Point-by-point response to editor's and reviewers' comments

Part 1: Response to the Anonymous Referee #1

General Comments. The manuscript developed a new food protection dataset for China based on the relevant policy and multi-source data. Such a dataset is urgently needed as it is a foundation of reliable flood risk assessment and effective risk management, but scarce in realty. This dataset revealed how an area should be protected according to the relevant policy. Thus it helped to identify the potential social divergence and the vulnerable groups in terms of lower flood protection. There is a limited amount in the literature on this topic, so it fills an important gap. The manuscript is generally well written and interesting. Specific comments are as follows.
Accepted: Thanks for confirming the relevance of our manuscript and the suggestions for further improvement. We have thoroughly revised our paper, addressing your valuable comments and suggestions.

Specific Comment 1. Lines 12-13. The validation can only reveal that the policy-based FPLs is a reliable proxy for the actual FPLs in Chinese case. It should be with caution to extend the conclusion.
Accepted: Thanks for this suggestion. We have revised the sentence. Please check from *line 12 on page 1*. Now it reads as:

> This suggests that the policy-based FPLs is a valuable proxy for actual FPLs in China.

Specific Comment 2. Lines 13-14. More explanations are needed on how Chinese flood risk may have been overestimated.
Accepted: Thanks for the suggestion. The overestimation of Chinese flood risk in previous studies resulted from an underestimation of Chinese flood protection. We revised the sentence accordingly. Please check from *lines 12–14 on page 1* or as follows:

> The FPLs are significantly higher than previously estimated in the FLOPROS global dataset, suggesting that Chinese flood risk was probably overestimated.

Further, we compared the FPL dataset against the FLOPROS using the Paired Sample T Test and found that the protection levels are significantly higher in the former than in the latter ($p<0.01$). Please check from *Supplementary Table S4*.

Specific Comment 3. Line 62, references are needed to say the FPL data are not well accessible.
Accepted: Thanks for the suggestion. References have been added *(line 66 on page 3)* and the sentence now reads as:

> FPL data are typically difficult to access at a large scale in China (Jiang et al. 2020).

References:

Jiang, Y., Zhi, Y., Zhao, H., Liang, L., Cao, y., and Gu, J.: Research status and prospects on water conservancy big data, Journal of Hydroelectric Engineering, 39, 1-32, 2020.

Specific Comment 4. Lines 93, the data source of the GDP data should be specified.

Accepted: Thanks for the suggestion. The data source was the Statistical Yearbook of Chinese Cities 2016, which has been added *(lines 100–101 on page 5)*.

References:

Division of Urban Social and Economic Survey of National Bureau of Statistics: Statistical Yearbook of Chinese Cities, China Statistical Press, Beijing, 2016.

Specific Comment 5. Table 2, the caption is unclear. Are the vulnerable exposed population in the brackets different from the followed vulnerable population?

Accepted: Thanks for the suggestion. The caption of Table 2 has been clarified. Please check from *lines 519–521 on page 22*, or as below.

Table 2. Exposed population (total, vulnerable, children, and elders) for each flood protection level (FPL), in absolute amounts and as percentage of the whole exposed population. The rightmost column reports the ratio of vulnerable to the total exposed population.

FPL (years)	Total exposure in millions (%)	Vulnerable exposure in millions (%)	Exposed children in millions (%)	Exposed elders in millions (%)	Vulnerable-to-total exposed population ratio
Low	**188.4 (44.9)**	**38.3 (52.3)**	**19.4 (52.9)**	**18.8 (51.6)**	**20.3%**
10–20	2.0 (0.5)	0.4 (0.6)	0.2 (0.6)	0.2 (0.6)	21.0%
20–30	96.5 (23.0)	19.9 (27.1)	10.1 (27.5)	9.8 (26.8)	20.6%
30–50	89.9 (21.4)	18.0 (24.6)	9.2 (24.9)	8.9 (24.3)	20.0%
High	**231.1 (55.1)**	**35.0 (47.7)**	**17.3 (47.1)**	**17.7 (48.4)**	**15.1%**
50–100	50.8 (12.1)	9.0 (12.2)	4.5 (12.1)	4.5 (12.3)	17.6%
100–200	82.5 (19.7)	13.6 (18.6)	6.9 (18.8)	6.7 (18.3)	16.5%
≥200	97.8 (23.3)	12.4 (17.0)	5.9 (16.2)	6.5 (17.8)	12.7%
Sum	**419.5 (100)**	**73.3 (100)**	**36.8 (100)**	**36.5 (100)**	**17.5%**

Specific Comment 6. Figure 2, the axis of flood protection levels should increase from the left to the right.

Accepted: Thanks for the suggestion. Figure 2 has been clarified. Please check from *lines 526–527 on page 24*, or as below.

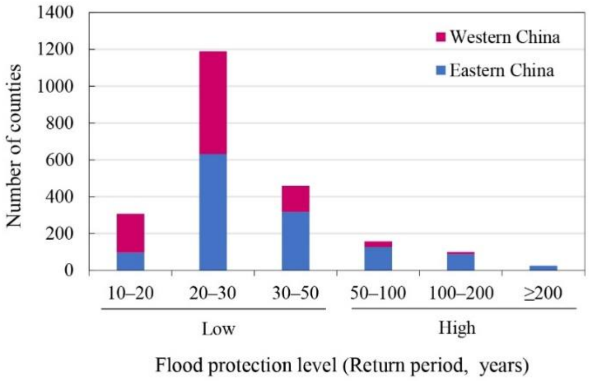

Figure 2 The number of counties with different flood protection levels. (The map of western and eastern China is

shown in Figure 3)

Specific Comment 7. Figure 3, the boundary lines are difficult to identify, particularly for the provincial level.

Accepted: Thanks for the suggestion. Figure 3 has been clarified accordingly. Please check from *lines 528–531 on page 25*, or as below.

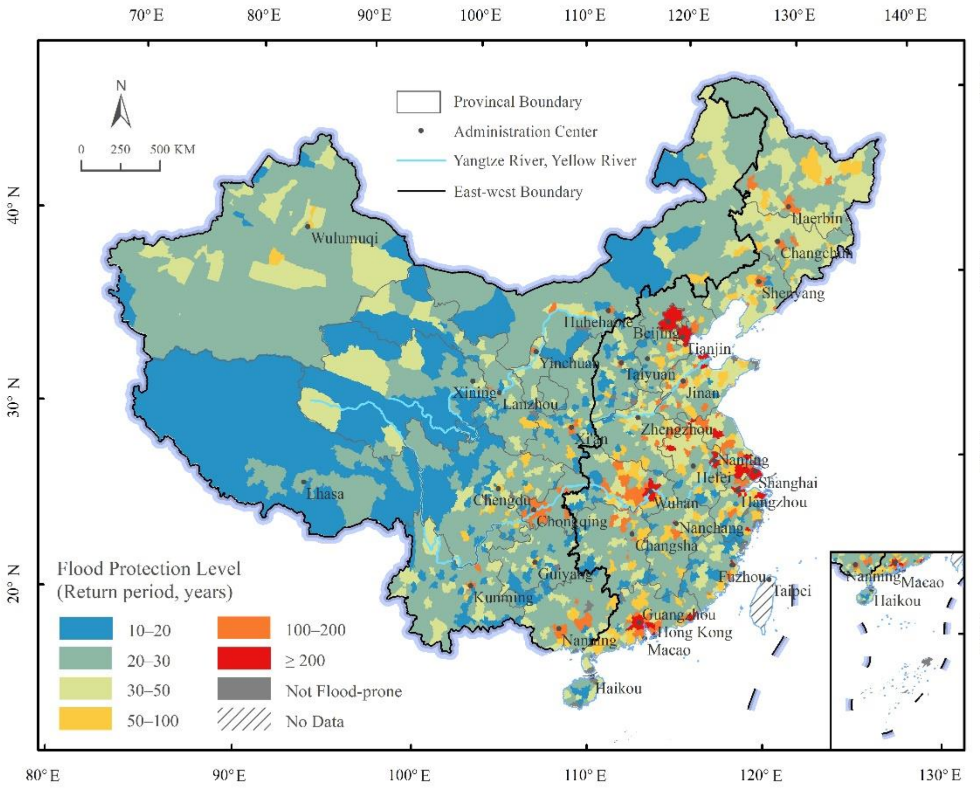

Figure 3 Flood protection level (FPL) for Chinese counties. The FPL is limited to the scope of floodplains but plotted to cover the entire counties. The data should only be viewed as a proxy of the actual FPLs, not equating to the actual FPLs. The Shapefile format data are available as a supplement.

Part 2: Response to the Anonymous Referee #2

General Comments. This paper develops a county-level flood protection level (FPL) dataset for China on the basis of the prescriptions of the 2014 Chinese policy document Standard for flood control. It then analyses this against the amount of children and elders in the country, also by county. The paper is generally well written, and even though I do not think it can be considered particularly substantial as a research article (as the bulk of the work consists in essentially overlapping GIS datasets following a policy document), I believe the results are nevertheless interesting and useful to the community. Thus, in my opinion the article may be considered for publication in NHESS, although several improvements are necessary.

Accepted: Thanks for confirming the relevance of our manuscript and the suggestions for further improvement. We have thoroughly revised the paper, addressing your valuable comments and suggestions.

General comment 1. The paper defines floodplain as the maximum extent of the 100-year flood map, and the exposed elements are then defined as the elements within that area. Should this refer to a defended or an undefended 100-year flood extent? Is there a reference to this aspect in the policy document, i.e. a guideline on how the actual quantification of exposed elements should be performed? This point needs to be clearly addressed in the article, as it will necessarily affect the estimation of FPLs. Moreover, taking into account that the 100-year hazard map used in this study (Rudari et al., 2015) already implicitly considers the existence of flood defences based on GDP, does its application impact the estimation of FPLs? Please discuss.

Accepted: Thank you for the suggestion. The 100-year flood map we applied, which was provided by Dr. Roberto Rudari from the CIMA Foundation, is explicitly based on undefended terrain. The undefended data were used instead of the defended one for two major reasons. First, the flood defenses were generally designed based on the potentially protected population and assets that would be under threat of floods prior to the defenses. Therefore, the exposed elements should be identified from the undefended flood maps, which provides a clue for inferring the flood defenses, as shown in the Chinese flood control policy. Second, flood defenses cannot ensure the protected areas' absolute safety; thus, the population and assets should not be excluded from flood exposure analysis. We now specify this important feature in the manuscript, also following General Comment 4 of Referee #3. Please check from *lines 88–91 on page 4*.

Further, we clarified how we defined the flood exposure, also following General Comment 4 of Referee #3. The flood exposure was calculated as the elements within the maximum extent of the 100-year return period flood. This definition is consistent with the flood risk assessment by Shi et al (2015) and the flood exposure analysis by Jongman et al (2012), Du et al (2018), and Fang et al (2018). Please check from *lines 104–107 on page 5*.

References:

Du S, He C, Huang Q, Shi P, 2018. How did the urban land in floodplains distribute and expand in China *from 1992–2015? Environmental Research Letters, 13(3): 034018.*

Fang Y, Du S, Scussolini P, Wen J, He C, Huang Q, et al., 2018. Rapid Population Growth in Chinese Floodplains from 1990 to 2015. International Journal of Environmental Research and Public Health, 15(8): 1602.

