

## ➤ Referee #3

### **Overall comments**

This study quantifies flood-induced population movements (FIPMs) between and within municipalities in response to varying flood magnitudes from heavy precipitation events, using the difference-in-differences (DiD) method, a statistical causal inference technique. The influence of these movements on projected future flood damages from heavy precipitation is then assessed, revealing modest effects at the national level (1–2%) but considerably stronger impacts in some individual municipalities (above 10%). The authors conclude that locally concentrated effects suggest that FIPMs are particularly relevant for flood risk management and policy evaluation at the municipal scale. I have the following comments:

#### **Response:**

We sincerely thank the reviewer for carefully reviewing our manuscript and for the concise summary of our study. We are grateful for the constructive comments on the interpretation and presentation of the results. In response to the reviewer's comments, we revised the manuscript to clarify the flood types considered in the analysis, specify that the future damage assessment focuses on fluvial flood damage, better explain how empirical relationships estimated from observed flood data are applied to future projections, and clarify the interpretation of increases and decreases in estimated damage costs due to FIPMs. Detailed responses to each specific comment are provided below.

## **Comment 1**

Make explicit throughout that only precipitation-induced flooding (not riverine or coastal) is analysed – currently this is missing in the title, abstract and introduction. At l. 51, consider whether riverine flooding is also relevant to your framing – if it is excluded, state so explicitly; if it is partially covered, clarify the scope.

### **Response:**

We thank the reviewer for this important comment. We revised the manuscript to clarify the flood types considered in the study. In response to this and related comments, we changed the title and terminology throughout the manuscript to specify that the future damage assessment focuses on fluvial flood damage. We also revised the Introduction to make the fluvial flooding focus explicit in the framing of the study in Japan. At the same time, the observed flood-related data used to estimate FIPMs are based on heavy precipitation events and do not fully separate fluvial and pluvial components. Therefore, we retained “flood” or “flooding” when referring to observed flood events, flood exposure, and flood-related damage records, while using “fluvial flood damage” when referring to the future damage assessment. We further clarified this point in the limitations. Specifically, we clarified that the DiD analyses use observed flood-related data without separating fluvial and pluvial components, whereas coastal flooding is outside the scope of the predictive damage assessment. We also clarified that the fluvial flood inundation model used for future projections partly includes the effect of pluvial flooding through basin-scale rainfall–runoff processes, but it does not explicitly account for inland water drainage facilities. This clarification is intended to distinguish the scope of the future fluvial flood damage assessment from a comprehensive assessment of all flood types. Representative examples of the revisions are shown below; similar terminology changes were made throughout the manuscript where the future damage assessment is discussed.

### **Title**

<b>Original title</b>	<b>Revised title</b>
Integrating flood-induced population movements into future flood damage estimates in Japan	Integrating flood-induced population movements into future <b>fluvial</b> flood damage estimates in Japan

### **Abstract**

<b>Original text</b>	<b>Revised text</b>
This study evaluated the impacts of FIPMs on future flood damage costs in Japan, a country that faces flood risk and population decline. (p. 1, lines 14–15 in the original manuscript)	This study evaluated the impacts of FIPMs on future <b>fluvial</b> flood damage costs in Japan, a country that faces flood risk and population decline.

## Introduction

Original text	Revised text
<p>In Japan, many urban areas lie below river water levels, making them highly vulnerable to large-scale flood damage (Ministry of Land, Infrastructure and Transport of Japan [MLIT], 2006).</p> <p>(p. 2, lines 51–52 in the original manuscript)</p>	<p>In Japan, many urban areas lie below river water levels, making them highly vulnerable to large-scale <b>fluvial</b> flood damage (Ministry of Land, Infrastructure and Transport of Japan [MLIT], 2006).</p>
<p>These topographical and climatic conditions contribute to Japan’s high susceptibility to flooding. Furthermore, Japan is projected to experience a significant population decline (Jarzebski et al., 2021). Given the dual challenges of flood damage and population decline, evaluating the impact of FIPMs on future flood damage costs in Japan is essential.</p> <p>(p. 2, lines 55–57 in the original manuscript)</p>	<p>These topographical and climatic conditions contribute to Japan’s high susceptibility to <b>fluvial</b> flooding. Furthermore, Japan is projected to experience a significant population decline (Jarzebski et al., 2021). Given the dual challenges of <b>fluvial</b> flood damage and population decline, evaluating the impact of FIPMs on future <b>fluvial</b> flood damage costs in Japan is essential.</p>

