether these years are correct?
11. Figure 4: Is this a Histogram? Please show the full Histogram.
12. Add the Sources underneath the tables (e.g., Table 1).
13. References should be placed in an alphabetical order. More references worth including are as follows:
 - i) Karim, A., & Noy, I. (2016). Poverty and natural disasters—a qualitative survey of the empirical literature. *The Singapore Economic Review*, 61(01), 1640001.
 - ii) Karim, A., & Noy, I. (2016). Poverty and natural disasters: a regression meta-analysis. *Review of Economics and Institutions*, 7(2), 26.
 - iii) Karim, A. (2018). The household response to persistent natural disasters: Evidence from Bangladesh. *World Development*, 103, 40-59.
 - iv) Kolstad, I., Karim, A., Lujala, P., & Wiig, A. (2023). Expert adoption of composite indices: a randomized experiment on migrant resettlement decisions in Bangladesh. *Natural Hazards*, 119(1), 261-297.
 - v) Karim, A. (2024). Knowledge, perception or disaster experience? The new determinants of household disaster preparedness behaviour in Bangladesh. *Journal of International Development*, 36(6), 2557-2580.

(Remarks to the Author)

This study makes a significant contribution by providing a national-scale spatial assessment of exposure to hydrogeomorphic hazards in Bangladesh and highlighting the disproportionate impact on poorer populations. The methodology is well described, and the findings are compelling.

In general, the conclusion of the study quantifying the effect of hydrogeomorphic hazard on the poverty will be very useful for mitigation of the effects. However, the following points need to be addressed:

1. Incorporate the Four Hazard Types into the Introduction:

The introduction currently mentions only two predominant processes: (i) river and coastal erosion and deposition; and (ii) the wetting and drying of deltaic land. While these are key, the study later categorizes hydrogeomorphic processes into four distinct types:

- (i) Riverine erosion and accretion
- (ii) Conversion of deltaic land to water bodies
- (iii) Complex patterns of wetting and drying of land
- (iv) Coastal erosion and accretion

Including these four categories in the introduction with justification would provide a more complete picture of the study's scope from the outset. This would also better prepare the reader for the later analysis and categorization of different hydrogeomorphic hazards. Highlighting the four types early would immediately establish the breadth of the study and its specific focus on these diverse processes.

2. Exposure analysis

A potential area for further exploration could involve investigating the impact of using a specific threshold for the Channelized Response Variance (CRV) to define hydrogeomorphically hazardous areas. Currently, the study uses all non-zero CRV values as indicators of change, with the intensity of the CRV indicating the frequency and magnitude of change. While this approach captures a broad spectrum of hydrogeomorphic activity, including all non-zero CRV threshold may overestimate the exposed population. The current approach may be influenced by annual anomalies such as image classification errors or short-term wetting events. These may not reflect sustained hydrogeomorphic changes. A CRV threshold could help filter out these anomalies by focusing on areas with more consistent and significant changes.

3. Refine Poverty Bias Analysis by Addressing Urban-Rural and regional Skews:

The current analysis compares the wealth distribution of populations exposed to hydrogeomorphic hazards with the wealth distribution of the entire country. While this shows a clear exposure bias, it may be skewed by the general urban-rural wealth disparity that is likely present across Bangladesh.

To isolate the impact of hydrogeomorphic hazards on poverty, it's recommended to refine the analysis as follows:

National Level Comparison: Compare the wealth distribution of the exposed population with the wealth distribution of only the rural population of Bangladesh. This would remove the influence of wealthier urban areas from the baseline.

Regional Level Comparison: For each region, compare the wealth distribution of the exposed population with the wealth distribution of the rural population within that specific region. This will reveal how exposure to hazards affects people within the same regional context, but residing in different areas (exposed and not exposed).

By comparing the exposed population with the rural population of the whole country, or specific region (as appropriate), a clearer picture of the impact of the hazard on the poor can be established. This method would help to isolate the impact of hydrogeomorphic hazards from the broader urban-rural poverty gradients or general regional disparity.

The study already notes that the northern divisions of Rangpur and Mymensingh have the highest proportion of exposed populations with the lowest relative wealth and attributes this to those regions already having low levels of wealth, rather than a disproportionate impact of hydrogeomorphic hazards. Refining the analysis in the manner described above would help to provide further insight.

4. Analyse Differences Between Hazard Types:

The study identifies four distinct types of hydrogeomorphic hazards but does not thoroughly explore the variations in how these hazards impact populations. While the paper provides an overview of these different types, a comparative analysis would be beneficial.

A more detailed analysis of the differences between the four hazard types would enhance the study's impact. Such an analysis could explore:

Specific Socio-economic impacts: How does riverine erosion affect livelihoods differently from coastal erosion? How do the economic consequences of waterlogging compare to the effects of coastal accretion?

Vulnerability Variation: Are populations more vulnerable to certain types of hazards based on their location, economic activities, or access to resources?

Long-term implications: Do some hazard types lead to more persistent poverty traps than others?

By comparing the distinct impacts of these four hazard types, more targeted interventions can be designed. For example, this would help to identify whether similar policies would be relevant for each of the four regions, or whether regionally distinct approaches are more appropriate.

Although the study notes that all four regions experience land loss or change, it does not thoroughly explore how the effects on livelihoods vary. For instance, the impact of river erosion on agricultural land in the Jamuna region is likely different from the effect of waterlogging on aquaculture in the south-west. A comparative analysis would illuminate these differences and provide greater detail to the impacts of each hazard type.

Version 2:

Reviewer comments:

Reviewer #5

(Remarks to the Author)

The authors have addressed all comments comprehensively and satisfactorily. Their revisions have significantly improved the manuscript's clarity, scope, and analysis, particularly regarding the categorization of hydrogeomorphic hazards, the refined exposure analysis using CRV thresholds, and the nuanced discussion of urban-rural wealth disparities in exposure. The elaborations on the distinct impacts of various hazard types further strengthen the paper's contribution. I recommend this revised manuscript for publication.

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Reviewer Comments

Reviewer 1

We would like to thank the Reviewer for providing their constructive feedback. The Reviewer's comments resulted in analyses being re-done and results being re-interpreted to ensure they reflect the processes taking place on the ground. We hope that the revised version of the manuscript addresses the Reviewer's concerns. Below, we provide responses to the Reviewer's comments.