Jongman B, Ward P J and Aerts J C J H 2012 Global exposure to river and coastal flooding: long term trends and changes Glob. Environ. Change 22 823–35

Shi PJ, Wang JA, Xu W, Ye T, Yang SN, Liu LY, Fang WH, Liu K, Li N and Wang M. 2015 World Atlas of Natural Disaster Risk (Heidelberg: Springer)

General comment 2. The validation of FPLs is carried out not against a sample of actual flood protection infrastructure, but rather against local flood protection plans. Therefore, this exercise can be viewed more as a check on whether county-level flood protection policies are aligned with the national one from 2014, rather than an actual validation of computed FPLs. Although the authors acknowledge this limitation in the article, I am not convinced with statements such as "validating the policy-based FPLs as a reliable proxy for actual FPLs", which I find partly unsupported. I think the article would benefit significantly from a more robust validation with ground-truth data for a number of counties. Is this information for some counties not available or obtainable at all, e.g. with river basement management authorities?

Accepted: Thank you for the suggestion. Indeed, the only data we can find for the validation are documents of flood protection design, rather than the actual protection due to the lack of accessible ground-truth data. We agree that the flood protections in design documents are different from actual protection. However, we believe it is plausible to assume the actual protection of protection infrastructures that are completed and qualified to be equal to or higher than the designed standards, as a result of strict and tight control in the authoritarian administration of China. Following your critical comment and General Comment 3 of Referee #3, we dedicated additional efforts to enhance the validation, increasing the validation sample size from 51 counties to 171 counties. Now, as we specify in Section 2.4, the validation samples represent 7.6% of the surveyed Chinese counties, 34.0% of the exposed population, and 13.0% of Chinese exposed arable lands. We believe the expanded sample provides a substantially more solid base for the validation. Please check from *lines 129–131 on page 6* and *Supplementary* Table S1.

Besides, we have refined the selection process in the manuscript *(lines 121–129 on page 6)*. We selected the protection design documents for a relatively recent period from 2007 to 2012, neither too old that may be outdated nor too new that may be uncompleted and unqualified. Those documents would be kept in the validation data only if they stated that the design would be completed by 2015. Additionally, new flood protection design documents starting from 2015 were also employed, only if they stated the current (2015) flood protection standards.

Additionally, we revised the sentence about the validation statement. Now, it reads as: “This suggests that the policy-based FPLs is a valuable proxy for actual FPLs in China.” *(line 12 on page 1)*

General comment 3. Still related to the comparison of county level plans and the national policy regarding protection level, can you please provide some additional information on how these counties were selected? It would be relevant to understand if these counties are representative of the different realities in China, particularly in terms of the variables defined in the policy (rural/urban, exposed population, arable land). You found an agreement in FPLs in 66.7% of the counties – can this be attributed in some way to specific properties of these counties, for example? Additional information on the validation counties and additional discussion on this would be useful.

Accepted: Thank you for the suggestion. The validation counties are selected based on the date of the flood protection design documents: the data should represent the flood protection of the year 2015. From accessible authority websites and literature, we found a raw sample of 304 counties with flood protection documents dating from 1998 to 2019. For the first round, we only selected the relatively new documents released from 2007 to 2012, neither too old that may be outdated nor too new that may be uncompleted and unqualified. Those documents were kept in the validation data only if they stated that the design would be completed between 2010 and 2015. A sample of 110 counties was selected from this round. For a second round, new flood protection design documents starting from 2015 were researched and these were kept only if they stated the current (2015) flood protection standards. Another 61 counties were selected then. Now, we have added how the validation sample is selected in the manuscript. Please check from *lines 121–129 on page 6*.

Additionally, we clarified the representativeness of the validation sample, also following your critical General comment 2 and General Comment 3 of Referee #3. With an expanded validation sample from 51 to a total of 171 counties, the validation data include 122 urban counties (19.1%) and 49 rural counties (3.1%). These represent 34.0% of the total exposed population and 13.0% of Chinese exposed arable land. Thus, we believe the validation counties can now be taken as representative of general Chinese territory. Please check from *lines 129–131 on page 6*.

Specific comments

Specific comments 1. Title: I feel that the use of "social divergence" raises a reader's expectations above what is actually presented in the article, which is limited to age groups. Please adjust the title to reflect this, or otherwise expand the analysis to include other factors that influence social vulnerability – the latter would certainly be more insightful and make the article more interesting.

Accepted: Thank you for the suggestion. We have expanded the social divergence to include the exposed rural and urban population following your critical comment. Accordingly, we revised sections 3.3 and 3.4 *(lines 219–222 on page10 and lines 240–244 on page 11)*; and added the supplementary Table S3 for the urban and rural population. However, the paper still does not consider all the aspects of social divergence, due to data limitation, which is now further clarified in section 4.3 *Limitation and future perspectives (lines 333–336 on page 15).*

Specific comments 2. L37: Remove 'Each year' (I assume these are aggregate numbers for

1990-2017)

Accepted: Thank you for this suggestion. It is indeed average data. We revised the sentence *(lines 39–41 on page 2)* and now it reads:

> Between 1990 and 2017, floods in China averagely affected 149 million people, led to 2165 deaths, and caused an economic damage of US$ 34 billion per year (Du et al., 2019).

Specific comments 3. L58: I do not fully understand what the second research question means, in the sense that the policy document does not make reference to demographics in the definition of FPLs, and so the answer to this is already known. Please clarify.

Accepted: Thank you for this suggestion. We clarified the second research question, also following General Comment 2 of Referee 3. Now it reads as: "Since the FPL policy does not consider population demographics, what are the implications for the protection of vulnerable social groups?" Please check from *lines 62–63 on page 3.*

Specific comments 4. L65: My interpretation of Jonkman, 2013 is that it states the actual opposite of what you are saying in this sentence. For example, Jonkman, 2013 says that ": : : the actual protection levels could differ by more than a factor of 10 from the protection standard, and the effect on risk will be similar." Please discuss and revise.

Accepted: Thanks for this suggestion. We revised the sentence *(lines 68–70 on page 3)* and now it reads:

> Flood protection policies provide an opportunity to establish a large-scale FPL dataset (Mokrech et al., 2015) as they generally contain information on how a region should be protected from floods, although some authors suggest that the actual protection levels could differ from the protection standard from policy (Jonkman, 2013).

Specific comments 5. Eq. 1: I find "GDP-weighted PopE" a poor name for a variable, as it is a bit long and at first sight it appears to be GDP minus: : : Please improve.

Accepted: Thanks for this suggestion. We also would prefer a shorter variable name, but this would require another abbreviation, while we think we have enough. We have changed it to "GDP weighted PopE".

Specific comments 6. L119: Section 2.5 is unexpected and feels disconnected from what comes before in the article, because up to this point you have not yet stated that this is an analysis you will be doing. Is this cluster analysis meant to address a research question? Please contextualize beforehand, and when doing so provide an explanation on why this analysis is useful.

Clarified: Thank you for the suggestion. This section is associated with the first research question "What level of protection against river floods does Chinese policy imply across the country?" Based on the derived flood protection levels (FPLs), we can have a map and describe the distribution of the FPLs (high values and low values). More than that, the spatial pattern analysis of the FPL data quantitatively shows where the significant high/low values are located and how the high/low values are clustered. We think this method is important, as it adds a rigorous spatial analysis. Meanwhile, it can present the regional risk: a high-FPL county should also be at risk if its surroundings suffer severe flooding. We added an explanation of this at *lines 135–138 on page 6*.

Specific comments 7. L163: Unclear which previous studies this sentence refers to. Is it only Scussolini et al., 2016? Please clarify.

Accepted: Thank you for the suggestion. This sentence has been clarified as follow *(lines 182–183 on page 8)*:

> Therefore, Chinese FPLs are probably underestimated in previous studies (Scussolini et al., 2016).

Specific comments 8. L197: Because FPLs also change over time but only current FPLs are considered in this section, I am unsure about the usefulness of the analysis carried out here. For the same reason, I also find this section title a bit misleading. Please improve and clarify.

Clarified: Thank you for the suggestion. Indeed, both FPLs and population change over time. In this section, we focus on how the exposed population changes if flood protection is kept constant over time. Such a method clearly and directly shows how the total population and the demographic characteristics changed in areas of currently different flood protection levels and how the change rate varied between current high and low flood protection levels. We believe such a strategy can clearly indicate the importance of considering population dynamics and demographic characteristics in the flood protection policy, which is critical for improving the policy.

Specific comments 9. L235: This could also simply be the result of FPLs being calculated on the basis of present-time exposed population, couldn't it? We do not have information about FPLs in 1990; therefore, stating that a faster increase in exposed population may have occurred in these counties because in the past their FPL was already high seems speculative. Please discuss.

Accepted: Thanks for the suggestion. We have revised this sentence to avoid confusion. Now the sentence reads as follows *(lines 265–267 on page 12)*:

> The possibility of a similar outcome should be considered in China, as suggested by the faster increasing trend of the exposed population in the high-FPL counties than in the low-FPL counties.

Specific comments 10. Table 1: Note at the bottom is unclear.

Accepted: Thanks for the suggestion of Table 1. This note has been clarified. Please check from *lines 514–518 on page 21*, or as below.

Table 1. Urban and rural standards for evaluating the flood protection level (FPL) (source: Standard for flood control GB 50201-2014)

Urban FPL Indicators		Urban FPL (Return period, years)	Rural FPL Indicators		Rural FPL (Return period, years)
Population exposure (million)	GDP weighted population exposure* (million)		Population exposure (million)	Arable lands exposure (thousand ha)	
<0.2	<0.4	30–50	<0.2	<20	10–20
≥0.2	≥0.4	50–100	≥0.2	≥20	20–30
≥0.5	≥1	100–200	≥0.5	≥66.7	30–50
≥1.5	≥3	≥200	≥1.5	≥200	50–100

Note: * GDP weighted population exposure is the population exposure multiplied by the ratio between the relative per capita gross domestic product (GDP) and the national average.

Specific comments 11. Figure 2: Remove “the” in y-axis label.

Accepted: Thanks for the suggestion for Figure 2. This label has been corrected. Please check from *lines 526–527 on page 24*, or as below.

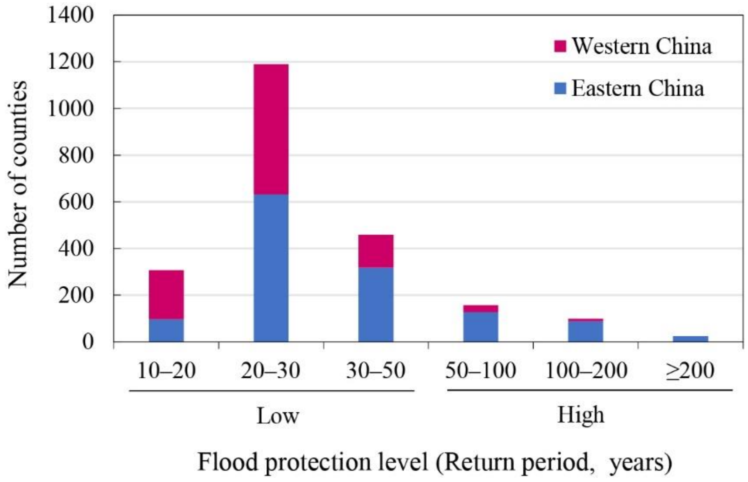

Figure 1 The number of counties with different flood protection levels. (The map of western and eastern China is shown in Figure 3)

Specific comments 12. Figure 5: In the y-axis label, replace “Exposure” with “Exposed population”.

