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Profiling households through a combined vulnerability and flood exposure index in Ho Chi Minh City, Vietnam

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ABSTRACT

As climate risks escalate worldwide, comprehending the household-level vulnerability to flood is critical for sustainable adaptation, particularly in rapidly urbanizing cities like Ho Chi Minh City. This study develops a household vulnerability index to a flood exposure index within the frameworks of contextual vulnerability and the risk-hazard model. Using six sub-components of vulnerability, we assess a composite index through a detailed analysis of qualitative and quantitative data collected from a survey of 1000 households across four districts. A hierarchical weighting model and geostatistical analysis tools are employed to calculate the vulnerability index and examine the spatial patterns of vulnerability. The findings reveal three key insights into household-level vulnerability: First, the flood does not directly cause or strongly correlate with vulnerability in the survey households. Second, equal levels of general inequality do not imply similar distributions of vulnerability across specific components and areas. Third, vulnerability and flood risk tend to be more pronounced in urban than rural areas, with notable spatial clustering. This study provides insights that can guide policymakers in prioritizing adaptation, and enhancing understanding of the interactions between social vulnerability, hazard exposure, and household-centered adaptation. The study also highlights important considerations for inequality and climate finance, and underscores the need for future research on vulnerability across multiple scales.

1. Introduction

Vulnerability has been developed as a concept, model, metric, and tool in the course of the changing human and environmental perspectives [1]. The concept of vulnerability can be understood through two interpretations based on the manifestations of different discourses and framings of the climate change problem: outcome vulnerability - vulnerability as an inherent condition and a fixed attribute of the system components, and contextual vulnerability - vulnerability resulting from structures, boundary conditions, and processes in a system [2,3]. Outcome vulnerability reflects a linear result of climate impacts and the (limited) human capacity to cope and adapt [2]. Contextual vulnerability, on the other hand, reflects an inherent process of human coping and adaptation to climate impacts within a system [2]. In this study, we assess the contextual vulnerability at the household level to flood in Ho Chi Minh City.

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Based on the concept of vulnerability, scholars have developed models to elaborate the different dimensions of vulnerability [1,4,5]: "What, where, and when are the hazard consequences" for the risk-hazard model [6,7]; "Who, how, and why are particular people vulnerable" for the political economy or political ecology model [8,9]; "Which humans are constantly interacting with environmental change" for the ecological resilience model [4,10]. These models cut across disciplines (e.g., geography, political science, and ecology, etc.), scales (e.g., household, municipality, country, and country, etc.), and objects (e.g., cause or consequence of harm and damage). In addition, we recognize that the concept and model of vulnerability should be measured in terms of social vulnerability and hazard vulnerability respectively, which distinguishing between the influences of human activities and those of climate change for specific scales and objects.

Vulnerability assessments typically utilize both quantitative and qualitative approaches to develop comprehensive vulnerability metrics. This dual approach enables the linking of attributes, mapping, ranking, and comparison of vulnerabilities of the system components [9,11,12]. Quantitative approaches are effective for selecting and testing indicators derived from qualitative research, while qualitative approaches offer valuable narratives and contextual insights that inform quantitative analyses [13,14]. Together, the combined application of these approaches can support integrated climate adaptation and targeted policy interventions by identifying harm thresholds, exploring causal processes, or elucidating the vulnerability attributes.

Subsequently, the assessment of vulnerability index relies on both expert or statistical methods of integrating intersectional information and different types of data [10,15]; [16,17]. Expert knowledge plays a crucial role in selecting and weighting indicators based on insights from local stakeholders. One example is the World Risk Index, developed by Welle and Birkmann [18], which selects relevant indicators, determines their relationship, and generates a list of sub-components based on existing scientific knowledge [15], aligning with the Intergovernmental Panel on Climate Change [19]. On the other hand, statistical methods were used to identify the drivers of vulnerability, and to subsequently weigh the sub according to the contribution of various indicators [20]. A notable example is the social vulnerability index (SoVI) developed by Cutter [21], which operates at the municipality level. This index considers the social context that influences susceptibility to harm from hazards, drawing on the political ecology model that has been developed across temporal and spatial scales [22–24]. Therefore, vulnerability index should be viewed as metrics that provide specific information tailored to different contexts and scales.

Efforts to develop a vulnerability index, particularly for low- and medium-income countries, face significant conceptual and data-related challenges [1]. For example, in Vietnam, many flood risk or vulnerability assessments lack a clear conceptual framework and often neglect discussions on the social context, with metropolitan regions receiving more attention than smaller cities [25]. Furthermore, household-level vulnerability assessments, encompassing both social and hazard dimensions, have also often been overlooked in these regions. While previous studies have highlighted the general vulnerability of urban areas in Southeast Asia, there remains a critical gap in household-level assessments that consider both social and physical dimensions of flood exposure.