## Methods

Original text	Revised text
<p>For grid cells in the treatment group, the maximum inundation depth was calculated based on values provided in the flood inundation maps. Details regarding the total population data at the 500 m grid-cell level, data on areas affected by water-related disasters, and flood inundation maps are provided in Sect. S2.</p> <p>(p. 4, lines 92–95 in the original manuscript)</p>	<p>For grid cells in the treatment group, the maximum inundation depth was calculated based on values provided in the flood inundation maps. <b>The flood inundation maps provide estimates of inundated areas and inundation depths during the target heavy rainfall events and do not distinguish between fluvial and pluvial flooding. Therefore, the grid-cell-level analysis uses the estimated inundation without separating fluvial and pluvial components.</b> Details regarding the total population data at the 500 m grid-cell level, data on areas affected by water-related disasters, and flood inundation maps are provided in Sect. S2.</p>
<p>To represent flood magnitude, we used the following municipality-level indicators: the proportion of households affected below floor level by flooding, the proportion of households</p>	<p>To represent flood magnitude, we used the following municipality-level indicators: the proportion of households affected below floor level by flooding, the proportion of households</p>

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affected above floor level by flooding, and the proportion of households that were completely destroyed (including washed away) by flooding. These indicators were expressed as percentages of the total households, following the method of Okamoto et al. (2023). (pp. 5–6, lines 134–138 in the original manuscript)

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affected above floor level by flooding, and the proportion of households that were completely destroyed (including washed away) by flooding. **These indicators were calculated to represent household damage associated with both fluvial and pluvial flooding.** They were expressed as percentages of the total households, following the method of Okamoto et al. (2023).

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## **Limitations**

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### **Added text**

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Third, the treatment of flood types requires careful interpretation. This study focuses primarily on future fluvial flood damage. As described by Yanagihara et al. (2024), the fluvial flood inundation model used for future projections partly includes the effect of pluvial flooding through basin-scale rainfall–runoff processes, but it does not explicitly account for inland water drainage facilities. To maintain consistency with this modeling framework, the flood data used in the DiD analyses were treated without separating fluvial and pluvial components. Thus, neither the observational data nor the predictive model fully separates fluvial and pluvial components, although their treatment of flood types is not identical. Coastal flooding is outside the scope of the predictive damage assessment. This limitation may introduce uncertainty in areas where drainage-related pluvial flooding or coastal flooding strongly influences population movements. Therefore, the results should be interpreted as an assessment of the impact of FIPMs on future fluvial flood damage, rather than as a comprehensive assessment of all flood types.

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## **Comment 2**

The concluding statement about "importance for flood risk management frameworks" is not convincingly supported by 1–2% national-level effects. Either soften the claim to focus on local relevance (>10% in some municipalities), or strengthen it with additional argumentation.

### **Response:**

We thank the reviewer for this important suggestion. We agree that the original concluding statements were too broad, given the limited national-level effects of FIPMs. Accordingly, we have revised the relevant statements to focus on implications at the municipal level, where some municipalities showed reductions in estimated fluvial flood damage costs exceeding 10 %.

<b>Original text</b>	<b>Revised text</b>
These findings highlight the importance of accounting for FIPMs in flood risk management frameworks and policy evaluations. (p. 1, lines 21–22 in the original manuscript)	These findings highlight the importance of accounting for FIPMs in <b>municipal-level fluvial</b> flood risk management frameworks and policy evaluations.
These findings highlight the importance of incorporating FIPMs into future flood risk assessments and policy evaluations, particularly at the local level. (p. 18, lines 421–423 in the original manuscript)	These findings <b>suggest that</b> incorporating FIPMs <b>may be important for municipal-level fluvial</b> flood risk assessments and policy evaluations, <b>despite their limited influence at the national level.</b>
Thus, future assessments and policy evaluations at the local scale should explicitly consider the effects of FIPMs. (p. 19, lines 454–455 in the original manuscript)	Thus, <b>municipal-level fluvial flood risk</b> assessments and policy evaluations should consider the effects of FIPMs.