- Here, authors aggregated different models which are mainly developed by other communities and applied a few statistical tests to figure out exposure biases. Authors successfully identified research gaps, but their potential contribution to bridging these gaps is limited to generating a few percentages and mapping only a few spatial datasets. I find no novelty in this.
We thank the Reviewer for sharing their concern. Although methodologies were applied by other communities, combining them within one spatially explicit framework has not been done before. Using existing models and datasets to answer new questions is novel. This manuscript links hydrogeomorphic hazards with exposed populations and their levels of wealth for the first time, and this is done at a politically important scale - the national scale. The Government of Bangladesh has acknowledged that hydrogeomorphic hazards, such as erosion, and poverty are linked (e.g., in the Bangladesh Delta Plan 2100), but this link has not yet been spatially assessed. We have reworked the manuscript to highlight this novelty more and have refocused the narrative of the study on how the framework can be used to answer pressing questions on exposure to hydrogeomorphic hazards in deltaic nations. We hope that the substantial work that has gone into revising the manuscript will address the Reviewer's concern of its novelty.
- Misinterpretation of processes:
 - Due to lack of local experts' consultations and/or local field knowledge/validation, misinterpretation of deep learning model (in)outputs are also observed. Figure 2, which represented geographic hotspots generated by geographical hazards, is misinterpreted. Discarding changes in Land Use Land Coverage affected its results the most. I assume the authors mixed up flood water with other water pixels.
 - For example, in Figure 2, the Southwest region is represented as a high hotspot area with increasing erosion or waterlogging. But, intentionally created shrimp cultivation ponds in the dry season are mostly (approximately more than 60% area) marked here as waterlogged points compared to what really exists in the field as this is a solely remote sense-based model. Also, rainwater harvesting in the rice field (which are flood free in general) during October-November for Southwest Region can be misinterpreted as waterlogged by authors as this paper took October-March as their dry season. Instead, I suggest considering Dec-Mar imageries to avoid such confusion.
 - Similarly, in Figure 2, a large portion of northwestern Sylhet Haor area that the paper identified as drying or accreting, in reality, has recently been practicing dry-season Boro (rice) cultivation intentionally drying up mid-portion of those natural wetlands. It is true that sedimentation has been happening in the Sylhet region but not in areas marked by authors, here in this paper.

We thank the Reviewer for these critical comments. We have re-assessed the results presented in the study and have made clear distinctions between the types of hydrogeomorphic processes taking place and have also distinguished changes observed as a result of large-scale changes in land use, such as highlighted in the south-west poldered region and the north-eastern Sylhet basin. The Reviewer will be able to see an updated Figure 2, as well as a reworked results section,

that delves into each of the main processes in more detail. The DeepWaterMap model uses dry season satellite images as its input; the risk of mixing up flood water with permanent water pixels is therefore minimised. Moreover, rather than using a series of dry season images per year as inputs to the model, we use a median image per dry season per year. This minimises the chances of capturing variations in tide levels, temporarily flooded rice fields, and other seasonal water pixels from being interpreted as permanent waterbodies. Shortening the dry season to Dec-Mar, as suggested by the Reviewer, would likely lead to similar results, given the averaging process per season. We have clarified this methodology in the manuscript and have extensively reworked the section to distinguish the different processes taking place.

- Authors may consider avoiding the term 'subsidence' from this study. The paper linking subsidence directly to all waterlogging and drying cases for southwest polders and Sylhet Haor region, respectively, in lines 190-198, may be considered as another gross mistake for the Bangladesh study region.

We agree with the Reviewer and have removed reference to subsidence from the study.

- It would add value if authors could have mentioned the exact proportion of permanent vs. temporary relocation/migration. If people permanently migrate from geomorphological hazard zones, the question might arise: how will the total population in hazardous zones keep rising? *Unfortunately, it is not possible to calculate the proportion of permanent vs temporary relocation using the data we have, but the Reviewer raises a very interesting point. The previous version of the manuscript included a detailed discussion on migration patterns, but such patterns were not reflected in the results. We have therefore adjusted the narrative of the discussion to focus on what the results imply, and their relevance for the policy context in Bangladesh. The focus on migration patterns has been removed.*
- A further explanation of CRV and how it works would make reading easy. *Further explanations of the CRV metric and how it works have been added into the manuscript.*

Reviewer 2

I want to thank the authors for this interesting work. Please find my general and detailed comments below:

We thank the Reviewer for providing detailed and constructive feedback. The Reviewer's comments have helped to strengthen and clarify the manuscript to make it more accessible to a wider audience. Below, we provide responses to the Reviewer's comments, which we hope adequately address the Reviewer's concerns.

Introduction:

- The introduction is well written; however, a crucial part is missing. As the study claims (Lines 10 and 65) that this is the first spatial study assessing the exposure to geomorphic hazards across populations and poverty groups, it is important to set the context of previous hazards-related work related to fluvially-induced landscape changes (Lines 37-38). For example, there has been previous work by Dewan et al., 2006 on flood hazards, Islam et al., 2016 on coastal multi-hazard vulnerability assessment, and others. Although these studies did not explicitly touch on poverty and population groups, it is important for the authors to establish the research gap with relevance to past works.

Thank you for this comment. We have incorporated the mentioned studies, as well as others, into the reworked Introduction:

"Although previous work in Bangladesh has assessed fluvially-induced channel changes²⁶⁻³⁰, as well as the vulnerability to erosion^{22,24,30-34}, and multiple coastal hazards^{1,35-37}, these studies did not focus on different hydrogeomorphic hazards at the national scale and did not explicitly combine these hazards with exposed populations and their associated levels of wealth."

- Also, it is a generally well-established knowledge that people living near or under the poverty line is more vulnerable to most hazard types (such as geomorphic). Hence given this knowledge, what novel contribution this study 'can' make to existing literature should be mentioned.

We agree with the Reviewer that it is well known that poorer people are generally more vulnerable to hazards. We have reworked the manuscript's narrative to emphasise that the novelty lies in the framework of linking hydrogeomorphic hazards with population and their associated levels of wealth, an approach that can be applied to other geomorphically dynamic areas across the world. Moreover, the framework allows us to quantitatively confirm the hypothesis that people living near or under the poverty line are indeed more vulnerable, and also provide a spatial assessment of this relationships across the entire country.

Methods:

- Section 2.1: Lines 103 and 112:
 - a) The methods outline that one composite image has been created from all the images for every 35 years, again, it has been mentioned that a metric was developed to track changes in channel morphodynamics over space and time. Further clarification is required on how temporal change assessment has been done once the composite image has been created. Otherwise, please mention composites of how many images were processed in this part.
 - b) The authors previously mentioned that geomorphic processes involving fluvially induced landscape changes will be considered in this study. It is important to outline how only the morphometric analyses of channels can cover this hazard type.

We have provided clarifications on both of the points raised by the Reviewer: A) we have added more information on how temporal changes were assessed from the composite images. The following text has been added to the manuscript:

“For each of the 35 years assessed, one composite image is created by taking the median value of all cloud-free pixels^{40,70}. Once 35 new images are created – one composite image per dry season per year – they are incorporated into the DeepWaterMap model.”

We hope that this clarifies the Reviewer’s point. B) We have clarified in the Introduction, and throughout the manuscript, the types of fluvially induced landscape changes that are considered.

- Section 2.3: Lines 154-162: How the population distribution was adjusted prior to assessing the vulnerability of the poverty-stricken population towards geomorphic hazards needs to be clarified. For example, the central part of the country (intersected by Jamuna, Ganges, and Padma) has highly active fluvial processes and also houses more people compared to the other parts of the country. Therefore, any of the high-population density central divisions (Line 132) could cause a majority bias during the significance test. In other words, due to the high number of poverty-stricken people (proportional to the population) in these regions, the results of tests comparing against the whole population of the country could become biased. Please mention how this was adjusted.