Accepted: Thanks for the suggestion. This label has been corrected. Please check from *lines 534–535 on page 27*, or as below.

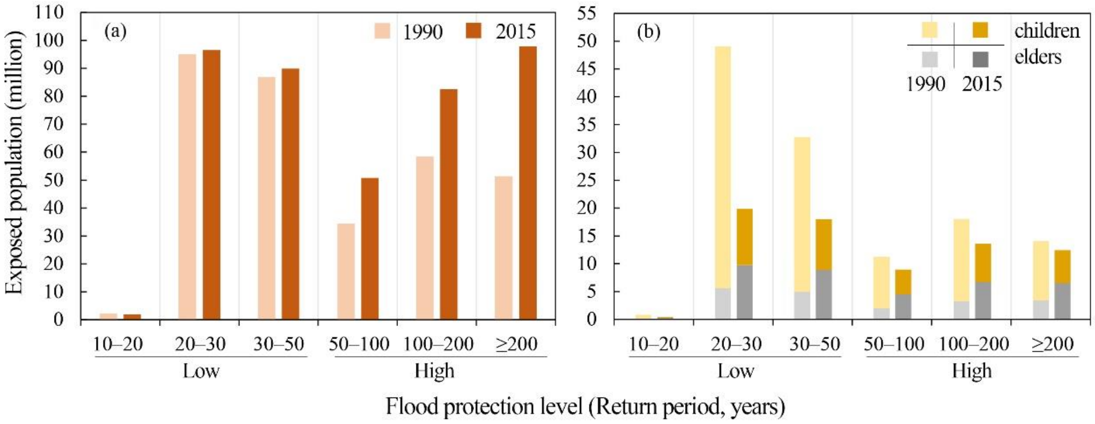

Figure 5 Changes in exposed total population **(a)** and vulnerable population **(b)** across different flood protection levels from 1990 to 2015.

Part 3: Response to the Anonymous Referee #3

General Comments. The objective of the paper is to develop and validates a Flood Protection Level (FPL) dataset for China, which is based on current Chinese policy on FPLs. Accordingly, base data and methodologies for its development are first discussed, and then results are critically analysed. Although the paper does not represent any significant improvement in research, it supplies relevant information for flood risk management in one of the biggest and most flood prone area of the world; and thus, it can be of interest for the journal audience. The paper is generally well written and organised; data, methods and results are quite well explained. However, before results can be published, shared and made available to the research community, I think that some conceptual aspects deserve more attention and clarification.

Accepted: Thanks for confirming the relevance of our manuscript and the suggestions for further improvement. We have thoroughly revised the paper, addressing your valuable comments and suggestions.

General Comment 1. The FPL generated by the dataset is a theoretical one (i.e. designed based) and not the real one. This must be very clear since the beginning of the paper and not marginally discussed at the end. Accordingly, authors should stress since the beginning why this information is useful, how it can be used for risk management, e.g. as a proxy of the flood risk in an area?

Clarify: Thank you for the suggestion. We have revised the paper accordingly in the *Introduction*. First, we further provide arguments for why the data is useful. Nowadays, flood risk assessment is drawing an increasing attention worldwide and playing a critical role in flood risk management. However, flood protection information, an essential element of flood risk estimates, is rarely available in reality, which dampens a reliable analysis of flood risk and its applications. Particularly for China, the only nation-wide available data is from the global database FLOPROS (Scussolini et al., 2016), which has a raw resolution of provinces. On the other hand, the Chinese flood control policy clearly stated how an area should be protected according to the exposed elements. We believe this information is useful for risk analysis and management. Please check from *lines 20–58 on pages 1–3*.

Second, we added how the newly developed database can be used for risk management, also following your Minor Comment 9. 1) Authorities can use this database to check if the relevant counties are protected properly. 2) Flood risk assessment could be conducted considering the developed flood protections. 3) The policy-based FPL can be an important foundation for relevant researchers to develop a more reliable FPL dataset of China and for the rest of the world. 4) It can help to reveal potential social divergence by combining the policy-based FPL with demographic data, which can further improve the flood protection policy, as indicated by the relevant analyses in this study. We have discussed this issue in Section 4.3. Please check from *lines 316–321 on page 14*.

General Comment 2. With respect to the last point, the second research question could then be changed in: Is FPL representative of the real risk in the area or its definition/evaluation should be changed? In fact, the present second research question (i.e. does the FPL policy take into account relevant demographics of the exposed population, such as elders and children who are known to be most vulnerable to floods?) is not clear at this point of the paper (i.e. why exactly this question?) as it is too much linked to an evidence that comes out only at the end of the manuscript

Accepted: Thank you for the suggestion. Also following Specific Comment 3 of Referee #2, we have revised the second research question to "Since the FPL policy does not consider population demographics, what are the implications for the protection of vulnerable social groups?" Please check from *lines 62–63 on page 3.*

General Comment 3. The validation process is very weak, so I do not agree with authors that theoretical FPL agrees with real one very well (see section 4.3). The validation process was carried out only for 51 (about 2%) out of 2237 counties and a match was observed only for 66.7% of the counties (abut 1,5%). This has important implication on the use of results (see comment 1)

Accepted: Thank you for the critical suggestion. We have made the following two efforts to strengthen the validation, also considering General Comment 2 of Referee #2.

First, we increased the validation sample size from 51 counties to 171 counties. Now, the match ratio between the FPL database and the validation data is 53.2%. It can reach 90.1% if we apply a free bound of one protection level (the protection levels are considered as a match if the difference is zero or one protection level). Please check from *lines 170–175 on page 8*, and *Supplementary* Table S1 and Table S2.

Furthermore, we also discussed the representativeness of the validation sample. It represented 34.0% of the total exposed population and 13.0% of exposed arable lands in China. Thus, we believe the expanded samples should provide a relatively more reliable validation. Please check from *lines 129–131 on page 6.*

General Comment 4. The calculation of FPL is based on the assumption that the exposed area coincides with the 100 years return period flooded area. As this critically affects the estimation of FPL, authors should explain the reasons of this assumption. Moreover, how such an area was derived? does the modelling consider or not the existence of flood protections? What this implies?

Accepted: Thank you for the suggestion. We clarified the flood exposure definition and the employed flood data, also following General Comment 1 of Referee #2.

First, we calculated the flood exposure as the elements within the maximum extent of the 100-year return period flood. This definition is consistent with the flood risk assessment by Shi et al (2015) and the flood exposure analysis by Jongman et al (2012), Du et al (2018), and Fang et al (2018). Please check from *lines 104–107 on page 5.*

Second, the 100-year flood map we applied is undefended, which was provided by Dr. Roberto Rudari from the CIMA Foundation. This dataset was produced based on hydrological and hydraulic models at a resolution of 1 km, which were validated against historical floods. And it has been effectively used for analyzing China's urban land expansion (Du et al., 2018) and population dynamics in floodplains (Fang et al., 2018). The undefended data were used instead of the defended one for two major reasons. First, the flood defenses were designed based on the protected population and assets, as shown in the Chinese flood control policy. Second, flood defenses cannot ensure the protected areas' absolute safety; thus, the population and assets should not be excluded from flood exposure analysis. We now specify this important feature in the manuscript. Please check from *lines 88–91 on page 4*.

References:

Du S, He C, Huang Q, Shi P, 2018. How did the urban land in floodplains distribute and expand in China from 1992–2015? Environmental Research Letters, 13(3): 034018.

Fang Y, Du S, Scussolini P, Wen J, He C, Huang Q, et al., 2018. Rapid Population Growth in Chinese Floodplains from 1990 to 2015. International Journal of Environmental Research and Public Health, 15(8): 1602.

Jongman B, Ward P J and Aerts J C J H 2012 Global exposure to river and coastal flooding: long term trends and changes Glob. Environ. Change 22 823–35

Shi PJ, Wang JA, Xu W, Ye T, Yang SN, Liu LY, Fang WH, Liu K, Li N and Wang M. 2015 World Atlas of Natural Disaster Risk (Heidelberg: Springer)

Minor comments

Minor comments 1. line 21 "With the emergence of large-scale flood models, the necessity to quantify FPLs has increased in recent years" the cause-effect relation is not clear to me, could authors comment more on this?

Accepted: Thanks for your suggestion. We have revised this sentence accordingly (*lines 22–23 on page 1*). Now it reads as:

> With increasing focus on large-scale flood risk assessment, which also depends critically on flood protection information (Ward et al., 2017; Alfieri et al., 2017; Winsemius et al., 2018), the necessity of quantifying FPLs has increased in recent years.

Minor comments 2. line 27 what "improved FPLs" means?

Accepted: Thank you for this suggestion. It means high FPLs. We revised the sentence (*line 29 on page 2*) and now it reads:

> High FPLs reduce the frequency of floods in flood-prone areas and decrease flood risk (Ward et al., 2013).

Minor comments 3. line 37 "China is one of the countries that experience the most serious floods and the fastest urbanization. Each year between 1990 and 2017, floods in China affected 149 million people, led to 2165 deaths, and caused an economic damage of US$ 34 billion"
I guess these figures refer to average data

Accepted: Thank you for this suggestion. It is indeed average data. We revised the sentence (*lines 39–41 on page 2*) and now it reads:

> Between 1990 and 2017, floods in China averagely affected 149 million people, led to 2165 deaths, and caused an economic damage of US$ 34 billion per year (Du et al., 2019).

Minor comments 4. line 85 "It originally has a spatial resolution of 100 m and is aggregated to a 1 km resolution to match the flood depth data, further to get population exposure using methods described in Fang et al. (2018)" I think that a brief explanation/recall of how the data were elaborated is required.

Accepted: Thanks for the suggestion. A brief explanation and relevant references were added. Please check from *lines 104–107 on page 5.*

Minor comments 5. line 151 "In 34 (66.7%) out of the 51 verification counties, the FPLs agree with the local official protection plans (full information in Supplement). The FPLs in the dataset are overestimated in four counties and underestimated in five counties" what about the other 8 counties?

Accepted: Thank you for the suggestion. It was a mistake. We revised the sentence with an expanded validation sample *(lines 169–172 on page 8)*. The sentence now reads as follow:

> In 91 (53.2%) out of the 171 verification counties, the FPLs agree with the local official protection design documents (Supplementary Table S1 and S2). The FPLs in the dataset are overestimated in 20 counties (11.7%) and underestimated in 60 counties (35.1%).

Minor comments 6. line 176 "These counties within the "low-high" FPL clusters can be more vulnerable when they are needed to sacrifice to protect their surrounding large cities that are more expensive to be flooded" not clear, more vulnerable than what? Could authors explain?

Accepted: Thank you for this suggestion. We have revised the sentence *(lines 196–199 on page 9)* and it reads as follows:

> These counties within the "low-high" FPL clusters can be vulnerable to floods when they are needed to sacrifice to protect their surrounding large cities that are more expensive to be flooded (Wang et al., 2016). For instance, in China, flood detention zones are planned in rural areas to protect surrounding cities in the Yangtze River and Huaihe River Basins of China (Du et al., 2020).

References:

Du, S., Shen, J., Fang, J., Fang, J., Liu, W., Wen, J., Huang, X., and Chen, S.: Policy delivery gaps in the land-based flood risk management in China: A wider partnership is needed, Environmental Science & Policy, 116, 128-135, https://doi.org/10.1016/j.envsci.2020.11.005, 2021.