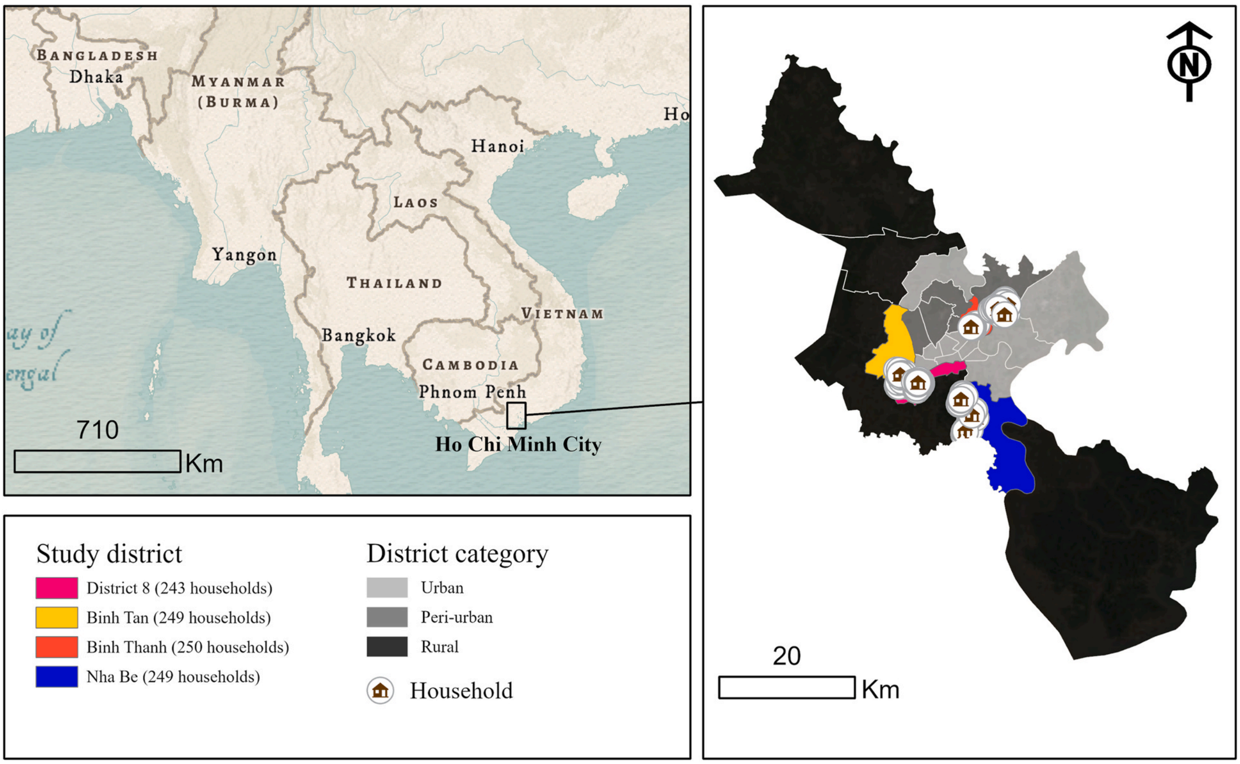

Fig. 1. Survey areas in Ho Chi Minh City with locations of the surveyed households. (Source left picture: Esri).

Taking this focus, only a limited number of studies on vulnerability to flood have been conducted for Ho Chi Minh City in Vietnam so far. Scussolini et al. [26] developed a household-level flood risk model, followed by a flood adaptation model developed by Cao et al. [27], and a flood precaution model developed by Harish et al. [28]. This highlights the need for a household-level vulnerability index that integrates intersectional factors, such as income, social practices, institutional arrangements, place of residence, and perceptions of exposure grounded in a clear conceptual framework and supported by collective data [29].

This study aims to develop a household-level vulnerability assessment for flooding in Ho Chi Minh City, through a combination of qualitative and quantitative approaches and data, following the concept of contextual vulnerability and the risk-hazard model. The research seeks to answer three key questions: First, does flood cause or correlate with vulnerability? Second, where and to what extent do vulnerability and flood impact affect households? Third, what are the drivers of household vulnerability and flood exposure in Ho Chi Minh City?

2. Methods

2.1. Study area

Ho Chi Minh City lies within the Dong Nai River system in southern Vietnam, northeast of the Mekong Delta and near to the South China Sea (Fig. 1). Ho Chi Minh City's geographical context – often characterized as being "with its feet in the water" – significantly heightens its risks to climate-related hazards. Positioned in a low-lying delta region, the city is increasingly susceptible to environmental challenges such as rising sea levels, frequent flooding, and extreme weather events, all of which are projected to intensify with climate change. These factors make Ho Chi Minh City one of the most exposed metropolitan areas in Southeast Asia [30]; [31] with impacts on households [32–34].

Since the implementation of the Doi Moi reforms and the liberalization of the economic markets in the 1980s, Ho Chi Minh City has been experiencing dramatic state-led industrialization and urbanization. These transformations have resulted in substantial population growth, largely driven by rural-to-urban migration, alongside constrained housing supply characterized by both missing quality control and quantitative limitations [35].

Ho Chi Minh City is administratively divided into 16 urban and 5 rural districts. In this study, we categorize districts into urban, peri-urban, and rural districts based on population density following the classification of [36,37]. Urban areas denominate districts with a concentration of political institutions, transport infrastructure, housing capacity, and economic activities; peri-urban areas describe areas where farmland is disappearing and mainly residential buildings are newly constructed along transportation lines and streets; and rural areas are regions mainly covered by natural spaces and agriculturally used land with only a loose number of buildings without merging with the city [33,38].