### **Comment 3**

Clarify the distinction between planned relocation (policy-driven resettlement) and spontaneous migration (individual household decisions) early in the introduction.

#### **Response:**

We thank the reviewer for this helpful comment. We agree that the distinction between planned relocation and spontaneous migration should be clarified early in the Introduction. We have therefore added text explaining that FIPMs can take different forms of population movement, including planned relocation or policy-driven resettlement and spontaneous migration by households or individuals. We also added references to support this conceptual distinction.

<b>Original text</b>	<b>Revised text</b>
<p>In contrast, recent studies have highlighted the importance of FIPMs (Del Rio Amador et al., 2025; Kakinuma et al., 2020; Kam et al., 2021). FIPMs can alter patterns of exposure to flood hazards, thereby influencing the extent of flood damage.</p> <p>(p. 2, lines 38–40 in the original manuscript)</p>	<p>In contrast, recent studies have highlighted the importance of FIPMs (Del Rio Amador et al., 2025; Kakinuma et al., 2020; Kam et al., 2021). <b>FIPMs can take different forms, including planned relocation or policy-driven resettlement and spontaneous migration by households or individuals. Planned relocation involves organized efforts to move residents away from hazardous areas (McAdam and Ferris, 2015), whereas spontaneous migration reflects household- or individual-level decisions to move (Black et al., 2011).</b> FIPMs can alter patterns of exposure to flood hazards, thereby influencing the extent of flood damage.</p>

#### **Added references**

Black, R., Adger, W. N., Arnell, N. W., Dercon, S., Geddes, A., and Thomas, D.: The effect of environmental change on human migration, *Glob. Environ. Change*, 21, S3–S11, <https://doi.org/10.1016/j.gloenvcha.2011.10.001>, 2011.

McAdam, J. and Ferris, E.: Planned relocations in the context of climate change: unpacking the legal and conceptual issues, *Camb. Int. Law J.*, 4, 137–166, <https://doi.org/10.7574/cjicl.04.01.137>, 2015.

## **Comment 4**

I suggest that Sections 3 onwards should be structured as subsections of the Methods section (Section 2) for consistency and clarity.

### **Response:**

We thank the reviewer for this helpful suggestion. In response, we have reorganized the manuscript by integrating the methodological framework, the quantification of flood-induced population movements (FIPMs), and the procedures for projecting future population, land use, and fluvial flood damage costs into a single unified “Methods” section. The revised structure is shown below, and the relevant section and subsection numbers have been updated accordingly throughout the manuscript.

### **[Original structure]**

2 Methodological framework

3 Quantifying FIPMs

3.1 Estimating changes in the total population at the 500 m grid-cell level due to flooding

3.1.1 Analysis target and period

3.1.2 Covariates

3.1.3 Analytical method

3.2 Estimating changes in the net migration rate at the municipality level due to flooding

3.2.1 Analysis target and period

3.2.2 Covariates

3.2.3 Analytical method

4 Projecting future population and land use and estimating flood damage costs

4.1 Projecting future population incorporating FIPMs

4.1.1 Population changes due to FIPMs at the municipality level

4.1.2 Population changes due to FIPMs at the 500 m grid-cell level

4.2 Projecting land use based on future population

4.3 Estimating future flood damage costs considering changes in rainfall and land use

### **[Revised structure]**

2 Methods

2.1 Methodological framework

2.2 Estimating changes in the total population at the 500 m grid-cell level due to flooding

2.2.1 Analysis target and period

2.2.2 Covariates

2.2.3 Analytical method

2.3 Estimating changes in the net migration rate at the municipality level due to flooding

2.3.1 Analysis target and period

- 2.3.2 Covariates
- 2.3.3 Analytical method
- 2.4 Projecting future population incorporating FIPMs
  - 2.4.1 Population changes due to FIPMs at the municipality level
  - 2.4.2 Population changes due to FIPMs at the 500 m grid-cell level
- 2.5 Projecting land use based on future population
- 2.6 Estimating future fluvial flood damage costs considering changes in rainfall and land use

## **Comment 5**

At l. 84, clarify whether the analysis is based on only two specific extreme events: if so, this is a significant scope limitation that should be stated clearly in both abstract and introduction. Alternatively, clarify whether the two events serve as empirical anchors for estimating movement assumptions used in the broader modelling.