We have adjusted this section of the methods to make it clearer. The text now reads:

“By overlaying all three layers (i.e., hydrogeomorphic hotspots, population, and wealth), the number of people living within hydrogeomorphic hotspots, and their levels of wealth, can be estimated. To fill in data gaps and areas without direct WI measurements, interpolation techniques were employed to estimate levels of wealth between the WI classifications. These interpolated wealth levels were then normalised by adjusting them to the highest-level frequency observed within the corresponding WI population group. This normalisation ensures that the estimated wealth distribution better reflects the wealth of the population across different wealth index levels, with the group having the highest frequency serving as the reference. The resulting wealth distribution of people exposed to hydrogeomorphic hazards is then compared to the wealth distribution of the country, to estimate whether there is an exposure bias of populations with lower levels of wealth towards hydrogeomorphic hazards. In order to assess whether the exposure bias is statistically significant (p -value < 0.05), the non-parametric Mann-Whitney U statistical test is performed, as the underlying distributions are non-normal.”

- Section 2.4: Lines 174 to 178: This could be a major limitation of the study. Please clearly outline in the discussion how this might affect the interpretation of the results of this study.

We have added more text in the methodology, as well as in the results section that acknowledge this uncertainty. The methodology now explicitly states:

“There is currently no model predicting future hydrogeomorphic change; hence, this exploration of future exposure assumes that hydrogeomorphic hotspots remain the same as observed over the past 35 years. While in the future we can expect the precise location of hydrogeomorphic changes to evolve, the general hotspots of hydrogeomorphic change are likely to remain active over the coming decades¹⁸. Although this assumption introduces uncertainties, exploring future population exposure within these hotspots can help identify

areas that may experience increased hazard exposure due to population growth or internal migration.”

Results:

- The results section contains some explanations and interpretations that are better appropriate in the discussion section (e.g., Lines 192-198 and Lines 213- 217)

We have reviewed the results section and have moved all interpretations of the findings to the Discussion section.

- Lines 223-225: This part clearly demonstrates the possible population artifact or effect of population distribution on the statistical test that I mentioned earlier. The exposure assessed in this study could be affected either by the locational changes of the geomorphic hazard hotspots or the population size in different regions.

We agree with the Reviewer and have explicitly acknowledged background population growth as a driver of change in the number of people exposed to hydrogeomorphic change:

“This can be attributed to greater background population growth in Dhaka and Chittagong, and more widespread recent hydrogeomorphic changes observed in the Sylhet basin.”

- Lines 248-250: Could be an oversimplification of the process. Alternatively, it is possible that the growth rate is lower compared to the whole country due to migration.

We agree with the Reviewer and have adjusted the text accordingly, which now reads:

“The slower growth rate of wealthier populations observed within hydrogeomorphically hazardous regions could suggest that wealthier people may choose not to live in these unstable areas and move away, whilst the population that remains may face more challenges finding resources to migrate to safer locations.”

- Figure 4: There could be a problem with the legend. It does not seem to cover the color range depicted on the map. Also, please consider using a contrasting color scheme that vividly captures the higher exposure.

This is now Figure 3 and has been adjusted to incorporate the Reviewer’s comments.

- Figure 5: Does the ‘0’ in the Wealth Index have any meaning?

Yes, a Wealth Index of 0 has a meaning, which we have added into the text, as follows:

“The WI values can be positive, negative, or zero (ranging between -1.165 and 2.185 for Bangladesh), with greater positive values indicating higher socio-economic status^{2,54}.”

- Figure 2 vs Figure 6: The normalized CRV values suggest that both the increases and decreases are high in the Khulna and Sylhet divisions. The background spatial poverty distribution (WI) also visually indicates that the poverty levels are higher in these regions compared to Rangpur or Mymensingh. Any reason why still the proportional percentage of the population in geomorphic hotspots are lower for Khulna and Sylhet compared to the other two divisions?

Figure 5 (former Figure 6) illustrates the wealth index of the population exposed to hydrogeomorphic hazards. Although the normalised CRV values show high rates of hydrogeomorphic instability in the Khulna and Sylhet divisions, Figure 5 shows that the population that lives within the hydrogeomorphically unstable areas is primarily within the wealth index bracket of -0.5 and 0.5. Contrastingly, although the area of hydrogeomorphically unstable land is lower in the Mymensingh and Rangpur divisions, the population that lives in the

unstable areas in these two divisions is primarily in the wealth index bracket of -1.2 and -0.5. We hope that this explanation answers the Reviewer's concerns on this figure.

Discussion:

- As the findings deal with geomorphic processes and future population exposure to geomorphic hazards, the effect of climate change on exacerbating future exposure should be discussed. Climate change is likely to cause severe loss of livelihoods and thus, shifting both the size and location of the poverty-stricken population. Additionally, it is likely to intensify the geomorphic processes, which include fluvial processes, and cause a change in the size of the hotspots identified in this study. Hence, mobility of poverty-stricken communities in geomorphic regions may become more restrictive due to surrounding areas, where resettlement typically occurs (as mentioned in Line 314), becoming environmentally unsuitable for relocation. This climate change-related discussion could be a new dimension included with the property-related discussion the authors have already provided to explain the results.

We would like to thank the Reviewer for this suggestion. We have re-worked the narrative of the Discussion section and have incorporated potential impacts of climate change on the distribution of exposed populations. The text now reads:

"Although not assessed in detail in this study, climate change is likely to intensify hydrogeomorphic processes, particularly fluvial dynamics, potentially expanding the extent and modifying the characteristics of identified hotspots and shifting the size and location of the poverty-stricken populations. This could lead to the emergence of new areas prone to hydrogeomorphic hazards or increased susceptibility in existing ones. The mobility of poverty-stricken communities residing in hydrogeomorphically unstable regions may become increasingly constrained, as surrounding areas might become unsuitable for relocation due to climate-related factors like sea-level rise or heightened flood risk. The influence of climate change on future population exposure to hydrogeomorphic hazards therefore warrants further study, as it would provide invaluable insights into the complex interplay between climate change, socio-economic vulnerabilities, and the spatial distribution of these hidden hazards."

Reviewer 3

Key Result: The key message of this paper is that the exposure to geomorphic hazards have been mostly ignored (a claim I dispute, see references). Using several decades of satellite imagery, the authors calculate a riverine geomorphic variability index, which they overlay over maps of the spatial distribution of population and poverty. The authors calculate that over 22 million people live within geomorphically hazardous regions, a figure that has increased by 5 million in the last 20 years with a strong exposure bias towards poorer demographics.