2.2. Household survey

The study uses results from a household survey, which was undertaken as part of the Vietnamese-German collaborative project "DECIDER" (Decisions for the Design of Adaptation Pathways and the Integrative Development, Evaluation, and Governance of Flood Risk Reduction Strategies in Changing Urban-Rural Systems). The face-to-face survey was carried out by native Vietnamese speakers from September to October 2020, using a structured approach that included information about households' socio-economic states and their experiences of flooding. A survey pre-test involving 60 households from three districts (Binh Tan, District 7 and District 2) was

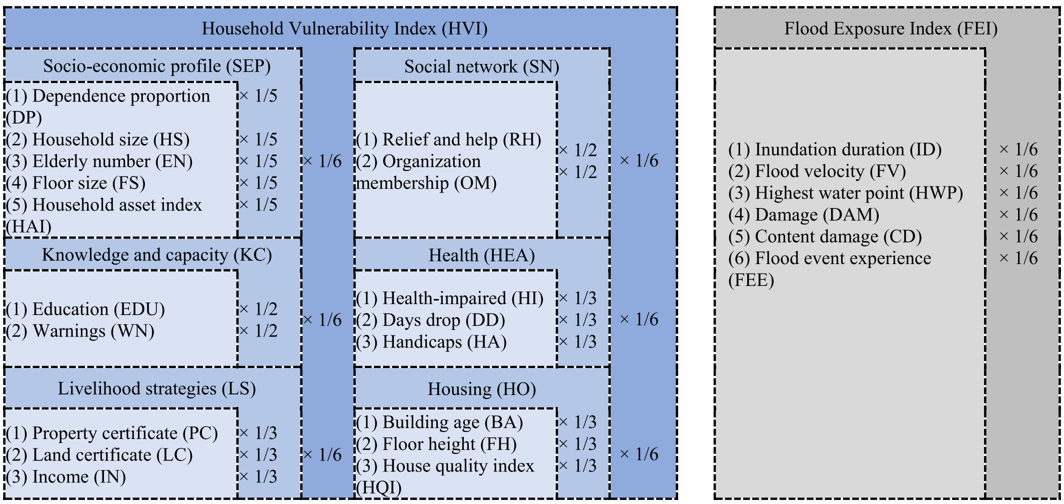

Fig. 2. Overview of the indicators of the household vulnerability index (HVI) and flood exposure index (FEI) and weights of each indicator/sub-component applied in the hierarchical weighting model.

conducted in December 2019 to test the validity of the questionnaire [28]. The questions were drafted based on the expertise of flood risk researchers, social scientists, and local stakeholders [28].

The selected households were located in four districts, District 8 (urban), Binh Tan (peri-urban), Binh Thanh (peri-urban), and Nha Be (rural), comprising eight wards (Binh Tri Dong B, An Lac, Ward 16, Ward 15, Ward 2, Ward 28, Phuoc Loc, Nhon Duc) and detailly inquired in case they experienced flooding between 2010 and 2020 (see Fig. 1). We collected 1000 valid responses from local households that had experienced floods within the past 10 years. We eliminated 9 households that were located outside Ho Chi Minh City. Hence, this study uses only 991 responses from the survey.

2.3. Selection of vulnerability and exposure indicators

In this study, the vulnerability metric is decomposed into the household vulnerability index (HVI) and the flood exposure index (FEI). The household vulnerability index reflects the intersection of the household profiles composed of six sub-components and follows the approach of [14] (see Fig. 2). The index is increased by 1) a low *socio-economic profile,* which makes the household potentially more dependent on low-quality assets and less prepared to recover from floods, 2) lack of *knowledge and capacity* about flood risks and adaptation options, 3) low quality in *livelihood strategies*, such as less diversified financial portfolios and land ownership, and 4) receiving a limited resource from cash transfers of association supportive programs from the *social network,* which may lead to negative coping strategies, 5) permanent *health* consequences and disabilities that make it difficult or impossible for households to return to work or reach previous levels of productivity after flooding, 6) deteriorated *housing* built with makeshift materials, which leads to higher damage compared to formal housing built with solid material [39].

The Flood Exposure Index reflects the household's experience of the flood. The household's experience reflects the severity, losses, and damages of floods. Fig. 2 shows an overview of the conceptual framework, and the weights applied in the hierarchical weighting model (details see section 2.4).

The sub-component *Socio-economic profile (SEP)* is determined by five indicators: *dependence proportion (DP)* represents the ratio of persons under the age 15 and over the age 64 to total persons in households; *household size (HS)* represents the total number of persons living in the household; *elderly number (EN)* represents the total number of persons over the age of 64 years living in the household; *floor size (FS)* represents the ratio of the floor area of the house (m^2) to the household size (HS), which refers to the size of the occupation per person in the household; *household asset index (HAI)* reflects a summary normalization index to the number of household assets in different levels of household need: (a) basic household assets: landline telephone, ventilator (sealed, stand-alone), bicycle; (b) advanced household assets: television, mobile phone, refrigerator, oven (gas, electricity), motorbike (older than 1 year), and other; (c) assets indicating raised standard of living: computer (desktop, laptop), cable/wireless internet, air condition, washing machine, and motorbike new (in one year); (d) luxury assets: car, van, and truck. Each category was scored based on the number of products in the household's level of need. For example, one landline telephone and two ventilators add up to three for basic household assets (BA).