Minor comments 7. line 217 "The newly developed data show that almost one third (33.1%, 741) of the evaluated Chinese counties are protected with a ⩾30-year FPL" should be protected…. It's a theoretical FPL

Accepted: Yes, it's a theoretical FPL. Accordingly, this sentence has been revised as follows:

> The newly developed data show that almost one third (33.1%, 741) of the evaluated Chinese counties are should be protected with a ≥30-year FPL, while this FPL is only in 5 (14.7%) out of 34 provinces in the FLOPROS (Scussolini et al., 2016). *(lines 248–250 on page 11)*

Minor comments 8. line 224 "For instance, global flood risk assessments show huge flood risk across Chinese provinces both in current condition and future scenarios (Willner et al., 2018a), which are considered to further propagate a devastating indirect impact to other countries through the global trade and supply network (Willner et al., 2018b). However, those global assessments are based on the FLOPROS database, which significantly underestimate Chinese FPLs, e.g., presenting Beijing with a 20-year FPL, which should be 200 years in the newly developed result (Fig. 3) and in the local official document (full information in Supplement). The real flood risk should thus be much lower than the estimates in previously studies if the new FPL is considered" The authors cannot made this statement as the correspondence between theoretical and real FPLs have been evaluated only for 51 out of 2237 counties; the case of Beijing is a fortunate one where a perfect match occurs. But, can authors exclude that counties exist where there is not a FPL at all in practice, in front of a theoretical FPL, or a real FPL that is lower to designed based one? In this case, the risk can be underestimated. Please, comment.

Accepted: Thanks for the suggestion. We have increased our validation sample size from 51 to 171, also following your critical General Comment 3 and General Comment 2 of Referee #2. And now the validation samples represent 7.6% of the surveyed Chinese counties, 34.0% of the exposed population, and 13.0% of Chinese exposed arable land. Besides, the FPL dataset has a higher resolution than the FLOPROS; the former is based on counties and the latter is based on provinces. Therefore, we believe the FPL data are a valuable proxy. Please check from *lines 129–131 on page 6*.

Meanwhile, the reason for the overestimation of Chinese flood risk mainly results from an underestimation of Chinese protection against flood. Therefore, we have compared the difference between FPL and FLOPROS by Paired Sample T Test. Please check from *Supplementary* Table S4. Furthermore, we have revised the sentence *(lines 257–259 on pages 11–12)* and it reads as follows:

> However, those global assessments are based on the FLOPROS database, which is significantly lower than the policy required FPLs as indicated by the Paired Sample T Test ($p<0.01$, supplementary Table S4). For instance, FLOPROS presented Beijing with a 20-year FPL, while it should be 200 years according to the Chinese protection policy (supplementary Table S1).

Minor comments 9. line 245 "A neglect of the real-world flood protection lagging behind the policy-based flood protection can distort the selection of adaptation measures" this is exactly the point. Then, how theoretical FPL can be used (see general comment 1)?

Accepted: Thanks for the suggestion. Also following your General Comment 1, we added a discussion on how the theoretical FPL can be used:

> 1) The authorities can use this database to check if the relevant counties are

> protected properly. 2) Flood risk assessment could be conducted considering the developed flood protections. 3) The policy-based FPL can be an important foundation for relevant researchers to develop a more reliable FPL dataset of China and the rest of the world. 4) It can help to reveal potential social divergence by combining the policy-based FPL with some social data, which can further improve the flood protection policy, as indicated by the relevant analyses in this study.

Minor comments 10. line 266 “Such a strategy, however, may aggregate flood risk because the less protected areas coincide with high social vulnerability that is caused by a disproportional distribution of vulnerable people, particularly elders” what authors mean with “aggregate flood risk”

Accepted: Thanks for your suggestion. It was unfortunately a misspelling. It should be “aggravate”, which was corrected (*lines 299–301 on page 13*).

Minor comments 11. line 300 “This study thus agrees with the argument of Scussolini et al. (2016) that flood protection policy is a valid proxy for actual FPL” I do not agree, see general comment 4

Accepted: Thanks for the suggestion. We revised the paper accordingly. First, we expanded the validation sample size from 51 counties to 171 counties, also following your insightful General Comment 3. Second, we revised the statement as follows:

> This study thus agrees with the argument of Scussolini et al. (2016) that flood protection policy is a valuable proxy for actual FPLs. *(lines 341–342 on page 15)*

Minor comments 12. Figure 1 I think that a full description of the framework is required in the text, i.e. in Section 2.1, to support readers in the full comprehension of following contents.

Accepted: Thanks for your suggestion. A full description of the framework has been added. Please check from *lines 78–84 on page 4*.

Minor comments 13. Figure 3 colours used for the FPLs 30-50 and 50-100 cannot be distinguished in the figure.

Accepted: Thanks for the suggestion. *Figure 3* has been improved accordingly. Please check from *lines 528–531 on page 25* or as below.

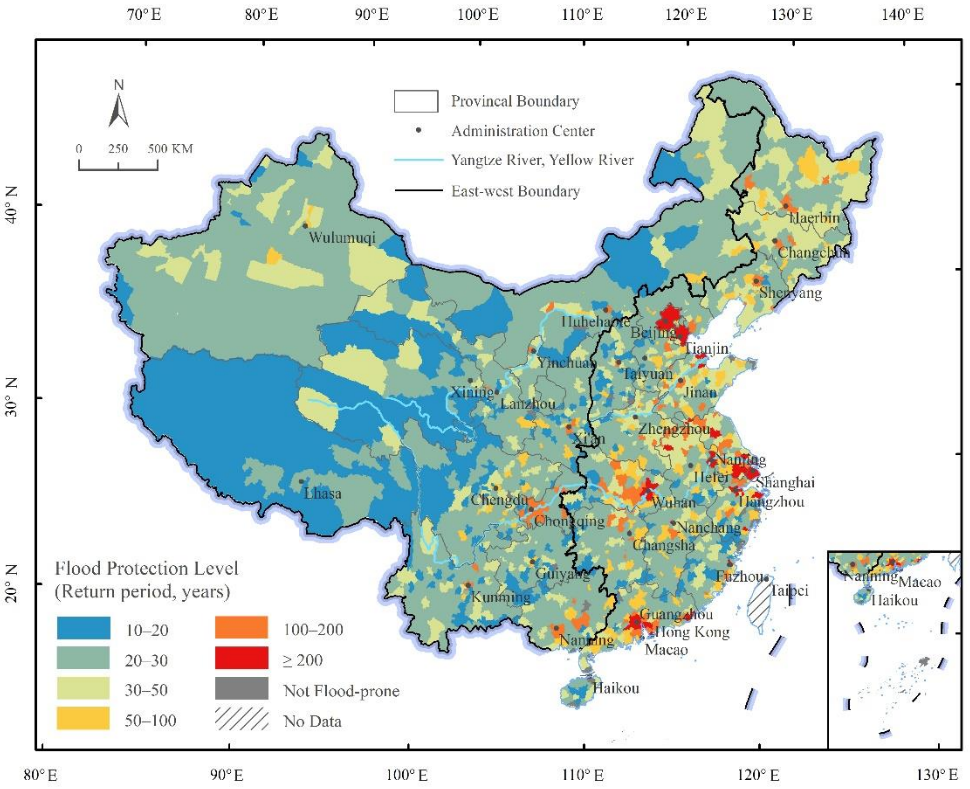

Figure 3 Flood protection level (FPL) for Chinese counties. The FPL is limited to the scope of floodplains but plotted to cover the entire counties. The data should only be viewed as a proxy of the actual FPLs, not equating to the actual FPLs. The Shapefile format data are available as a supplement.

Assessing Chinese flood protection and its social divergence

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Abstract. China is one of the most flood-prone countries, and development within floodplains is intensive. However, flood protection levels (FPL) across the country are mostly unknown, hampering the present assertive efforts on flood risk management. Based on the flood-protection prescriptions contained in the national flood policies, this paper develops a dataset of likely FPL for China and investigates the protection granted to different demographic groups. The new dataset corresponds with local flood protection designs in 91 (53.2%) of the 171 validation counties, and in 154 counties (90.1%) it is very close to the designed FPLs. This suggests that the policy-based FPLs is a valuable proxy for actual FPLs in China. The FPLs are significantly higher than previously estimated in the FLOPROS global dataset, suggesting that Chinese flood risk was probably overestimated. Relatively high FPLs (≥50-year return period) are seen in 282 or only 12.6% of the evaluated 2237 counties, which host a majority (55.1%) of the total exposed population. However, counties with low FPLs (<50-year return period) host a disproportionate share (52.3%) of the exposed vulnerable population (children and elders), higher than their share (44.9%) of the exposed population. These results imply that to reduce social vulnerability and decrease potential casualties, investment into flood risk management should also consider the demographic characteristics of the exposed population.

1. Introduction

Flood protection level (FPL) is the degree to which a flood-prone location is protected against flooding (Scussolini et al., 2016). It is a key determinant of flood risk, making its quantification a prerequisite to reliable risk assessment (Ward et al., 2013). With increasing focus on large-scale flood risk assessment, which also depends critically on flood protection information (Ward et al., 2017;Alfieri et al., 2017;Winsemius et al., 2018), the necessity of quantifying FPLs has increased in recent years. For example, Jongman et al. (2014) estimated the FPLs in major European river basins by assuming that high-risk areas have high FPLs. Hallegatte et al. (2013) created an FPL dataset for coastal cities through combining design information of flood defenses and expert estimates to improve coastal flood risk assessment. Scussolini et al. (2016) developed FLOPROS, a global database of FPLs based on information included in protection design documents, and in protection policy documents, in addition to FPL estimates based on flood risk modeling.

High FPLs reduce the frequency of floods in flood-prone areas and decrease flood risk (Ward et al., 2013). From a cost-benefit view, high FPLs are more economically attractive in areas with a high density of population and economy (Ward et al., 2017). However, high FPLs can have a 'levee effect': creating a sense of security and lowering risk awareness, which boosts floodplain development and population growth and can, in turn, cause catastrophic consequences once a low-probability flood happens (Di Baldassarre et al., 2015;Haer et al., 2020). On the other hand, low FPLs generally mean limited human and financial resources and therefore imply a lower capacity of flood risk reduction (Cheng et al., 2018;Cross, 2001;Han et al., 2020). Moreover, the low FPLs may coincide with a concentration of vulnerable people, e.g., the elders and children, increasing the severity of the human consequences of floods (i.e., more likely fatalities), and more in general exacerbating the local social vulnerability (Birkmann et al., 2016;Gu et al., 2018). Therefore, FPL study is also a key to understand the integrated socio-hydrological system.

China is one of the countries that experience the most serious floods and the fastest urbanization. Between 1990 and 2017, floods in China averagely affected 149 million people, led to 2165 deaths, and caused an economic damage of US$ 34 billion per year (Du et al., 2019). Moreover, flood risk changes rapidly due to socioeconomic dynamics (Du et al., 2018) and, in the longer-term, due to climate change (Alfieri et al., 2017;Winsemius et al., 2018). For instance, Du et al. (2018) found that urban lands in the floodplain increased by 26,430 km^2, i.e., 542%, from 1992 to 2015, a process which is still in full swing and thus likely to exacerbate flood risk in the future. Moreover, the urbanization process witnesses an enormous migration from the countryside to cities (Li et al., 2018;Liu and Li, 2017), which selectively leaves the vulnerable population behind, and may increase social vulnerability in the countryside (Cheng et al., 2018).