We would like to thank the Reviewer for their detailed and constructive comments, which have helped to strengthen the manuscript. We have re-worked the manuscript and have adjusted its narrative. The novelty of the manuscript is that it links hydrogeomorphic hazards with exposed populations and their associated wealth, a framework that can be applied to other hydrogeomorphically unstable regions in the world. We provide responses to each of the Reviewer's comments below and hope that the revised manuscript now addresses the Reviewer's main concerns.

Validity: I broadly support the conclusions from the data presented, but I do have some questions:

- a) While I recognise that geomorphic hazards is an accepted terminology, I think you should be more specific about the hazards you are addressing the exposure to here. Clearly the main ones are riverbank erosion and growth are of most concern here. I am not sure subsidence is covered by the data, at least not to the extent you are implying. The data over the Sylhet region shows the historical presence/absence of water not subsidence.

We have made the definition of hydrogeomorphic hazards very clear in the Introduction. We agree with the Reviewer that the modelling results did not provide direct evidence for subsidence, and thus have removed consideration of this hazard from the manuscript.

- b) I am also surprised at how little change has occurred along the coastlines of Bangladesh. Could you please comment on this?

We have adjusted the narrative of the manuscript and now focus on four key areas of hydrogeomorphic change, including the coastline of Bangladesh. The final paragraph of Section 3.1 on the hotspots of hydrogeomorphic change elaborates on the changes observed along the coastline.

- c) I am not too sure of the definitions of poverty you are using here. Can you define them more clearly? How do they compare to the UN \$1.9 per day at PPP? Although I note, with appreciation, your section on multi-dimensional poverty.

We agree with the Reviewer that there was confusion on how poverty was defined. In the revised manuscript, we use the term “wealth index” or “wealth population groups” rather than poverty, and have added an explanation in the methodology:

“The WI is based on relative wealth and takes many factors into account; therefore, it cannot be mapped onto traditional definitions of poverty thresholds (e.g., less than US\$1.90 per day in purchasing power parity). As a result, this study uses higher and lower wealth population groups, defined by the WI, to assess disparities in exposure to hydrogeomorphic hazards.”

Significance:

- a) The results are clearly important, but I am unsure as to how significant they are. Perhaps a discussion around a comparison of this number with the Bangladeshi government targets and plans would help clarify.

We have re-worked the narrative for the Discussion section. We have added the significance of the findings in this study for the Bangladesh Delta Plan 2100, particularly with regard to the Government’s plans to accelerate land creation in the Meghna Estuary. We hope that the re-worked Results and Discussion sections now provide the Reviewer with more certainty on the significance of the findings.

- b) Lines 248-250: Or could it be that wealthy people chose not to live in these regions and move out?

We agree with the Reviewer and have added this as a possible interpretation. The text now reads:

“The slower growth rate of wealthier populations observed within hydrogeomorphically hazardous regions could suggest that wealthier people may choose not to live in these unstable areas and move away, whilst the population that remains may face more challenges finding resources to migrate to safer locations.”

- c) Overall, I think the discussion is lacking. This should be a place for you to discuss the significance of “your results” and “put this” into a broader context. You talk about a lot of things in there that would probably be better placed in the introduction. For example the Charlands

discussion is interesting, but how and why your results are relevant to this is unclear. Same for the land ownership section.

We agree with the Reviewer and have restructured the Discussion section to focus on what the results of the study show and what they mean for decision-making in Bangladesh.

- In line 290, you mention that geomorphic change can be episodic or chronic. Is there a way to separate these out in your data analysis? You could at least expand on this point in the discussion, especially since you mention that the majority of migration happens due to seasonal changes. If this is mostly just due to annual flooding is this a relevant statistic here? What are the implications of this to your assessments of exposed populations?

Unfortunately, separating episodic and chronic hydrogeomorphic changes is currently not possible, although we agree that this merits further study. As mentioned above, we have reframed the Discussion section, removing the previous text on migration patterns on charlands.

- Please discuss to what extent your exposure maps are entirely negative. Could those exposed to dry lands actually be in a position of new fertile land opportunity? How might this affect your final numbers?

We thank the Reviewer for this important point. We have added new text in the Discussion on the trends observed in land creation and the implications of this for the policy and delta management landscape in Bangladesh.

- Lines 332-345: This is interesting but please elaborate how this is relevant to the results from this study

We agree that the previous Discussion on migration patterns on charlands was not relevant to the results from the study. We have therefore removed this text and re-focused the Discussion to the implications of the findings.

- d) In contrast, I think the first part of your conclusion is nice! I'm not entirely sure the third paragraph is needed though.

The third paragraph of the Conclusion has been removed and the first paragraph has been slightly reworked to emphasise the importance of this work, in response to other Reviewer comments.

Data and methodology: The data used in this study broadly support the conclusions. However:

- a) Is the CRV measurement something that can be done on an annual basis? Could you then do this for every year from 2000 and measure the actual number of people affected each year?
This is an excellent suggestion and could be undertaken in a follow-up study that assesses annual trends in more detail. In this study, we aim to identify the areas that have been hydrogeomorphically unstable at the decadal scale, and link these with exposed populations and their associated levels of wealth. The detailed annual changes in population exposed to hydrogeomorphic changes are beyond the scope of this study.
- b) Also, how do you account for periods/areas of floods in your data?
We take the median image across each year's dry season, which minimises the possibility of including flooded areas in the dataset of semi-permanent and permanent waterbodies.

Analytical approach:

- a) While I don't see anything particularly wrong with the methodology I am unsure of the 'novelty' the analytical approach. It seems the authors have applied an existing methodology to

a stack of satellite data over Bangladesh and overlain the results over existing population datasets. Similar work has been conducted elsewhere, e.g. [1] - [2].

We have taken an existing model and have run it at larger spatial (national) and temporal (35 years) scales and intersected this with high-resolution population and poverty data. Although these are existing models and datasets, we believe that using them to answer new questions is novel. Moreover, population exposure (and their levels of wealth) to hydrogeomorphic change has never been assessed at this scale before, and the framework for combining these openly available datasets and models is directly transferable to other hydrogeomorphically unstable areas in the world. The novelty of this has been emphasised more throughout the manuscript.

- b) Similarly for the exposure bias, which emulates the work detailed in Winsemius et al, 2018. However, in that study the authors weight the ratio of exposed poor/total poor with a factor that reflects the representativeness of the households to all other households. Could you explain why you didn't include this factor in your work? Also, as you mentioned the DHSWI is a household level estimate. Can you explain how you got from this to population counts?

Here, we are interested in undertaking a spatial assessment that is based on grided population, rather than relative household wealth. We identify the number of people that are exposed to hydrogeomorphic hazard, before we delve into the wealth dynamics of this exposed population. Although the WI is based on household-level information, it has been spatially addressed to represent grid cells.

- c) Perhaps I am misunderstanding it, but could you also explain the Steele et al, 2017 dataset in more detail. Were the DHSWI created on an annual basis? From their paper it seems that they used several Bangladeshi datasets from the years 2011-2014 to estimate the DHSWI. How relevant then is using this data to estimate your poverty exposure bias in 2020?