The sub-component *Knowledge and capacity (KC)* is determined by two indicators: *education (EDU)* reflects the highest level of education in the household. The highest level of education is measured on a scale of one to eight, e.g., no member ever attended school is eight, primary school is seven, secondary school is six, high school is five, vocational training is four, university bachelor is three, master is two, Ph.D. or higher is one; *warning (WN)* reflects the total number of flood warnings from different sources received by the household. This could cover own-knowledge, TV, radio, newspaper, social media/internet, neighbors/friends, loudspeaker announcements, police officers, and others.

Livelihood strategies (LS) are determined by three indicators: *poverty certificate (PC)* reflects whether the household is below the poverty line, which means limited access to clean water, education, and health care; *land certificate (LC)* reflects the household's ownership of land from full to part and no ownership of the land; *income (IN)* reflects the monthly available income of the household.

Social network (SN) was determined by two indicators: *relief and help (RH)* reflects the amount of external support the household had received after the flood events in the past. Relief and help include money, shelter, food, drinks, labor support, medicals, or others; *organization membership (OM)* reflects the total number of governmental and non-governmental organizations in which the household members participate and (in-)directly receive support.

Health (HEA) was determined by three indicators: *health-impaired (HI)* reflects the proportion of household members who were injured, sick, or diseased during flood events to the household size (HS); *day drop (DD)* reflects the number of days that household members missed work or school due to flood; *handicap (HA)* reflects the ratio of persons with disabilities (e.g., cardiovascular disease, lung disease, immobility due to age, deafness, blindness, severe mental handicaps, and others) to household size (HS).

Housing (HO) was determined by three indicators: *building age (BA)* reflects the number of years since construction; *floor height (FH)* reflects the relative height of the building's floor relative to the street; *house quality index (HQI)* describes the quality of the building structure and material from the foundation, floor, wall, roof, and doors/windows. Building structures were classified based on the main materials used for the different building components.

Flood exposure index (FEI) is determined by six indicators: *inundation duration (ID)* refers to the total number of hours that floodwater remains in the house; *flood velocity (FV)* refers to the household's description of the flood speed ranging from calm to torrential velocity; *high water point (HWP)* refers to the highest level of the flood from the ground floor of the house; *damage (DAM)* refers the reparation costs of physical damages caused by the flood event (including the cost estimates if damages were not repaired or repaired by own labor); *content damage (CD)* is the cost to repair or replace the damaged content (e.g., furniture, electronics, kitchen equipment, motor/vehicles, and others) that is caused by the flood event; *flood event experience (*FEE*)* refers to the average amount of flood events per year that the household has experienced from 2010 to 2020. It has to be noted that data used for these indicators are household estimates and not on measured data and therefore influenced by their perceptions of the flood.

2.4. Household vulnerability index and flood exposure index

A hierarchical weighting model is applied to determine the household vulnerability, and flood exposure index from the sub-components (Appendix A). This model is a static approach that uses equal fractions to aggregate the indicators into corresponding sub-components and the final index (Fig. 2). The equal weighting of indicators allows for distinguishing the contribution of each indicator within its respective sub-component.

In the first step, the indicators are quantified by transforming descriptive, as noted above, into a category, number, or percentage. We then standardized each indicator using min-max normalization (see Equation (1)). In addition, the indicator is calculated such that lower values correspond to lower vulnerability and vice versa.

$$I_n = \frac{I_{act} - I_{min}}{I_{max} - I_{min}} \tag{1}$$

Where I_n represents the indicator value of household n, I_{act} is the value of the *indicator* (I) for household n, I_{min} and I_{max} are the minimum and maximum values of the *indicator* (I), respectively. A detailed description of the standardization of each indicator is presented in Appendix B.

Subsequently, the six sub-components of the household vulnerability index are calculated as the average of the indicators by weighting them equally:

$$S_c = \frac{\sum_{1}^{m} (I_n + \ldots + I_n)}{m} \tag{2}$$

Where S_c represents the sub-component value, I_n represents the indicator value of the sub-component, and m refers to the number of indicators of the sub-component.

Then the household vulnerability index HVI was obtained according to equation (3):

$$HVI = \frac{\sum_{i=1}^{6} (S_c + \ldots + S_c)}{6} \tag{3}$$

With six sub-components forming the household vulnerability index, and $\sum_{i=1}^{6} S_c$ representing the sum of the sub-components