### **Response:**

We thank the reviewer for this important comment. We agree that the role of the two observed flood events was not sufficiently clear in the original manuscript. We revised the Abstract, Introduction, and Methods to clarify that the two events are used in the grid-cell-level analysis to estimate empirical relationships between flood magnitude and FIPMs, and that these observed events themselves are not directly extrapolated. We also clarified that the municipality-level analysis is not based only on these two events, but uses municipality-level data from flood-affected municipalities during 2015–2020. The estimated empirical relationships are then applied to future population projections using flood magnitude indicators derived from future fluvial flood inundation analyses.

<b>Original text</b>	<b>Revised text</b>
<p>We develop a methodological framework that uses statistical causal inference to quantify FIPMs, integrates these estimates into future population and land-use projections, and evaluates future flood damage costs under scenarios of climate and land-use change. The results indicate that incorporating FIPMs leads to only modest changes in estimated flood damage costs at the national level (generally below 1 %), and similarly modest impacts at the prefectural level, except for a few prefectures with changes of approximately 2 %.</p> <p>(p. 1, lines 15–19 in the original manuscript)</p>	<p>We <b>developed</b> a methodological framework that uses statistical causal inference to quantify FIPMs, integrates these estimates into future population and land-use projections, and evaluates future <b>fluvial</b> flood damage costs under scenarios of climate and land-use change. <b>Empirical relationships between flood magnitude and FIPMs were estimated using grid-cell-level data from two flood events in 2019 and 2020 and municipality-level data from municipalities affected by flood disasters during 2015–2020, and then applied to future population projections using flood magnitude indicators derived from future fluvial flood inundation analyses.</b> The results indicate that incorporating FIPMs leads to only modest changes in estimated <b>fluvial</b> flood damage costs at the national level (generally below 1 %), and similarly modest impacts at the prefectural level, except for a few prefectures with changes of approximately 2 %.</p>

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Against this background, this study aims to evaluate the impacts of FIPMs on future flood damage costs in Japan. To achieve this, we propose a methodological framework for projecting future population and estimating flood damage costs that accounts for FIPMs. To quantify population movements between and within municipalities in response to varying flood magnitudes, this study employs the difference-in-differences (DiD) method – a statistical causal inference technique developed in the fields of econometrics and sociology.  
(p. 3, lines 66–70 in the original manuscript)

FIPMs were quantified at both the grid-cell and municipality levels utilizing available demographic data to capture population movements occurring within and between municipalities in response to varying flood magnitudes. Detailed methodologies for quantifying FIPMs are presented in Sect. 3, while methodologies for the subsequent processes of the framework are described in Sect. 4.  
(p. 4, lines 77–80 in the original manuscript)

Against this background, this study aims to evaluate the impacts of FIPMs on future **fluvial** flood damage costs in Japan. To achieve this, we propose a methodological framework for projecting future population and estimating **fluvial** flood damage costs that accounts for FIPMs. **Specifically, we use the DiD method to quantify FIPMs between and within municipalities in response to varying flood magnitudes and incorporate the estimated relationships into future population and land-use projections. These empirical relationships are estimated using grid-cell-level data from two flood events in 2019 and 2020 and municipality-level data from flood-affected municipalities during 2015–2020. They are then applied to future population projections using flood magnitude indicators derived from future fluvial flood inundation analyses, rather than by directly extrapolating the observed events themselves.**