The Reviewer is correct that the Steele et al. (2017) study used datasets from 2011-2014 to estimate the DHSWI. Although this timeframe does not align with poverty exposure bias in 2020, to our knowledge, it is the most detailed and recent national dataset on poverty for Bangladesh.

- d) Section 3.2: Could you discuss what might have caused the rate of increase in the fraction of people exposed to these hazards to decrease between 2008-2018?

We have removed the figure showing temporal trends from the manuscript, as the focus of the manuscript is on the spatial assessment. The fluctuations in exposure over time are linked to population dynamics within the hydrogeomorphically unstable areas.

- e) Lines 156-157: Can you clarify what you mean by interpolating between wealth index levels. Interpolate what? I'm also not entirely sure what you mean by "normalised to the highest-level frequency population group". If this interpolation is what results in Figure 5. Please also include on that figure the actual measurement points.

This text has been adjusted to add clarity:

"To fill in data gaps and areas without direct WI measurements, interpolation techniques were employed to estimate levels of wealth between the WI classifications. These interpolated wealth levels were then normalised by adjusting them to the highest-level frequency observed within the corresponding WI population group. This normalisation ensures that the estimated wealth distribution better reflects the wealth of the population across different wealth index levels, with the group having the highest frequency serving as the reference."

- f) A discussion around the uncertainties in your results is lacking. How might the uncertainties in the various datasets propagate to the uncertainty of your final numbers?

We have added a bit more text on the uncertainties in the datasets, as well as the assumptions that had to be made, particularly with regards to the assumption that future hydrogeomorphic instability will remain the same.

- g) I don't understand Figure 4. Shouldn't the population exposed be zero in areas with no geomorphic activity?

We opted to illustrate background population density in areas outside hydrogeomorphic instability.

- h) Figure 5: It's interesting that Mymensingh, Rajshahi and Kulna don't show the poverty offset like Dhaka and Sylhet despite having large CRV. Could you comment on why?

We have removed the divisional distributions because we wanted the focus to remain on the national scale. The exposure bias (or as the Reviewer notes, the 'poverty offset') for Dhaka and Sylhet are stronger because Dhaka and Sylhet have a greater proportion of the population with a higher wealth index (as evident in the Supplementary map). The disparity in exposed populations to hydrogeomorphic hazards is more starkly evident in these two divisions because the background wealth levels are higher, but the exposed populations are predominantly those with lower wealth indices.

Suggested improvements: I've suggested some other, mostly minor, improvements below:

- Line 9: Not entirely true, e.g. see [2]-[3] references below
We have adjusted the Introduction to ensure that the research that has been done in Bangladesh (and elsewhere) regarding vulnerability to erosion hazards is reflected.
- Line 15: How is poverty defined here?
A detailed definition of poverty is provided in the methodology section.
- Line 51: Please define the poverty line
The poverty line has been defined as USD1.90 per day in purchasing power parity (2019).
- Lines 151-153: Where does extreme poverty sit on this line and how does that compare to the income definition (1.9 per day)?
We have adjusted how the term "poverty" is used and have added the following text in the Methodology section to clarify the Reviewer's point: "The WI is based on relative wealth and takes many factors into account; therefore, it cannot be mapped onto traditional definitions of poverty thresholds (e.g., less than US\$1.90 per day in purchasing power parity). As a result, this study uses higher and lower wealth population groups, defined by the WI, to assess disparities in exposure to hydrogeomorphic hazards."
- Line 185: How does this compare to the total land surface area?
The country's total land surface areas have been added to the text.
- Lines 186-187: Are these calculated as total amount of area with a non-zero CRV?
Yes. This clarification has been added to the text.
- Figure 2: In the table please put the value you used to delimit the High CRV and Low CRV.
We have adjusted the table in the figure to say "positive" and "negative" rather than "high" and "low". We hope this clarifies the Reviewer's confusion.
- Figure 3: I am not sure about this colour scheme. Where are the yellow and green colours coming from?
We have adjusted the colour scheme of the figure.
- Figure 4 Caption: Please specify the time period over which the percentage change applies
We have removed Figure 4 from the manuscript, but we believe the Reviewer's comment is with regards to Figure 3. The caption has been adjusted to specify the time period over which the percentage changes apply.

- Lines 231-232: Are these accepted definitions for poverty and extreme poverty? If not please define and relate to accepted definitions.
We have removed references to “extreme poverty” and “poverty” to reflect the Reviewer’s valuable comment.
- Figure 6 caption: Please state clearly that redder background colours represent higher levels of poverty
We have added that red colours represent lower levels of wealth into the caption of Figure 5.
- Line 288: “vast” is too vague language, please be specific.
This has been adjusted.

References noted in review:

- [1] Winsemius, H.C., Jongman, B., Veldkamp, T.I., Hallegatte, S., Bangalore, M. and Ward, P.J., 2018. Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, 23(3), pp.328-348. [this has already been cited in manuscript]
- [2] Tha, T., Piman, T., Bhatpuria, D. and Ruangrassamee, P., 2022. Assessment of Riverbank Erosion Hotspots along the Mekong River in Cambodia Using Remote Sensing and Hazard Exposure Mapping. *Water*, 14(13), p.1981.
- [3] Bhuiyan, M.A.H., Islam, S.M. and Azam, G., 2017. Exploring impacts and livelihood vulnerability of riverbank erosion hazard among rural household along the river Padma of Bangladesh. *Environmental Systems Research*, 6(1), pp.1-15.

Other references worth reading/including:

- [1] Kabir, M.E. and Kamruzzaman, P., 2022. Exploring the drivers of vulnerability among disadvantaged internal migrants in riverbank erosion prone areas in north-west Bangladesh. *Journal of South Asian Development*, 17(1), pp.57-83.
- [2] Islam, M.F. and Rashid, A.B., 2011. Riverbank erosion displacees in Bangladesh: need for institutional response and policy intervention. *Bangladesh Journal of Bioethics*, 2(2), pp.4-19.
- [3] Islam, T., Azman, A., Singh, P., Ali, I., Akhtar, T., Rafatullah, M., Ismail, N. and Hossain, K., 2019. Socio-economic vulnerability of riverbank erosion of displacees: Case study of coastal villages in Bangladesh. *Indian Journal of Ecology*, 46(1), pp.34-38.
- [4] Das, T.K., Haldar, S.K., Sarkar, D., Borderon, M., Kienberger, S., Gupta, I.D., Kundu, S. and Guha-Sapir, D., 2017. Impact of riverbank erosion: A case study. *Australasian Journal of Disaster and Trauma Studies*, 21(2), pp.73-81.
- [5] Hassan, A., Siddik, M.A., Akhtar, M.P. and Rahman, M.H., RIVER BANK EROSION AND ASSOCIATED IMPACTS ON LIVELIHOOD: A CASE STUDY OF HARINATPUR, BARISHAL.
- [6] Majumdar, S., Das, A. and Mandal, S., 2022. River bank erosion and livelihood vulnerability of the local population at Manikchak block in West Bengal, India. *Environment, Development and Sustainability*, pp.1-38.