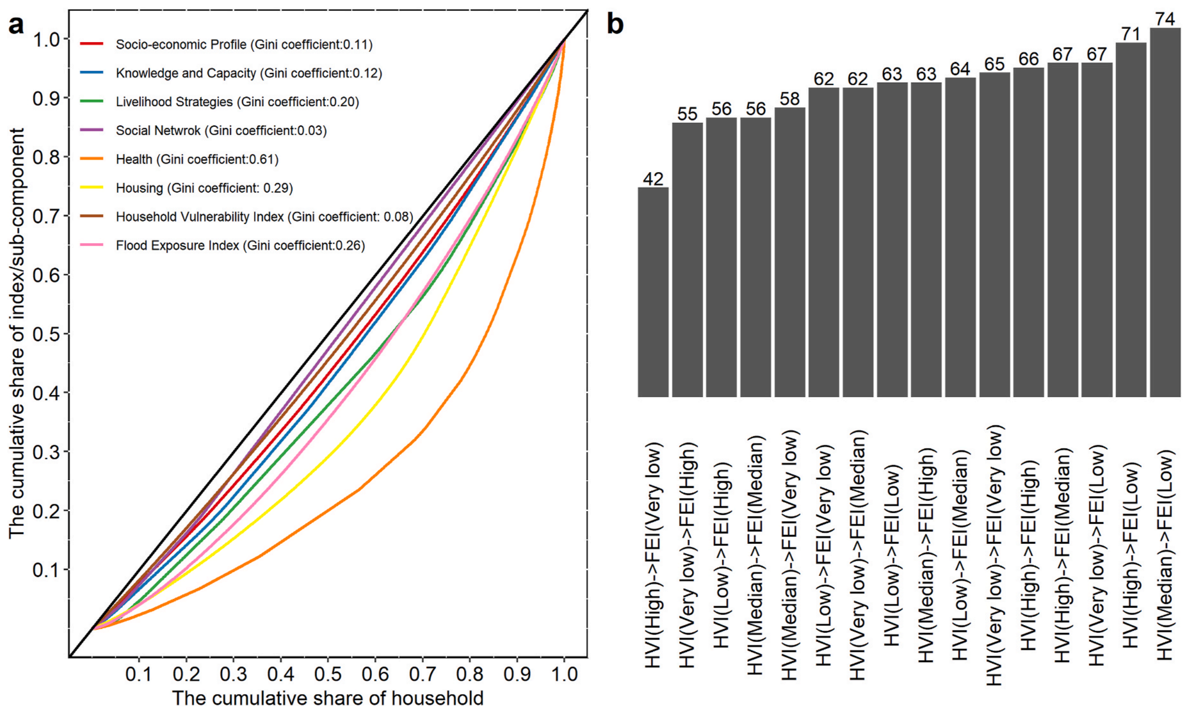

Fig. 3. a) Lorenz curve and the Gini coefficient of the index and sub-component; b) the quartiles of the Household Vulnerability Index (HVI) and Flood Exposure Index (FEI).

calculated in equation (2). The final household vulnerability index HVI can also be expressed as:

$$HVI = \frac{SEP + KC + LS + SN + HEA + HO}{6} \tag{4}$$

The flood exposure index FEI is directly calculated from the indicators as shown in equation (1):

$$FEI = \frac{ID_n + FV_n + HWP_n + DAM_n + CD_n + FEE_n}{6} \tag{5}$$

2.5. Inequality and spatial analysis

We use the Lorenz curve and the Gini coefficient to analyze the distribution of inequality in the household vulnerability index and the flood exposure index (Fig. 3a). The Lorenz curve graphically represents levels of inequality of a variable within a group: a flatter curve signals greater disparity, while a steeper curve diverging to a diagonal line of 45° implies an equal distribution [40]. The curve shows the cumulative share of household vulnerability index values against various portions of HVIs, sorted by their index values. To complement the analysis, we use the Gini coefficient by quantifying inequality on a scale from 0 (perfect equality) to 1 (perfect inequality), based on the area between the curve and the line of perfect equality (results are presented in Appendix C). Additionally, we applied the Lorenz curve to examine sub-components of these indices.

To further understand the distribution of inequality, we grouped households based on a quartile combination of the vulnerability, and flood exposure index (see Appendix D for detailed results). These indices were divided into four levels: very low (from the minimum to the first quartile (Q1)), low (Q1 to the median or 50th percentile), medium (from the median to the third quartile (Q3)), and high (Q3 to the maximum). We then paired each household's vulnerability index with its flood exposure index and visualized the relations using a bar chart.

For spatial analysis, we employed both Local Moran's I and Global Moran's I to explore the geographic dynamics of household vulnerability and flood exposure indices using ArcGIS 10.6. Local Moran's I is used to identify clusters where households are surrounded by others with similar index values, producing four cluster types: high-high (high-value households near other high-value households), low-low, high-low, and low-high [41]. Outlier households, which lack spatial clustering, are excluded from the results.

Meanwhile, Global Moran's I is used to evaluate the overall spatial pattern of these indices, assessing whether values are clustered, dispersed, or randomly distributed across the study area [42].

3. Results

3.1. Does flood exposure cause or correlate with household vulnerability?

Our results suggest that flood exposure does not causally impact household vulnerability. This is based on three aspects: inequality distribution, quartile combination, and Pearson correlation, of the household vulnerability index and the flood exposure index, respectively.