However, little information is available about China's FPLs, which hampers reliable flood risk assessment and challenges scientific risk management. The existing few studies of China's FPLs, to our best knowledge, are only about a specific flood control facility and at local scales. For example, Deng et al. (2015) analyzed the FPL of Taihu Lake levees to inform flood risk management in catchments. Zhou (2018) studied the impact of land subsidence on the FPL in the downstream of the Daqing River. Liu (2017) inferred the FPL in Quzhou through hydrodynamic simulation. Although the fore-mentioned global database FLOPROS can show an overall FPL for China, it still misses details. For example, in the FLOPROS the FPLs are only of 20-year return period in 29 (or 85.3%) of the 34 Chinese provinces including the capital Beijing, which is probably incompatible with the massive Chinese investment in improving FPLs in the past decades particularly for metropolises (Du et al., 2019). Therefore, it is reasonable to presume that the FPLs of China are significantly underestimated in the FLOPROS, especially for urban areas. With such sparse data, the picture of FPL on the national scale is still unclear, representing a critical knowledge gap in the context of rapid urbanization. This also limits the understanding of the relationship between population exposure, vulnerability, and flood protection.

Therefore, the paper here develops and validates the first FPL dataset for China, based on the current Chinese policy on FPLs, that is the *Standard for flood control (No: GB 50201-2014)*, which clearly stated how an area should be protected according to the exposed elements. On this basis, the following questions are addressed. 1) What level of protection against river floods does Chinese policy imply across the country? 2) Since the FPL policy does not consider population demographics, what are the implications for the protection of vulnerable social groups?

2. Materials and methods

2.1 China's flood protection policy and the study framework

FPL data are typically difficult to access at a large scale (Jiang et al., 2020). Scussolini et al. (2016) proposed that FPL can be assessed based on protection design documents, policies, or assumed based on hydrodynamic and flood risk simulations, and on wealth distribution. Flood protection policies provide an opportunity to establish a large-scale FPL dataset (Mokrech et al., 2015) as they generally contain information on how a region should be protected from floods, although some authors suggest that the actual protection levels could differ from the protection standard from policy (Jonkman, 2013). Presently, the key policy document for China is the *Standard for flood control (No: GB 50201-2014)* which was released in 2014 by the *Ministry* *of Housing and Urban-Rural Development of the People's Republic of China*. It stipulates the FPLs for urban and rural areas depending on three exposure indicators: the amount of exposed population, the per-capita gross domestic product (GDP), and the arable lands. Here a framework is developed using spatial information on these indicators of exposure, to infer the policy-prescribed FPLs across China (Figure 1).

[Insert Figure 1]

This is conceptually akin to the *policy layer* of the FLOPROS dataset, but the framework yields information at the much finer spatial scale of the county. In the study framework, based on the relevant datasets, the FPL of an urban county (in Chinese: *shi* or *qu*) is evaluated by population exposure and GDP weighted population exposure; the FPL of a rural county (*xian*) is evaluated by the population exposure and arable-land exposure (Table 1), as prescribed in the *Standard for flood control*. Additionally, local flood protection design documents are collected to verify the policy-based FPL dataset. At the same time, the spatial pattern of the FPLs is identified using spatial statistics techniques; and the FPL of the exposed population, including the elders, children, rural and urban population are evaluated by combing the FPL with demographic information. Note that the vulnerable population is mainly comprised of the elders and children.

[Insert Table 1]

2.2 Data

Six datasets are employed. First, an administrative boundary is adopted from He et al. (2016), which considered administrative boundary adjustments from 1990 to 2010. Second, an undefended fluvial flood depth map with a 100-year return period is provided by the CIMA foundation (Rudari et al., 2015), which is accessible from the Global Risk Data Platform (http://preview.grid.unep.ch/). It has a spatial resolution of 1 km and has been used for analyzing China's urban land expansion (Du et al., 2018) and population dynamics in floodplains (Fang et al., 2018). Third, population density maps for 1990 and 2015 are acquired from the China Temporal Dataset of Harvard Dataverse, published by the WorldPop program (http://www.worldpop.org.uk). It originally has a spatial resolution of 100 m and is aggregated to a 1 km resolution to match the flood depth data. Fourth, the demographic information of 1990 and 2015 is obtained from China's national census data (National Bureau of Statistics of China, 2015). It includes the proportions of children (aged ≤ 14 years), elders (aged ≥ 65 years), rural and urban population to the county-level total population, which are used to calculate the vulnerable population exposure. Fifth, the land use data of China for 2015 comes from the Data Center of Resources and Environmental Sciences, Chinese Academy of Sciences, which is provided on the Resource and Environment Data Cloud Platform (http://www.resdc.cn/). It has a resolution of 1 km and is used to extract arable lands in floodplains. Besides, the county-level gross domestic product (GDP) in 2015 (Division of Urban Social and Economic Survey of National Bureau of Statistics, 2016) is used to calculate the GDP weighted population exposure.

2.3 Assessment of flood protection level

Three exposure indicators are employed to assess the FPL of a certain flood-prone county: population exposure (PopE), GDP weighted PopE, and arable-land exposure (ArableE). For county *i*, the PopE is calculated as the population in the floodplain, which is defined as the maximum extent (i.e., where flood depth > 0 cm) of the undefended 100-year flood map, following previous flood exposure analyses (Du et al., 2018;Fang et al., 2018;Jongman et al., 2012). The calculation is conducted by overlaying the flood depth map and the population density maps using a geographical information system (Fang et al., 2018). Then, for an urban county *i*, the PopE is transformed into the GDP weighted PopE using the relative factor of the county's GDP per capita to the national average GDP per capita, following Eq. (1),

$$GDP\text{ - }weighted\ PopE = PopE \times \frac{G_i}{G_a} \tag{1}$$

where G_i refers to the GDP per capita in county *i;* and G_a refers to the national average of GDP per capita in China.

For a rural county *i*, the ArableE is calculated as the area of arable lands in the 100-year floodplain by overlaying the flood depth and land use maps. Based on the three calculated indicators, the FPL can be estimated by applying the criteria specified in the *Standard for flood control (GB 50201-2014)* (Table 1). The FPL of an urban county is the larger value between FPLs based on the PopE criteria $FPL_{(PopE,\ i)}$ and based on the GDP weighted PopE criteria $FPL_{(GDP\ weighted\ PopE,\ i)}$, while the FPL of a rural county is the larger value between $FPL_{(PopE,\ i)}$ and the FPL based on the ArableE criteria $FPL_{(ArableE,\ i)}$, following Eq. (2),

$$FPL(\mathrm{i}) = \begin{cases} \max[FPL(PopE, i), FPL(\text{GDP- weighted } PopE, i)], & \text{i=an urban county} \\ \max[FPL(PopE, i), FPL(ArableE, i)], & \text{i=a rural county} \end{cases} \tag{2}$$

The FPLs are assessed for 2237 counties that fully or partially fall within the 100-year floodplain. The result is presented by six FPLs: ≥ 200 years, 100–200 years, 50–100 years, 30–50 years, 20–30 years, and 10–20 years. Further, ≥50-year FPLs are summarized as relatively high FPL, while <50-year FPLs are summarized as low FPL.

2.4 Verification of the flood protection levels

Local documents of flood protection design are collected to verify the policy-based FPL results. The validation counties are selected based on the date of the flood protection design: the data should represent the flood protection of the year 2015. A raw sample of 304 counties is found from accessible flood protection documents dating from 1998 to 2019. Two-round selection is further implemented. For the first round, we only select the relative new documents released from 2007 to 2012, neither too old that may be outdated nor too new that may be uncompleted and unqualified. Those documents are kept in the validation data only if they state that the design would be completed between 2010 and 2015. A sample of 110 counties is selected from this round. For a second round, new flood protection design documents starting from 2015 are researched and these are kept only if they state the current (2015) flood protection standards. Another 61 counties are then selected. Therefore, the validation sample size is 171 counties, representing 7.6% of the surveyed Chinese counties, 34.0% of the exposed population, and 13.0% of Chinese exposed arable lands. Assuming that the designed flood protection standards reflect the reality of flood protection implemented in practice, the agreement between the policy-based FPLs and those derived from the local design documents is checked for the 171 counties and the overall accuracy is further calculated.

2.5 Pattern clustering of flood protection level

The spatial pattern of FPLs, i.e., the clustering of counties with homogenous FPL is essential to understand regional flood risk distribution. It also informs on indirect dimensions of flood risk, as, e.g., high-FPL counties may suffer indirect flood risk if their surrounding counties have low-FP and thus suffer severe flooding (Cheng et al., 2018;Han et al., 2020). The spatial pattern of the FPL data is then identified using the LISA (local indicator of spatial association) or local Moran's *I* (Anselin, 1995). The local Moran's *I* statistic is calculated as follows (Chakravorty et al., 2003),

$$I_i = \frac{\left(x_i - \overline{x}\right)}{s^2} \sum_{j=1,\, j \neq i} W_{i,j} \left(x_j - \overline{x}\right) \tag{3}$$

where I_i is the local Moran's I in county i; x_i and x_j refer to the FPL of county i and its neighboring county j, respectively; $\bar{x}$ is the mean FPL across all counties; $W_{i,j}$ is a n-by-n weight matrix defining the spatial contiguity between county i and any county j, where $W_{i,j}$=1 if county i and county j share a border and otherwise $W_{i,j}$=0; s^2 is the variance of FPLs across all flood-prone counties.

A positive value for the local Moran's I statistic indicates that FPL in a county is similar to those in its neighboring counties, while a negative I value indicates dissimilar values (Zhu et al., 2018;Frigerio et al., 2018;Shen et al., 2019). The local Moran's I is calculated by applying the Queen Contiguity matrix in software GeoDa (version 1.12), which is available from http://geodacenter.github.io. The significance is evaluated at an alpha level of 0.05. Four different LISA clustering patterns of FPLs are identified. 1) High-High: both the county and its neighbors have high FPL. 2) High-Low: the FPL is high in a county while low in its neighboring counties. 3) Low-High: FLP is low in a county while high in its neighboring counties. 4) Low-Low: both a county and its neighbors have low FPL.

2.6 Dynamic analysis of population exposure and vulnerable population exposure

PopE refers to the population exposure in a certain county, which is calculated as the population in the floodplain by overlaying the flood depth and the population density maps (Sect. 2.3). Exposed vulnerable population comprises the exposed children and elders because children and elders are generally considered more vulnerable to flooding, due to limited mobility and physical resistance (Gu et al.;Salvati et al., 2018). Assuming that the proportion of exposed children to the total population is spatially homogeneous within a county, the exposed children are calculated in each county using Eq. (4),

$$Exposed\ children = \frac{children}{total\ population} \times PopE \tag{4}$$

where *PopE* refers to the population exposure in the county; *children* and *total population* are respectively the number of children and total population in a county. Similarly, the exposed elders can be calculated. The exposed vulnerable population is the sum of exposed children and exposed elders. Additionally, the exposed rural and urban population are estimated following the method.

Equation (5) is used to calculate the growth rate of population exposure from 1990 to 2015,

$$Growth\ rate\,(\%) = \frac{PopE_{2015} - PopE_{1990}}{PopE_{1990}} \times 100\% \quad (5)$$

where $PopE_{2015}$ and $PopE_{1990}$ refer to the population exposure in 2015 and 1990, respectively. Similarly, the growth rates of exposed children, elders, and vulnerable population are calculated, so are the growth rates of exposed rural and urban population.