We thank Reviewer 3 for providing these additional references, which have been incorporated into the manuscript.

Reviewer 4

The paper provides an interesting assessment of geomorphic hazards exposure across population and to some extent, attempted to explore the impacts on some socio-economic dimensions considering Bangladesh as a case study. Although the paper attempted to address variations in

disaster risk exposure indicating coastal and riverine erosion, land subsidence and siltation of water bodies; I have found substantial lack in the approaches that had been showcased to exhibit the relationship between poverty and key development dimensions. Therefore, my major concerns are as follows:

We would like to thank the Reviewer for their comments on our manuscript. This study aims to provide a framework for spatially assessing population exposure to hydrogeomorphic hazards, also touching on the exposed population's levels of wealth. The manuscript does not act as a comprehensive study linking natural hazards with dynamic changes in poverty and development dimensions. We have provided responses to each of the Reviewer's comments below, but with the clarified scope of the study in mind, we hope that the Reviewer's main concerns are addressed.

- The paper seems to highlight the geomorphic modeling part more compared to articulating a concrete methodology to understand the impacts on the exposed population and poverty groups, in particular. In this regard, a thorough literature review is extremely vital as recent literatures do not exhibit substantial evidences in establishing a general conclusion to showcase the relationship between poverty and natural disasters (see Karim and Noy, 2016 which have used a meta-regression technique to establish this relationship). A conceptual framework is also mandatory. The authors need to explore more on the methodological approaches and should go beyond spatial assessment, as most of the development impacts provide evidences using micro-household data where spatial assessment would likely going to provide only a proportion of the scenario. Moreover, there could be major differences in the findings using these two approaches; although self-reported data is expected to provide more accurate picture compared to geospatial data (See Karim, 2018 on the comparison between self-reported and geospatial data on exposed populations in Bangladesh).

We thank the Reviewer for this important and valid comment. However, as mentioned above, this manuscript provides a spatial assessment, not a comprehensive study on the links between hydrogeomorphic hazards and poverty. We agree that a more detailed assessment of how poverty dynamics interact with hydrogeomorphic changes merits further study, but it goes beyond the scope of this national-scale spatial assessment.

- The paper utilizes poverty maps developed by Steele et al. which have used the 2011 DHS data to construct the wealth index. The DHS is a publicly available dataset and recent versions are available with more coverage and updated data. Importantly, literatures have shown that income patterns are more generalized followed by consumption despite trade-offs with longer term outcomes. Perhaps, it would be crucial to explore the impacts on poverty using some income-based indices too in the context of geomorphic hazards in the global context.

We have provided more text in the methodology of the manuscript justifying the use of the DHS wealth index over income-based indices. We hope that this clarifies to the Reviewer that income-based indices for this assessment would not provide the multi-faceted nature of wealth/poverty of the exposed population.

- The conclusion needs to be validated in a generalized form across other disaster-prone nations with more diversification in approaches and thereby development dimensions and data. The title also needs to be more specific e.g., risk exposure.

We are unsure what the Reviewer is suggesting with regards to 'validating across other disaster-prone nations with more diversification in approaches and thereby development dimensions and data'. The model and datasets used have been validated – in the case of the DeepWaterMap model and the poverty dataset, these have been validated to Bangladesh specifically. We disagree with the Reviewer's suggestion to change the title to "risk exposure" because these concepts (i.e., risk, and exposure) are two different concepts, where exposure makes up part of

the concept of risk (as per the IPCC). This study focuses on a spatial assessment of exposure, and disparities in this exposure, so we have kept the title as “Disparities in exposure to hydrogeomorphic hazards in Bangladesh”.

We would like to thank all three Reviewers for their constructive comments that have helped to strengthen the manuscript. We have done further analysis to gain a better understanding of where the most hazardous areas are located and how many people are exposed to more extreme hydrogeomorphic instability, we have included a conceptual model, and have elaborated on how the different hydrogeomorphic hazard types affect the population differently. We hope that with these new insights and refined discussion and interpretation of the findings, the Editor will consider the manuscript for publication in *Nature Communications*.

Reviewer comments:

Reviewer 2 (Remarks to the Author):

Thanks to the authors for their response and reviewing the manuscript based on the comments. We would like to thank Reviewer 2 for acknowledging the additional work that has been done to address the previous reviewer comments.

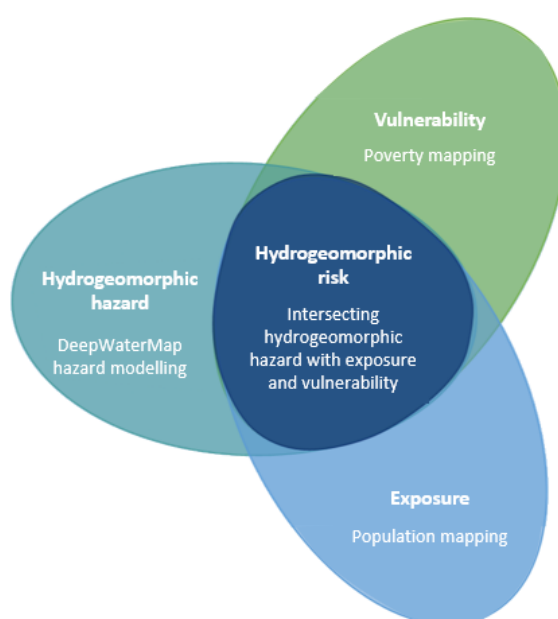
Reviewer 4 (Remarks to the Author):

Despite selected issues had been addressed in the revised manuscript, some major concerns still remain. They are as follows:

Major Concern(s):

1. The authors must include a theoretical/conceptual framework and showcase the pathway towards contribution/advancement to the literature.

Thank you for this comment. We have provided a new figure in the Supplementary Information of the manuscript which highlights the conceptual framework that is used for this study and illustrates this study's contribution (and refer readers in the Introduction to the Supplementary Information). We copy the framework schematic here as well, for ease of reference for the Reviewer. The framework is based on the IPCC's schematic of risk. Importantly, in the manuscript, we emphasise that the paper's contribution is empirical – the novel combination of existing datasets to address an unresolved question of urgent policy relevance.



2. Detailed clarification(s) on distinctions between hydrogeomorphic processes (aggregated) and specific natural hazards (in isolation) in exhibiting various estimates (and also the correlations) needs to be articulated.

In the Introduction, we have provided further clarification on the four processes that we assess, which now link more directly with what is presented in the results. The aim of Figure 2 in the results section is to show the hydrogeomorphic processes taking place across the whole country, as well as highlighting the individual types of processes evident. Unfortunately, it is not possible to isolate the four processes from one another and calculate, for instance, the number of people exposed to only riverbank erosion, without introducing significant bias. However, we have elaborated more on how the four processes lead to different impacts, in response to comments received from another reviewer.