First, the household vulnerability index has a lower Gini coefficient than the flood exposure index (see Fig. 3a), indicating that

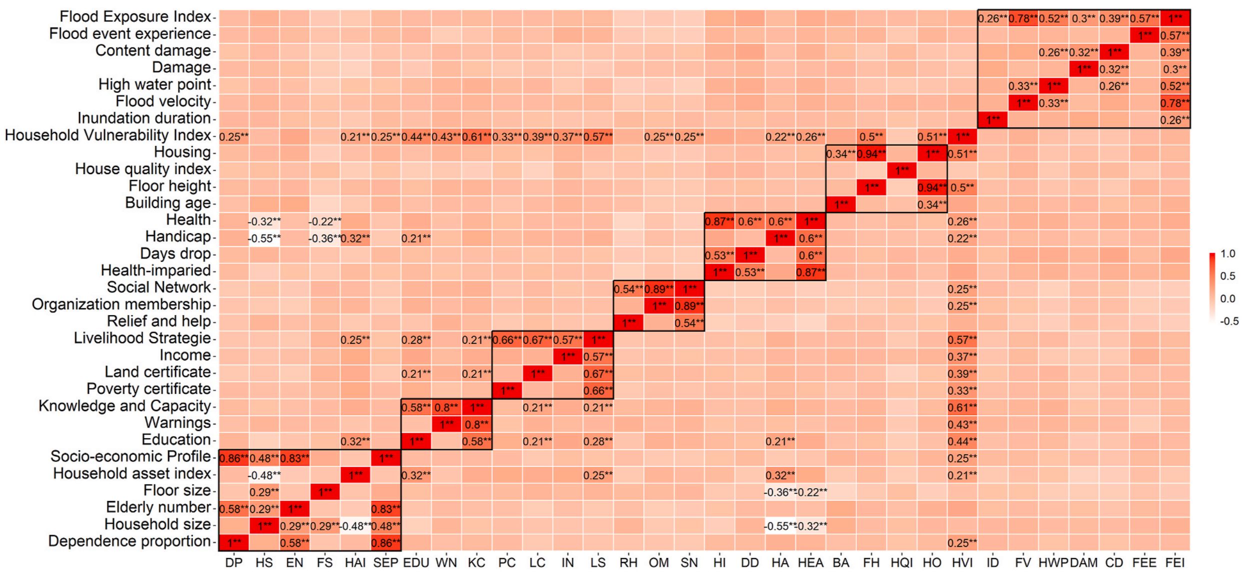

Fig. 4. The Pearson correlation coefficient of indicators, sub-components, and indexes (r > 0.2 or r < - 0.2, *p < 0.05; **p < 0.01; ***p < 0.001).

household vulnerability is distributed more equitably than flood exposure. Second, the quartile combination of the household vulnerability index and the flood exposure index represents a uniform distribution (Fig. 3b). Every one of the quartile clusters has a similar household number, and the average is 61.9 ± 1.9 households (95 % confidence interval) per cluster. This shows that degree of vulnerability and flood exposure are evenly distributed among the sample households.

Finally, the household vulnerability index shows a weak correlation with the flood exposure index, reflected by a low Pearson correlation coefficient and statistical significance (r: 0.06 and p: <0.05) (see Fig. 4). Vulnerability and flooding are linked to some extent, though the connection is weak.