3. Results

3.1 Validation of the new policy-based FPL dataset

The policy-based FPL dataset matches to a good degree the information from protection design documents. In 91 (53.2%) out of the 171 verification counties, the FPLs agree with the local official protection design documents (Supplementary Table S1 and S2). The FPLs in the dataset are overestimated in 20 counties (11.7%) and underestimated in 60 counties (35.1%). Most (90.1%) of the overestimations and underestimations are only off by one FPL. In comparison, the FPLs of the global FLOPROS database match the protection design documents in 50 (29.2%) out of the 171 counties, and underestimate FPLs in almost all other counties, with 32.7% of the underestimations being off by only one FPL. Therefore, the policy-based FPL dataset constitutes a substantial improvement on previous knowledge of Chinese FPLs.

3.2 Spatial pattern of flood protection level

According to the prescriptions of the policy *Standard for flood control*, a majority (87.4%, or 1955) of Chinese counties have <50-year FPLs that are defined hereafter as relatively low FPLs (Figure 2), while only 282 counties (12.6%) have high FPLs (≥50 years). A considerable proportion (33.1%, or 741) of the evaluated Chinese counties are protected with a ≥30-year FPL, which is much higher than that in the global FLOPROS database (Scussolini et al., 2016), in which only 5 (14.7%) out of 34 provinces have ≥30-year FPLs. Therefore, Chinese FPLs are significantly underestimated in previous studies (Scussolini et al., 2016).

[Insert Figure 2]

The FPLs show significant divergence between eastern and western China (Figure 2, Figure 3), reflecting general differences in population exposure; and in economic performance. A dominant portion (85.5%, or 241) of high-FPL counties are located in eastern China. Particularly, all the 25 counties with the highest FPL (≥200 years) are located in the east. In contrast, only 4.3% (or 41) of the western Chinese counties have high FPLs, which is much lower than the share in eastern China (18.7%, or 241). The majority (68.4%, or 210) of the lowest FPL counties (10–20 years) are located in the west. In sum, western China is disproportionally protected with low FPLs.

[Insert Figure 3]

"High-High" FPL clusters include 112 counties. They are mainly located in the three primary urban agglomerations of the Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta (Figure 4). The three primary urban agglomerations are home to most of the counties with the highest FPLs of ≥200 years (Figure 3). Besides, the "High-High" FPL clusters are also located in the middle Yangtze River reaches. The "Low-High" FPL clusters include a total of 66 counties, surrounding the "High-High" FPL clusters. These counties within the "Low-High" FPL clusters can be vulnerable to floods when they are needed to sacrifice to protect their surrounding large cities that are more expensive to be flooded (Wang et al., 2016). For instance, in China, flood detention zones are planned in rural areas to protect surrounding cities in the Yangtze River and Huaihe River Basins of China (Du et al., 2021). "Low-Low" FPL clusters include 158 counties, which are mainly located in southwestern China and scattered along a belt from Hohhot to Kunming. Surrounding the "Low-Low" FPL clusters, 48 counties have relatively high FPLs and form "High-Low" clusters.

[Insert Figure 4]

3.3 Protection levels of the exposed (vulnerable) population in 2015

A majority (55.1%, 231.1 million) of the total exposed population is found in a minority of 282 counties with high FPLs (≥50 years) (Table 2). Particularly, 23.3% (97.8 million) of the total exposed population are protected by a ≥200-year FPL. In contrast, 188.4 million (44.9%) of the flood-exposed people are in low-FPL counties, lower than that in the high-FPL counties.

A majority (52.3%, 38.3 million) of the exposed vulnerable population is concentrated in low-FPL (<50 years) counties, higher than these counties' share of the total exposed population (44.9%) (Table 2). These low-FPL counties host 52.9% (19.4 million) of the exposed children and 51.6% (18.8 million) of the exposed elders. Particularly, counties with a 20–30 years FPL host the largest exposed vulnerable population (19.9 million, 27.1%) across all the six FPLs, including 10.1 million (27.5%) children and 9.8 million (26.8%) elders.

The ratio of vulnerable population to the total exposed population is as high as 20.3% in low-FPL counties, while it is 15.1% in high-FPL counties (Table 2). Both exposed children and elders are found disproportionally in the low-FPL counties. Specifically, the children's share of the total exposed population is 10.3% in the low-FPL counties, higher than in the high-FPL counties (7.5%); similarly, the elders' share is 10.0% in the low-FPL counties, higher than in the high-FPL counties (7.6%). Therefore, the low-FPL counties have a disproportionally high share of vulnerable population than the high-FPL counterparts, in terms of both exposed children and elders.

[Insert Table 2]

The protection divergence also happens between exposed rural and urban population. A majority (66.8%, or 107.3 million) of the exposed rural population are protected by low FPLs while this proportion is only 31.3% (81.1 million) for the exposed urban population (Supplementary Table S3). This implies that the rural people are not equally protected against flooding compared with urban inhabitants.

3.4 Changes in the exposed (vulnerable) population across protection levels

The total exposed population has grown by 60.3%, rapidly from 1990 to 2015 in counties that are presently protected by high FPLs, while it has remained relatively stable in the low-FPL counties (2.34%) (Figure 5a). In 1990, the exposed population was primarily located in counties with 20–30 years FPLs (95.0 million, 28.9%), while in 2015 it is primarily in counties with ≥200-year FPLs (97.8 million, 23.3%).

[Insert Figure 5]

The exposed vulnerable population has decreased by 41.9%, from 126.0 million in 1990 to 73.3 million in 2015; and decreased more sharply (by 53.7%) in the low-FPL counties (Figure 5b). The decrease of the exposed vulnerable population is mainly caused by a sharply declining exposed population of children. The exposed children, in total, have decreased by 65.6% from 106.8 million in 1990 to 36.8 million in 2015. The exposed children's share to the total exposed population has declined rapidly across all FPLs, which decreases the ratio of vulnerable population to the total exposed from 38.4% in 1990 to 17.5%

in 2015 (Figure 6).

In contrast, the exposed elders have increased across all the six FPLs, with a total growth of 90.2% from 19.2 million to 36.5 million (Figure 5b). This trend reflects China's aging population. Moreover, the elders' share of the total exposed population has risen from 5.9% in 1990 to 8.7% in 2015 Figure 6). Particularly in the low-FPL counties, it has increased from 5.7% in 1990 to 10.0% in 2015 with a growth of 4.3%, much higher than that in the high-FPL counties (1.7%).

[Insert Figure 6]

The exposed rural population has decreased by 26.5% from 218.6 million in 1990 to 160.7 million in 2015 and has decreased more (30.1%) in the low-FPL counties (Supplementary Table S3). However, there is a consistent disproportional distribution of the rural population in low-FPL counties. Meanwhile, the exposed urban population (177.7 million) of the high-FPL counties in 2015 is more than twice of that in 1990 (79.2 million). However, the low-FPL areas also witness a rapid increase in exposed urban population by 68.5%.

4. Discussion

4.1 Residual flood risk is nonstationary and should be effectively managed

Chinese FPLs should be much higher than that in previous studies, according to the prescriptions of the policy *Standard for flood control*. The newly developed data show that almost one third (33.1%, 741) of the evaluated Chinese counties should be protected with a ≥30-year FPL, while this FPL is only in 5 (14.7%) out of 34 provinces in the FLOPROS (Scussolini et al., 2016). Particularly, the newly developed data show that a considerable proportion (12.6%, or 282) of Chinese counties have ≥50-year FPLs that are defined as relatively high FPLs. Moreover, the high-FPL counties protect the majority (55.1%, 231.1 million) of exposed Chinese population. Those high-FPL counties are concentrated in eastern China, particularly in the urban agglomerations (Bai et al., 2014). The underestimation of Chinese FPLs can at least partially explain the high level of flood risk in previous studies (Alfieri et al., 2017;Willner et al., 2018). For instance, global flood risk assessments show huge flood risk across Chinese provinces both in current condition and future scenarios (Willner et al., 2018), which are considered to further propagate a devastating indirect impact to other countries through the global trade and supply network (Willner et al., 2018). However, those global assessments are based on the FLOPROS database, which is significantly lower than the policy required FPLs as indicated by the Paired Sample T Test (p<0.01, supplementary Table S4). For instance, FLOPROS presented Beijing with a 20-year FPL, while it should be 200 years according to the Chinese protection policy (supplementary Table S1). The real flood risk should thus be much lower than the estimates in previous studies if the new FPL is considered.

However, high-level flood protection does not represent absolute safety. On the contrary, low-probability floods can still occur and flood protection structures may technically fail, causing residual flood risk (Haer et al., 2020). Particularly, levee breaches can cause a catastrophe for the areas with a high density of population and assets (Jongman, 2018). In high-FPL counties, a sense of safety brought by the flood protection structures can reduce the perception of risk and cause “levee effect” — boosting floodplain development and increasing flood exposure (Cheng and Li, 2015;Kates et al., 2006). The possibility of a similar outcome should be considered in China, as suggested by the faster increasing trend of the exposed population in the high-FPL counties than in the low-FPL counties. The rapid increase in the exposed population can exacerbate residual flood risk, rendering these high-FPL areas vulnerable to low-probability and high-impact floods (Koks et al., 2015;Di Baldassarre et al., 2013). The residual risk can be further aggravated by future climate change (Alfieri et al., 2017;Winsemius et al., 2018). Alfieri et al. (2017) indicated that the future annual expected economic losses in China may be the highest of all countries, rising by 1.5-fold to 3.4-fold and reaching 50 to 110 billion EUR/year, based on global warming scenarios of 1.5℃ to 4℃, respectively.

The residual flood risk can be higher if the real-world flood protection lags behind the policy requirement and design. In fact, the policy-based FPL dataset only reflects how a county should be protected according to the flood protection policy, which also stipulates that the flood protection should be updated along with population growth and economic development. Unfortunately, a survey of 2013 found that 44% (284) of the 642 Chinese cities did not update their flood protection planning according to their socioeconomic growth (Cheng and Li, 2015). A neglect of the real-world flood protection lagging behind the policy-based flood protection can distort the selection of adaptation measures.

Flood risk management will inevitably face an ongoing challenge from population growth when reducing the residual risk. It is predicted that, in the next ten years, Chinese urban population will increase by 17% (United Nations, 2018), which will increase residual flood risk in the high-FPL counties because high-FPL counties are usually urban areas. The flood protection structures should be upgraded along with socio-economic development and climate change to keep the residual flood risk to an acceptable level (Kwadijk et al., 2010). Non-structural measures such as early warning systems, land use planning, building codes, and insurance/reinsurance can be a complement to the flood protection structures for effectively managing flood risk (Aerts et al., 2014;Jongman, 2018;Du et al., 2020).

4.2 Demographics should be included in the flood protection policy

Although the low-FPL counties see less exposed population, the majority (52.3%, 38 million) of exposed vulnerable population are concentrated there. Particularly, the elders' share of the total exposed population was increasing rapidly in these low-FPL counties. These findings are consistent with other studies (Cheng et al., 2018). Meanwhile, a great number of exposed rural people are found to be concentrated in these low-FPL counties. The low-FPL counties located in rural areas are with an economic downturn and insufficient job opportunities, which causes a large number of young adults to temporarily migrate to cities for work opportunities (He et al., 2016;Meng, 2014). Therefore, it may be difficult for these low-FPL counties to respond to and recover from flooding due to economic backwardness and labor shortages.