The purpose of this study is to highlight the trends and hotspots of hydrogeomorphic risk and how those intersect with dense and vulnerable populations. Disentangling the hydrogeomorphic processes and their associated impacts on the population is an excellent suggestion; however, answering this question would require a high-resolution dynamical model of bio-physical and human dynamics which is currently not available and will be the subject of future work.

3. Line 202: Why these particular years?

We selected 2030, 2050, and 2080 as our assessment timeframes to align with standard planning horizons used in, for example, climate adaptation and development frameworks. While these specific years also correspond to critical policy milestones in global climate agreements and sustainable development goals, we identify that 2030 could represent pattern identification for immediate actionable targets, 2050 aligning with national development strategies, infrastructure cycles and mid-century carbon neutrality commitments, and 2080 capturing longer-term climate/societal impacts that require multi-generational planning. Additionally, these intervals provide practical temporal spacing that balances the need to capture both near-term policy-relevant projections and longer-term trends while remaining consistent with the temporal resolution of available demographic projection datasets.

The sentence now reads as follows:

“Future population exposure is assessed at the country-wide scale, as well as within the identified hydrogeomorphic hotspots, for the short-term (2030), medium-term (2050) and long-term (2080), aligning with standard planning horizons in development frameworks and demographic projection intervals.”

4. A limitations section needs to be separately added.

A limitations section is not typical for *Nature Communications* articles; thus, rather than creating a new section detailing the limitations, we have made more explicit mention of the limitations of the study throughout the manuscript, particularly in the methodology section. For instance, the following statement has been added:

“It should be noted that this is a static dataset of wealth – a concept that is highly dynamic – with a basis from census data captured in 2011, and surveys undertaken in 2014⁵⁶. However, this dataset still provides the most granular and detailed information on wealth distribution across Bangladesh.”

5. Line(s) 237, 239: These lines need to be edited.

These lines have been edited to clarify that the modelling results use dry season imagery and thus it is unlikely that the waterlogging observed in south-west Bangladesh is due to seasonal/monsoonal flooding.

6. An online appendix (following the journal protocol) could be added including step-by-step details on the construction/procedures of the map(s) and the indices (e.g., wealth index).

Thanks for this comment. We have added more detail into the methodology section to improve the clarity of the process and believe that now, researchers will be able to follow our approach step-by-step. Given the level of detail we already provide in the manuscript, we prefer not to include an online appendix to avoid repetition. For the DeepWaterMap model and how it works, the manuscript highlights the work of Jarriel et al., 2020 where further detail can be found, and for the wealth index, we direct readers to Steele et al., 2017 for further information on how the wealth indices were created and mapped.

7. Question to clarify: Is there any evidence that the rest of the country (besides the identified hydrogeomorphic hazard prone areas) is not unstable/vulnerable to these hydrogeomorphic hazards?

Thank you for this important question. This study provides evidence over the last 35 years of where areas are stable and unstable in terms of hydrogeomorphic variability. Thus, according to satellite imagery and the modelling software, where there has been no change over the last 35 years, there is evidence of hydrogeomorphic stability. However, this does not mean that these areas will remain stable in the future. With unprecedented climatic changes and human activities within the GBM catchment, it is unknown whether hydrogeomorphic changes will remain where they are currently taking place. This assessment of future changes warrants further study (see also response to next comment).

8. The DeepWaterMap had been done based on a 35-year dataset. A hotspot analysis with future projections of hydrogeomorphic changes (due to climate change and others) should apprehend at least double this timeline.

We agree with this comment made by the Reviewer and believe that future estimations of hydrogeomorphic changes warrant further study. However, future hydrogeomorphic changes can, at best, be assessed in terms of zones of susceptibility and cannot be predicted with current geomorphological models. The focus of this study is on past hydrogeomorphic changes and identifying corridors and areas that are particularly susceptible to hydrogeomorphic hazards where dense and vulnerable populations may live. We have adjusted the sentence in the discussion to now read:

“Looking ahead, future work should investigate the influence of climate change on population exposure to hydrogeomorphic hazards in the intermediate (2050) and long-term (2080 to 2100) future through, for example, predictive coupled human and hydrogeomorphic dynamical systems models. This would provide invaluable insights into the complex interplay between climate change, socio-economic vulnerabilities, and the spatial distribution of these hidden hazards.”

9. Discussion section: More clarification regarding persistent hydrogeomorphic changes is required as it has been stated that these changes include both depletion and accretion. Therefore, a cut-off point analysis reflecting the areas of exploration highlighted in this study needs to be included.

Thank you for this important comment, which was also raised by another reviewer. We have looked at hotspots with more extremes for the total population and per wealth index bin and have incorporated these new findings into the manuscript to highlight areas and the number of people that are susceptible to more persistent hydrogeomorphic changes versus those that are, relatively, more stable. The detailed findings from the analysis have also been included in the Supplementary Information.

10. Line 385: Check whether these years are correct?

These dates are correct, as cited in Lázár et al., 2020.

11. Figure 4: Is this a Histogram? Please show the full Histogram.

We appreciate the Reviewer's question about Figure 4. The figure is, indeed, based on binned data points that we interpolated for visual clarity and communication of results. This current presentation of the smooth curves will allow readers to more easily compare the distributional differences between wealth indices in Bangladesh versus within hydrogeomorphic hotspots, which are central to the analysis. We had previously tested having the two histograms on one figure, but it looked rather messy and distracting, with the key message of the shift in distributions lost in the jaggedness of the plots.

12. Add the Sources underneath the tables (e.g., Table 1).

Table 1 (the only table in the manuscript) does not need any sources because the values are calculated within this study, not extracted from previous work.

13. References should be placed in an alphabetical order. More references worth including are as follows:

- i) Karim, A., & Noy, I. (2016). Poverty and natural disasters—a qualitative survey of the empirical literature. *The Singapore Economic Review*, 61(01), 1640001.
- ii) Karim, A., & Noy, I. (2016). Poverty and natural disasters: a regression meta-analysis. *Review of Economics and Institutions*, 7(2), 26.
- iii) Karim, A. (2018). The household response to persistent natural disasters: Evidence from Bangladesh. *World Development*, 103, 40-59.
- iv) Kolstad, I., Karim, A., Lujala, P., & Wiig, A. (2023). Expert adoption of composite indices: a randomized experiment on migrant resettlement decisions in Bangladesh. *Natural Hazards*, 119(1), 261-297.
- v) Karim, A. (2024). Knowledge, perception or disaster experience? The new determinants of household disaster preparedness behaviour in Bangladesh. *Journal of International Development*, 36(6), 2557-2580.

Following the formatting regulations of *Nature Communications*, the references are placed in the order that they appear in the manuscript. Thank you for highlighting the additional papers by Karim A. and colleagues. We have incorporated these into the manuscript.

Reviewer #5 (Remarks to the Author):

This study makes a significant contribution by providing a national-scale spatial assessment of exposure to hydrogeomorphic hazards in Bangladesh and highlighting the disproportionate impact on poorer populations. The methodology is well described, and the findings are compelling.

We would like to thank the Reviewer for acknowledging the importance and significance of this work.