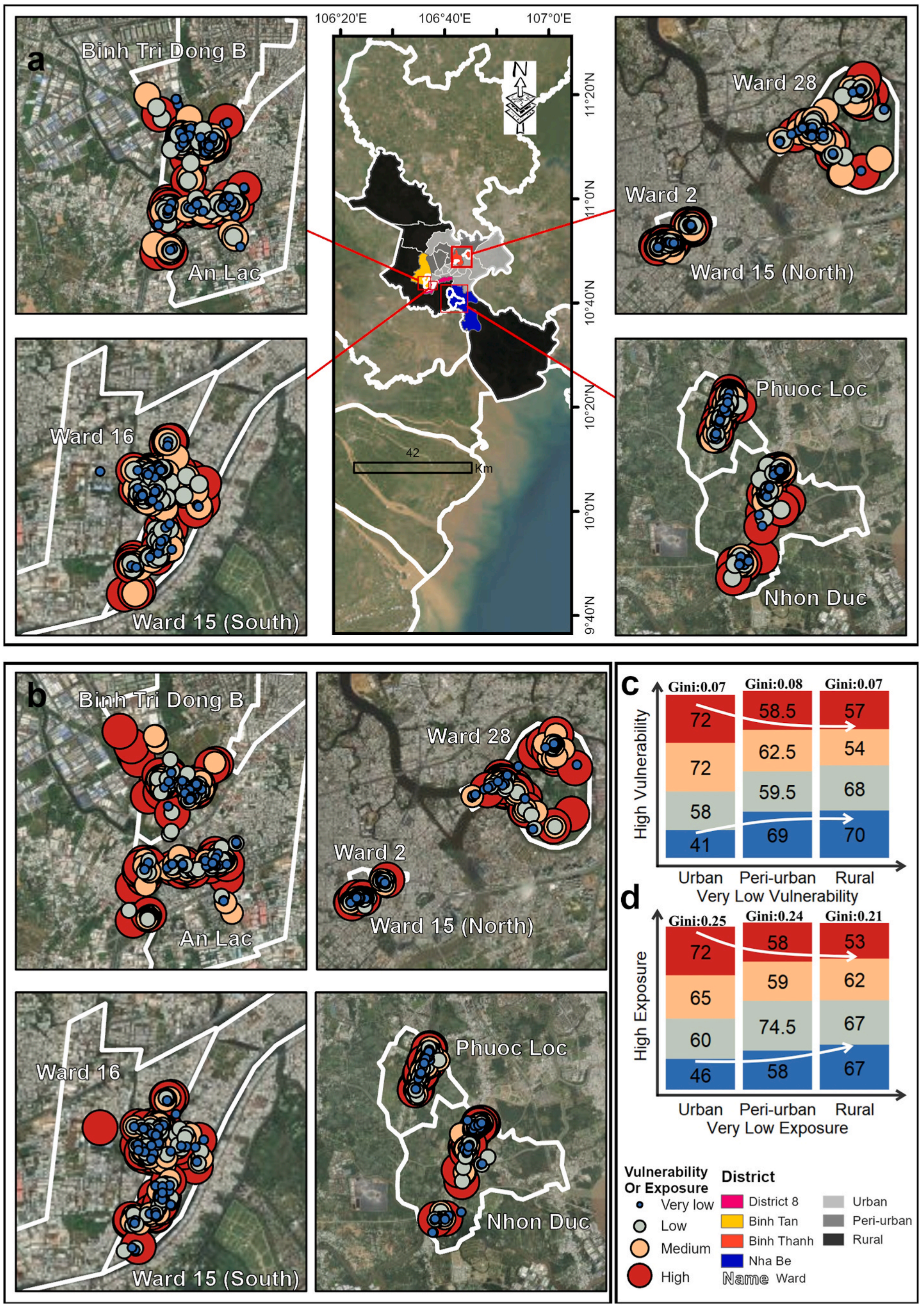

Fig. 5. Spatial distribution of sample households with the (a) household vulnerability, (b) flood exposure, and (c) quartiles of household vulnerability and (d) flood exposure in the urban, peri-urban, and rural areas, and their Gini coefficient.

3.2. Where and to what extent do vulnerability and flood impacts affect households?

Fig. 5 shows the spatial distribution of the household vulnerability index and the flood exposure index categorized into four levels from very low to high. Urban areas exhibit a higher number of households with high level of vulnerability and flood exposure compared to rural areas (see Fig. 5c and d). Additionally, urban areas have fewer households with very low levels of vulnerability and flood exposure than rural areas. This indicates that households characterized by higher vulnerabilities and flood exposure tend to be located in the urban districts.

Local Moran’s I shows that the flood exposure index (305 clusters) has a larger amount of spatial clusters than the household vulnerability index (228 clusters) (Fig. 6). Meanwhile, flood exposure has larger clusters in the high-high, and the low-low clusters than household vulnerability. The difference in the number of spatial clusters shows that the spatial context plays a higher role for the flood exposure than household vulnerability index. Also, the sub-components of household vulnerability, except for the *socio-economic profile are influenced* by their spatial reference. Local Moran’s I shows that the indicator *knowledge and capacity* (335 clusters) has the biggest number of spatial clusters, while *socio-economic profile* (115 clusters) has the least, and corresponds to a random spatial pattern based on the analysis according to the approach of Global Moran’s I (see Fig. 6).

When taking a look on the distribution of inequality, Fig. 3a shows that among the sub-components of the household vulnerability index, the *health* indicator has the highest Gini coefficient, while *social network* has the lowest. *Housing*, *livelihood strategies*, *knowledge and capacity*, and *socio-economic profile* lie between these two. The sub-components of household vulnerability vary across urban, peri-urban, and rural areas, revealing a paradox: a low Gini coefficient doesn’t necessarily indicate equality, as a larger proportion of households may still have a high level of a particular sub-component (see Fig. 7). For example, the sub-component *health* has a large share in the high-level category but shows the lowest Gini coefficient in urban areas. However, this pattern is less pronounced in rural areas. This indicates that households experience, to some extent, a similar inequality in health. The sub-component *social network* also exhibits similar inequality: despite a very low Gini coefficient, most of the households fall into the high-level vulnerability category.

The analysis of the flood exposure shows that our sample households to a higher degree affected by the severity of flood events than by their frequency. Inundation duration, content damage, damage, high water point, and flood velocity have higher Gini coefficients than flood event experience (see Appendix C).

3.3. What are the drivers of household vulnerability and flood exposure?

The Pearson correlation is used to identify the main drivers of the sub-components and indices of the household vulnerability and flood exposure, respectively (Fig. 4). The most influential drivers of the sub-components of household vulnerability, ranked from highest to lowest, are *knowledge and capacity*, *livelihood strategies*, *housing*, *health*, *socio-economic profile*, and *social network*. This ranking suggests that *socio-economic profile* and *social network* contribute less to overall household vulnerability. In other words, *knowledge and capacity*, *livelihood strategies*, *housing*, and *health* play a more significant role in shaping vulnerability than the sub-components *socio-economic profile*, and *social network*.

Fig. 8 represents the combination of household vulnerability and its sub-component based on quartile analysis. A steeper slope in the combination of sub-component and vulnerability level indicates a stronger the correlation. *Social network* (Fig. 8d) has an average of 123.88 ± 26.18 (95 % confidence interval) households per cluster. The low number of clusters and the high number of households