Hence with more vulnerable people, a higher potential casualty or injury rate caused by floods is expected in these low-FPL counties. The elder Chinese are predicted to more than double from 128 million in 2015 to 348 million in 2050 (The World Bank, 2019), implying an increase of exposed elders. This will further increase social vulnerability and challenge flood risk management, particularly in the low-FPL counties. However, the policy *Standard for flood control* neglects the demographic characteristics of the exposed population. It is economically reasonable to employ a relatively low FPL for areas that have a low density of population and economy. Such a strategy, however, may aggravate flood risk because the less protected areas coincide with the high social vulnerability that is caused by a disproportional distribution of vulnerable people, particularly elders.

Therefore, local demographic characteristics should be considered for an economically and socially beneficial strategy of flood adaptation (Koks et al., 2015). The low-FPL areas can employ decentralized and soft adaptation measures, such as elevation of buildings, wet flood-proofing, and dry flood-proofing to reduce flood vulnerability (Aerts, 2018;Du et al., 2020) since structural flood protections are generally less cost-effective in areas with fewer exposed population (Ward et al., 2017;Jongman, 2018). Considering the relative concentration of exposed vulnerable population in the low-FPL counties, flood risk information, adaptation measures, and emergency plans should be made accessible and understandable to children and elders (De Boer et al., 2014). Communities should pay more attention to children and elders during early warning, evacuation, and resettlement; and a one-on-one assistance scheme can be developed at the community level to help the vulnerable people. Emergency plan and flood adaptation design should consider the particular needs of children and elders, which can be promoted by their participation in the planning and designing processes (Liang et al., 2017).

4.3 Limitations and future perspectives

The newly developed FPL dataset reflects how China should be protected against river floods according to the flood protection policy. It does not report actual FPLs although it agrees with local flood protection design documents very well. Given the scarcity of the real-world flood protection data, the new dataset can be considered a valuable proxy of actual FPLs and can assist efforts to understand, evaluate, and manage flood risk in the following ways. 1) Authorities can use this database to check if the relevant counties are protected properly. 2) Flood risk assessment could be further conducted considering the developed FPL dataset. 3) The policy-based FPL can be an important foundation for relevant researchers to develop a more reliable FPL dataset of China and the world. 4) It can also help to reveal potential social divergence by combining the policy-based FPL with some social data, which can further improve the flood protection policy, as indicated by the relevant analyses in this study. It’s worth noting that the real-world FPLs are not fixed but are plausibly updated along with socio-economic development and climate change. Therefore, relevant departments, communities, and users are invited to use, verify, and improve the newly developed FPL result (which are accessible as supplementary data in shapefile format). With wide participation of public stakeholders, the flood protection data can be much improved in the future.

Limitations also come with our data and methods. The exposed population is calculated based on a gridded population dataset from the WorldPop program, which is a disaggregation result of census population using auxiliary variables such as land use conditions and nightlight brightness. However, neither the disaggregation methods nor the auxiliary data are free of uncertainty and error (Smith et al., 2019). Moreover, due to a lack of gridded demographic data, the exposed vulnerable population is calculated assuming that its proportion to the total population is spatially homogeneous within a county. But in fact, the demographic characteristics can be spatially heterogeneous (Han et al., 2007;Qiang, 2019). Nowadays, crowd-sourcing population data are emerging, thanks to social media (Goodchild and Glennon, 2010;Smith et al., 2019) and mobile phone records (Wu et al., 2012). These new data can help to improve the exposed (vulnerable) population accuracy and in turn, the FPL estimates. Besides, only some aspects of social divergence have been analyzed, due to data limitation. Under the FPL policy, other factors of social divergence, such as sex, income, and education level (Tian and Lemos, 2018;Huang et al., 2020), need to be further studied. For example, the education levels across different FPLs may help relevant authorities to develop suitable flood adaptation strategies or help researchers to further analyze the FPL policy's influence on social divergence.

5. Conclusions

A framework is developed to assess the county-level FPLs in China based on the flood protection policy and relevant socioeconomic variables of floodplains. The produced FPL dataset shows a match ratio of 53.2% with the designed FPLs included in specific flood protection documents in a sample of 171 counties. The policy-based FPL dataset constitutes a substantial improvement on previous knowledge and the dataset is relatively accurate. This study thus agrees with the argument of Scussolini et al. (2016) that flood protection policy is a valuable proxy for actual FPLs. However, there may be still significant differences between the policy-based FPLs and the actual flood protection because the latter *may* be behind or ahead of the policy-required FPLs. The FPL dataset was thus made open access to encourage relevant users to check and improve it.

The produced FPL dataset shows that western China is dominated by low FPLs while high-FPL counties are concentrated in the east. There are 282 counties with a high FPL (≥50 years), which account for only 12.6% of the total flood-prone counties but host 55.1% (231.1 million) of the total exposed population. In contrast, more exposed vulnerable population (52.3%, 38 million) are concentrated in the low-FPL counties. Moreover, exposed population grows rapidly (by 60.3%) in the high-FPL counties while the proportion of elders increases more rapidly in the low-FPL counties than in the high-FPL counties. These findings imply that the flood protection policy has a relatively efficient strategy to protect the majority of the exposed population within a minority of well-protected counties. However, the rapid growth of exposed population can increase residual flood risk. Moreover, the disproportional concentration and rapid increase of exposed vulnerable population, particularly the elders, in the low-FPL counties can probably increase the places' vulnerability.

Therefore, diversified adaptation measures including both structural flood defenses and non-structural solutions should be employed to reduce flood risk in both the high- and low-FPL counties. Local demographic characteristics should be considered for an economically and socially beneficial strategy of flood adaptation. Particularly, the vulnerable population in the low-FPL counties should receive dedicated attention. This study shows that combining FPL and demographic information is critical to understand and manage flood risk.

Data availability. The Chinese flood protection data are available as a supplement. Supporting data are accessible through the associated references.

Author contribution. Shiqiang Du designed this study. Dan Wang implemented data processing and analysis. Dan Wang, Paolo Scussolini, and Shiqiang Du prepared the manuscript with contributions from all co-authors.

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Table 1. Urban and rural standards for evaluating the flood protection level (FPL) (source: Standard for flood control GB 50201-2014)

Urban FPL Indicators			Rural FPL Indicators		
Population exposure (million)	GDP weighted population exposure* (million)	Urban FPL (Return period, years)	Population exposure (million)	Arable lands exposure (thousand ha)	Rural FPL (Return period, years)
<0.2	<0.4	30–50	<0.2	<20	10–20
≥0.2	≥0.4	50–100	≥0.2	≥20	20–30
≥0.5	≥1	100–200	≥0.5	≥66.7	30–50
≥1.5	≥3	≥200	≥1.5	≥200	50–100

Note: * GDP weighted population exposure is the population exposure multiplied by the ratio between the relative per capita gross domestic product (GDP) and the national average.

Table 2. Exposed population (total, vulnerable, children, and elders) for each flood protection level (FPL), in absolute amounts and as percentage of the whole exposed population. The rightmost column reports the ratio of vulnerable to the total exposed population.

FPL (years)	Total exposure in millions (%)	Vulnerable exposure in millions (%)	Exposed children in millions (%)	Exposed elders in millions (%)	Vulnerable-to-total exposed population ratio
Low	**188.4 (44.9)**	**38.3 (52.3)**	**19.4 (52.9)**	**18.8 (51.6)**	**20.3%**
10–20	2.0 (0.5)	0.4 (0.6)	0.2 (0.6)	0.2 (0.6)	21.0%
20–30	96.5 (23.0)	19.9 (27.1)	10.1 (27.5)	9.8 (26.8)	20.6%
30–50	89.9 (21.4)	18.0 (24.6)	9.2 (24.9)	8.9 (24.3)	20.0%
High	**231.1 (55.1)**	**35.0 (47.7)**	**17.3 (47.1)**	**17.7 (48.4)**	**15.1%**
50–100	50.8 (12.1)	9.0 (12.2)	4.5 (12.1)	4.5 (12.3)	17.6%
100–200	82.5 (19.7)	13.6 (18.6)	6.9 (18.8)	6.7 (18.3)	16.5%
≥200	97.8 (23.3)	12.4 (17.0)	5.9 (16.2)	6.5 (17.8)	12.7%
Sum	**419.5 (100)**	**73.3 (100)**	**36.8 (100)**	**36.5 (100)**	**17.5%**

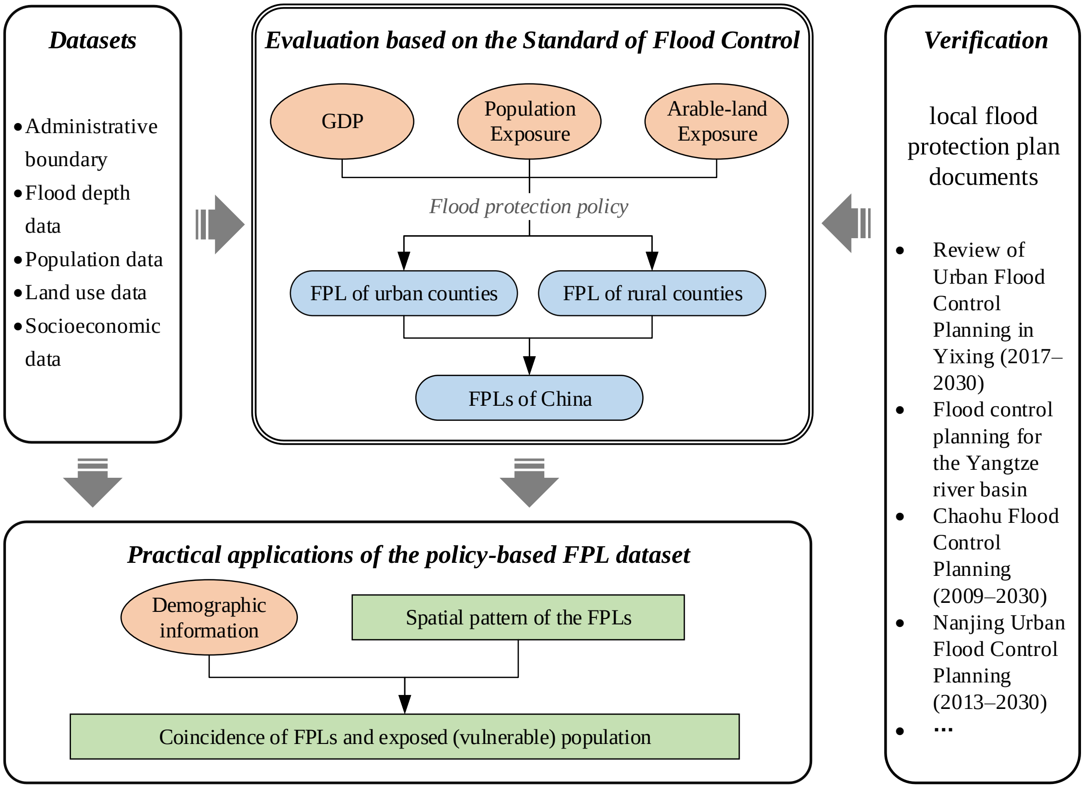

Figure 2 The study framework of flood protection level (FPL). Input datasets are indicated in orange circles; the new datasets produced in this study are indicated in blue rounded rectangles; the implications of the new datasets are in green rectangles.