FIPMs were quantified at both the grid-cell and municipality levels **using** available demographic data to capture population movements occurring within and between municipalities in response to varying flood magnitudes. **Specifically, FIPMs were quantified using two types of observed datasets that combine flood-related and demographic information. Within-municipality population changes were estimated using flood inundation maps for areas affected by Typhoon Hagibis (2019) and the heavy rainfall event of July 2020, together with 500 m grid-cell population data. Inter-municipality population movements were estimated using municipality-level flood damage records and annual migration data. These data were used to estimate empirical relationships between flood magnitude and FIPMs, rather than to directly extrapolate the**

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observed events themselves. The areas covered by the flood inundation maps used in the 500 m grid-cell-level analysis and the treated municipalities used in the municipality-level DiD analysis are shown in Figs. S1 and S2, respectively. Detailed methodologies for quantifying FIPMs are presented in Sects. 2.2 and 2.3, while methodologies for the subsequent processes of the framework are described in Sects. 2.4–2.6.

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## **Comment 6**

1. 333 / Figure 4: Specify the unit clearly – "persons per [what]?" needs to be defined (per km<sup>2</sup>, per municipality, per 1,000 inhabitants, etc.).

### **Response:**

We thank the reviewer for this helpful comment. The aggregation procedure was described in the original manuscript (pp. 13–14, lines 330–332): municipality-level population changes were summed across all municipalities in Japan, whereas grid-cell-level differences in population with and without FIPMs were aggregated nationwide. However, we agree that the unit in Fig. 4 could be made clearer. Figure 4 shows aggregated national-level population changes due to FIPMs, rather than rates or densities. Therefore, the unit is “persons,” not “persons per km<sup>2</sup>,” “persons per municipality,” “persons per grid cell,” or “persons per 1,000 inhabitants.” We have revised the main text and figure caption to clarify this point.

<b>Original text</b>	<b>Revised text</b>
Figure 4 presents the aggregated national-level population changes due to FIPMs at the municipality and the 500 m grid-cell levels. At the municipality level, absolute population changes due to FIPMs were obtained using Eq. (4) and summed across all municipalities in Japan. (p. 13, lines 329–331 in the original manuscript)	Figure 4 presents the aggregated national-level population changes due to FIPMs at the municipality and the 500 m grid-cell levels. <b>The values shown in Fig. 4 are expressed in persons and are not normalized by area, municipality, grid cell, or population.</b> At the municipality level, absolute population changes due to FIPMs were obtained using Eq. (4) and summed across all municipalities in Japan.
Figure 4: Aggregated national-level population changes due to FIPMs at the municipality and the 500 m grid-cell levels. Population changes are shown at five-year intervals from 2020 to 2100, with each value representing the cumulative population change over the preceding five-year period. The changes were calculated based on the average values estimated from five GCMs. Error bands indicate the range between the maximum and minimum population changes derived from the five GCMs. (Caption for Figure 4 in the original manuscript)	Figure 4: Aggregated national-level population changes due to FIPMs at the municipality and the 500 m grid-cell levels. <b>Values are expressed in persons and are not normalized by area, municipality, grid cell, or population.</b> Population changes are shown at five-year intervals from 2020 to 2100, with each value representing the cumulative population change over the preceding five-year period. The changes were calculated based on the average values estimated from five GCMs. Error bands indicate the range between the maximum and minimum population changes derived from the five GCMs.

## **Comment 7**

l. 345: Explain why flood damages are initially reduced under higher climate change scenarios – this is counterintuitive and needs explicit reasoning. Is it due to outmigration from high-risk zones reducing exposed population? Or overall population increase?

### **Response:**

We thank the reviewer for this helpful comment. We revised the text to clarify how the sign of the percentage change should be interpreted and to explain why the percentage changes in estimated fluvial flood damage costs were negative in the near future. Specifically, the initial reduction can be interpreted as a reduction in population exposure in flood-exposed areas due to FIPMs, rather than as a result of overall population increase. We further clarified that the percentage changes can shift from negative to positive toward the end of the 21st century when increases in population exposure in other areas that remain flood-exposed exceed reductions in exposure elsewhere.