In general, the conclusion of the study quantifying the effect of hydrogeomorphic hazard on the poverty will be very useful for mitigation of the effects. However, the following points need to be addressed:

1. Incorporate the Four Hazard Types into the Introduction:

The introduction currently mentions only two predominant processes: (i) river and coastal erosion and deposition; and (ii) the wetting and drying of deltaic land. While these are key, the study later categorizes hydrogeomorphic processes into four distinct types:

- (i) Riverine erosion and accretion
- (ii) Conversion of deltaic land to water bodies
- (iii) Complex patterns of wetting and drying of land
- (iv) Coastal erosion and accretion

Including these four categories in the introduction with justification would provide a more complete picture of the study's scope from the outset. This would also better prepare the reader for the later analysis and categorization of different hydrogeomorphic hazards. Highlighting the four types early would immediately establish the breadth of the study and its specific focus on these diverse processes.

We would like to thank the reviewer for this comment, which we fully agree with. We have adjusted the Introduction of the manuscript to clarify the four processes that we explore. The relevant text now reads:

“In this paper, the focus is on landscape changes that affect human and environmental processes in deltaic systems^{8,26}. These changes are expressed through four predominant processes: (i) riverine erosion and deposition; (ii) conversion of deltaic land to water bodies; (iii) wetting and drying of land due to land-use changes; and (iv) coastal erosion and accretion.”

2. Exposure analysis

A potential area for further exploration could involve investigating the impact of using a specific threshold for the Channelized Response Variance (CRV) to define hydrogeomorphically hazardous areas. Currently, the study uses all non-zero CRV values as indicators of change, with the intensity of the CRV indicating the frequency and magnitude of change. While this approach captures a broad spectrum of hydrogeomorphic activity, including all non-zero CRV threshold may overestimate the exposed population. The current approach may be influenced by annual anomalies such as image classification errors or short-term wetting events. These may not reflect sustained hydrogeomorphic changes. A CRV threshold could help filter out these anomalies by focusing on areas with more consistent and significant changes.

We thank the Reviewer for this suggestion, which we agree is an interesting avenue to explore further. We have therefore done additional analyses to assess hydrogeomorphic hotspots for different thresholds and have looked at the total population and population exposed per wealth index bin for the different hazard thresholds. Defining a CRV threshold for hydrogeomorphically hazardous areas could introduce subjectivity, and thus we have reported the top 25%, 10% and 5% most extreme areas of hydrogeomorphically instability. We have summarised the key findings in the manuscript but have included all detailed results of the threshold analysis in the Supplementary Information. It should also be noted that in the CRV analysis (excluding thresholds), we had already removed the lowest 5% of values from the CRV assessment to minimise errors from image classification. This has been clarified in the manuscript.

3. Refine Poverty Bias Analysis by Addressing Urban-Rural and regional Skews:

The current analysis compares the wealth distribution of populations exposed to hydrogeomorphic hazards with the wealth distribution of the entire country. While this shows a clear exposure bias, it may be skewed by the general urban-rural wealth disparity that is likely present across Bangladesh. To isolate the impact of hydrogeomorphic hazards on poverty, it's recommended to refine the analysis as follows:

National Level Comparison: Compare the wealth distribution of the exposed population with the wealth distribution of only the rural population of Bangladesh. This would remove the influence of wealthier urban areas from the baseline.

Regional Level Comparison: For each region, compare the wealth distribution of the exposed population with the wealth distribution of the rural population within that specific region. This will reveal how exposure to hazards affects people within the same regional context, but residing in different areas (exposed and not exposed). By comparing the exposed population with the rural population of the whole country, or specific region (as appropriate), a clearer picture of the impact of the hazard on the poor can be established. This method would help to isolate the impact of hydrogeomorphic hazards from the broader urban-rural poverty gradients or general regional disparity. The study already notes that the northern divisions of Rangpur and Mymensingh have the highest proportion of exposed populations with the lowest relative wealth and attributes this to those regions already having low levels of wealth, rather than a disproportionate impact of hydrogeomorphic hazards. Refining the analysis in the manner described above would help to provide further insight.

Although we agree with the Reviewer that the exposure bias may be skewed by the urban-rural wealth disparity in Bangladesh (which we highlight in the paper), we do not believe it would be appropriate to focus only on the rural population of Bangladesh. There are millions of urban poor, particularly in and around Dhaka, that are also exposed to hydrogeomorphic instabilities and thus should be captured in this assessment. We agree with the Reviewer that a future study could look at how exposure varies across the urban-rural gradient, but we believe this would detract from the main messages of this manuscript. We have added a sentence into the manuscript that reads:

“Interestingly, the spatial trends are also related to the location of cities relative to the hydrogeomorphic hazard areas (Dhaka and Chittagong), as cities are areas with better access to basic services and a greater concentration of assets, thus skewing the WI for the rest of the division. Although cities are hubs of assets and services, in Bangladesh, approximately 20% of the poor population live in urban areas⁷⁸. The poverty map utilised in this study⁵⁶ includes highly granular data in urban centres, to ensure that urban poverty (e.g., slums in and around Dhaka) is captured. Figures 4 and 6 demonstrate that both rural and urban poor, as well as wealthier urban populations, are exposed to hydrogeomorphic instability in large urban centres such as Dhaka and Chittagong.”

4. Analyse Differences Between Hazard Types:

The study identifies four distinct types of hydrogeomorphic hazards but does not thoroughly explore the variations in how these hazards impact populations. While the paper provides an overview of these different types, a comparative analysis would be beneficial.

A more detailed analysis of the differences between the four hazard types would enhance the study's impact.

Such an analysis could explore:

Specific Socio-economic impacts: How does riverine erosion affect livelihoods differently from

coastal erosion? How do the economic consequences of waterlogging compare to the effects of coastal accretion?

Vulnerability Variation: Are populations more vulnerable to certain types of hazards based on their location, economic activities, or access to resources?

Long-term implications: Do some hazard types lead to more persistent poverty traps than others?

By comparing the distinct impacts of these four hazard types, more targeted interventions can be designed. For example, this would help to identify whether similar policies would be relevant for each of the four regions, or whether regionally distinct approaches are more appropriate.

Although the study notes that all four regions experience land loss or change, it does not thoroughly explore how the effects on livelihoods vary. For instance, the impact of river erosion on agricultural land in the Jamuna region is likely different from the effect of waterlogging on aquaculture in the south-west. A comparative analysis would illuminate these differences and provide greater detail to the impacts of each hazard type.

We would like to thank the Reviewer for this suggestion and excellent prompting questions. We have elaborated in the Discussion on how the four processes lead to different impacts, by putting the findings into context with impact studies previously undertaken. Two paragraphs have been added to the Discussion section, but we would like to highlight to the Reviewer that undertaking a comprehensive comparative analysis to disentangle the hydrogeomorphic processes and their associated impacts on the population goes beyond what this article aims to do and would require a different analytical framework (i.e., a dynamical model, for example), and would be an excellent follow-on study.