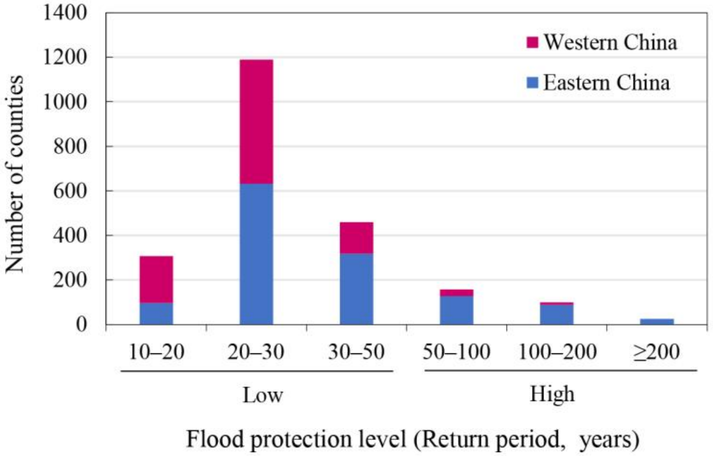

Figure 3 The number of counties with different flood protection levels. (The map of western and eastern China is shown in Figure 3)

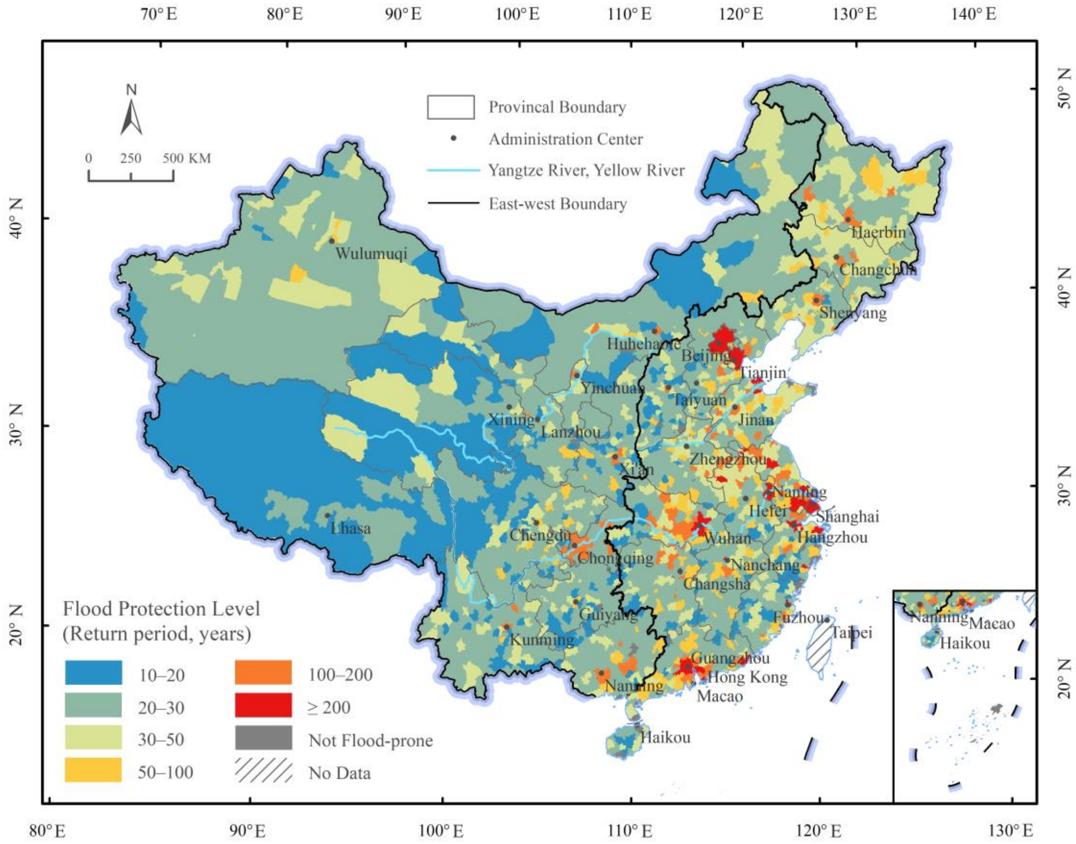

Figure 4 Flood protection level (FPL) for Chinese counties. The FPL is limited to the scope of floodplains but plotted to cover the entire counties. The data should only be viewed as a proxy of the actual FPLs, not equating to the actual FPLs. The Shapefile format data are available as a supplement.

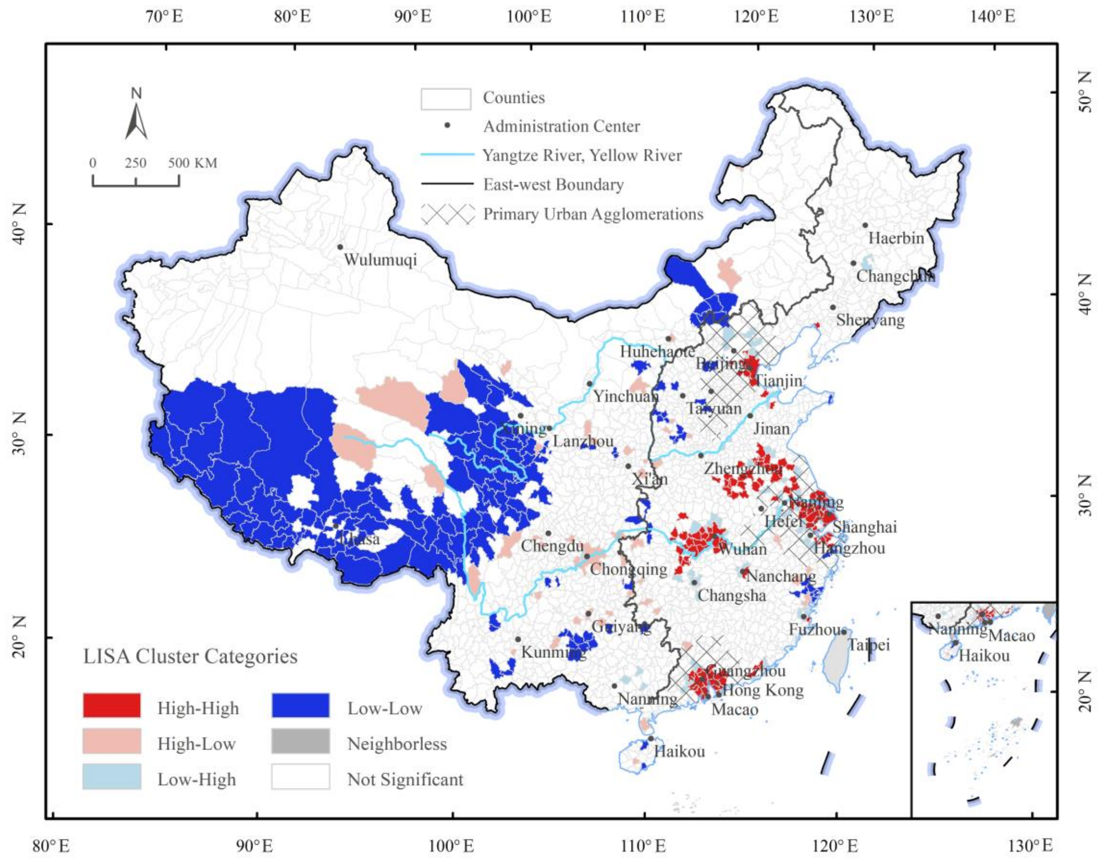

Figure 5 Spatial cluster of flood protection level in China

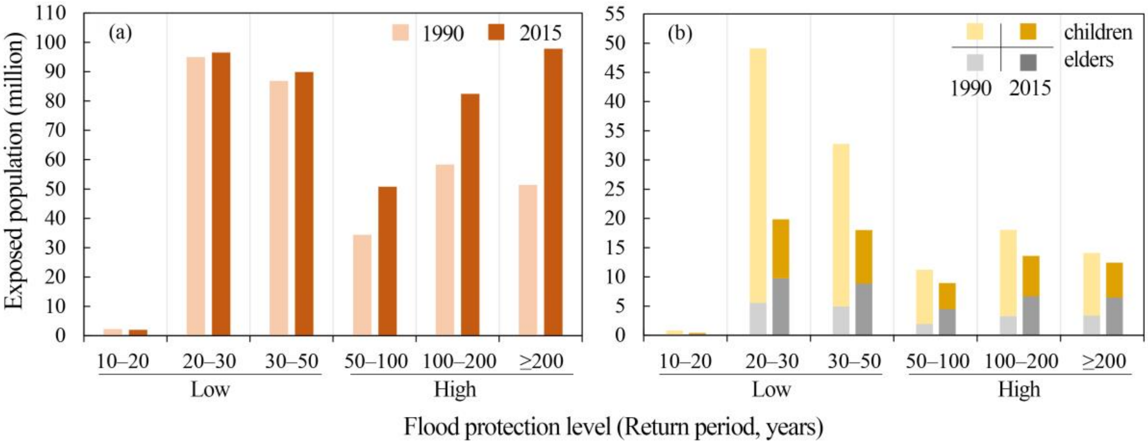

Figure 6 Changes in exposed total population **(a)** and vulnerable population **(b)** across different flood protection levels from 1990 to 2015.

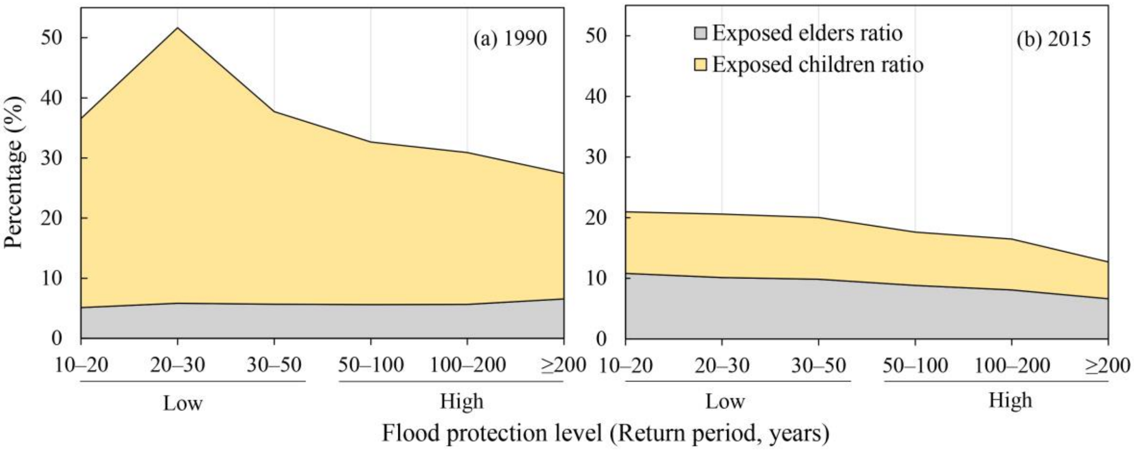

Figure 7 The ratios of exposed vulnerable population, exposed children, and exposed elders to the total exposed population across different flood protection levels in 1990 **(a)** and 2015 **(b)**. Note that flood protection levels refer to the situation of 2015 and keep constant between 1990 and 2015.