<b>Original text</b>	<b>Revised text</b>
Here, the percentage change in flood damage costs due to FIPMs is defined as the relative difference from estimates without considering FIPMs. At the national level, under JSSP1–RCP2.6, the percentage change due to FIPMs across Japan was –0.2 % in the near future and +0.3 % at the end of the 21st century, based on flood damage costs averaged across five GCMs. (p. 14, lines 343–346 in the original manuscript)	Here, the percentage change in <b>fluvial</b> flood damage costs due to FIPMs is defined as the relative difference from estimates without considering FIPMs. <b>Negative values indicate that incorporating FIPMs reduces estimated fluvial flood damage costs relative to the corresponding estimates without FIPMs. Conversely, positive values indicate that incorporating FIPMs increases estimated fluvial flood damage costs relative to the corresponding estimates without FIPMs.</b> At the national level, under JSSP1–RCP2.6, the percentage change due to FIPMs across Japan was –0.2 % in the near future and +0.3 % at the end of the 21st century, based on <b>fluvial</b> flood damage costs averaged across five GCMs.
National-level impacts of FIPMs on future flood damage costs are minimal, with absolute percentage changes consistently below 1 %. (p. 17, lines 406–407 in the original manuscript)	<b>As shown in Sect. 3.3, in the national-level estimates, the percentage changes in estimated fluvial flood damage costs due to FIPMs were negative in the near future. This indicates that FIPMs may reduce population exposure in flood-exposed areas, thereby lowering these costs. Toward the end of the 21st century, however, the</b>

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percentage changes shifted from negative to positive values. This shift can occur when increases in population exposure in other areas that remain flood-exposed exceed reductions in exposure in areas where exposure decreases. Nevertheless, national-level impacts of FIPMs on future fluvial flood damage costs are minimal, with absolute percentage changes consistently below 1 %.

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## **Comment 8**

Figure 5: Add a brief explanatory note in the text clarifying what it means when flood damages increase due to population movement – presumably this reflects in-migration into higher-risk areas, but this should be stated directly.

### **Response:**

We thank the reviewer for this helpful suggestion. We added explanatory text referring to Figs. 5 and 6. In the revised text, we explain that positive percentage changes at the prefectural and municipal levels may occur when greater population exposure in areas that remain flood-exposed exceeds reductions in exposure elsewhere. We did not state that these changes directly reflect in-migration into the highest-risk areas, because the present framework does not explicitly identify the destinations of population movements. Instead, we described the interpretation in terms of changes in population exposure within flood-exposed areas.

<b>Original text</b>	<b>Revised text</b>
<p>Our findings extend this understanding, showing that reductions in population growth can translate into lower future flood damage costs. From a practical perspective, although only a limited number of municipalities experienced notable cost reductions due to FIPMs, overlooking these effects could lead to an overestimation of the effectiveness of flood mitigation measures.</p> <p>(pp. 17–18, lines 418–421 in the original manuscript)</p>	<p>Our findings extend this understanding, showing that reductions in population growth can translate into lower future <b>fluvial</b> flood damage costs. <b>At the prefectural and municipal levels, Figs. 5 and 6 show that some prefectures and municipalities exhibited positive percentage changes, although their magnitudes were generally smaller than the largest reductions. As discussed above, such increases may occur when greater population exposure in some areas that remain flood-exposed exceeds reductions in exposure elsewhere.</b> From a practical perspective, although only a limited number of municipalities experienced notable cost reductions due to FIPMs, overlooking these effects could lead to an overestimation of the effectiveness of flood mitigation measures.</p>

## **Comment 9**

l. 422: The strong general claim is not well-supported given the small national-level numbers and the nuanced discussion preceding it. Consider limiting the claim to the local/municipal scale, where the evidence is stronger.

### **Response:**

We thank the reviewer for this important comment. This point has been addressed in our response to Comment 2. Specifically, we revised the relevant statements to avoid broad generalization and to focus on implications at the municipal level, where the evidence is stronger.

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<b>Original text</b>	<b>Revised text</b>
These findings highlight the importance of incorporating FIPMs into future flood risk assessments and policy evaluations, particularly at the local level. (p. 18, lines 421–423 in the original manuscript)	These findings <b>suggest that</b> incorporating FIPMs <b>may be important for municipal-level fluvial</b> flood risk assessments and policy evaluations, <b>despite their limited influence at the national level.</b>

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