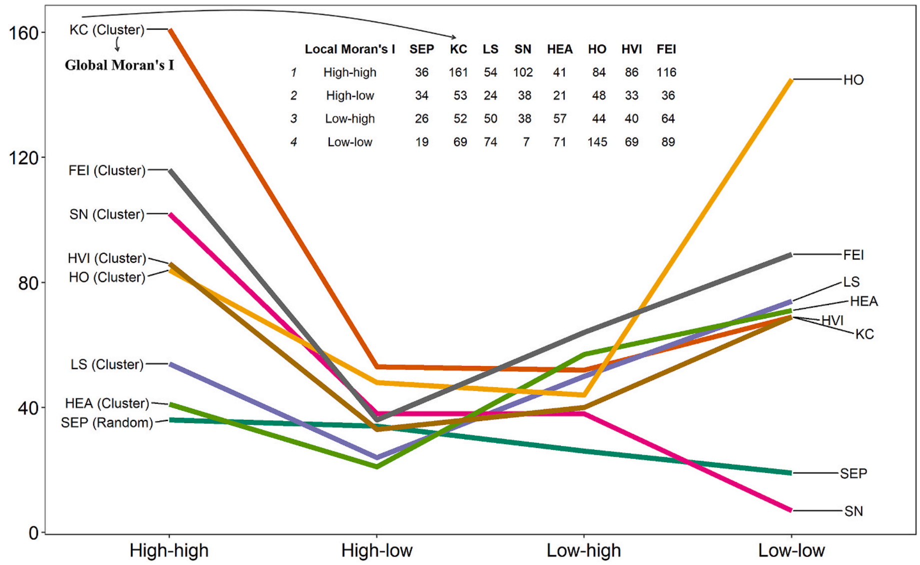

Fig. 6. The spatial patterns of *socio-economic profile (SEP)*, *knowledge and capacity (KC)*, *livelihood strategies (LS)*, *social network (SN)*, *health (HEA)*, *housing (HO)*, household vulnerability index (HVI), and flood exposure index (FEI) based on Local Moran’s I, and Global Moran’s I, respectively.

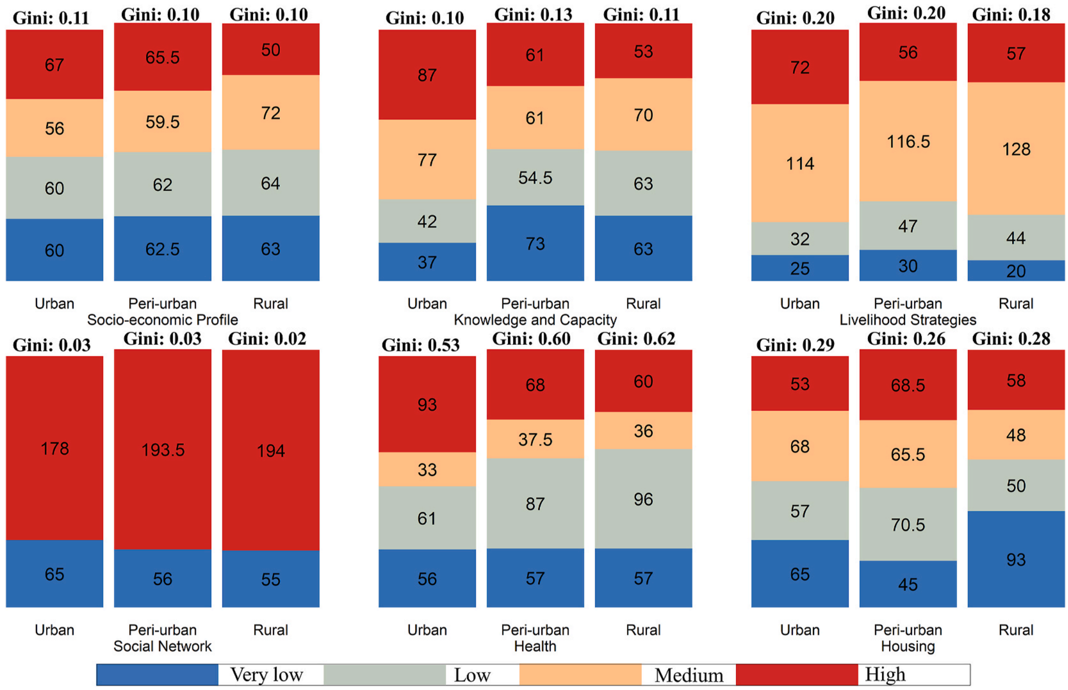

Fig. 7. Distributions of the four levels of vulnerability from very low to high for the sub-components along the urban, peri-urban, and rural areas and their Gini coefficient.

per cluster suggest that the households share a similar *social network* which contributes to a smaller degree to household vulnerability.

Subsequently, the correlation confirms the robustness of the hierarchical weighting model. The majority of the indicators represent a strong correlation and statistical significance with their respective sub-component, as well as the correlation between the sub-component and the index.

4. Discussion

This research contributes to the assessment of vulnerability by developing a household vulnerability index and a flood exposure index, using a customized, applied vulnerability assessment that integrates the contextual vulnerability and risk-hazard model. In the subsequent sections we interpret our findings, compare them with existing literature, discussing their significance, and address limitations.

Our findings show that household vulnerability and flood exposure are not causally linked or significantly correlated in our sample households. This is in line with previous studies stating that vulnerability is not simply the misfortune of climate events, but is often shaped by pre-existing human and socio-political factors [43,44]. In Vietnam, for example, vulnerability is influenced by government priorities, and climate-related events can sometimes conflict with development trajectories [44]. We found that urban households generally exhibit larger vulnerability or flood exposure index than those in peri-urban and rural areas. This is also the case for certain sub-components, such as knowledge and capacity. This finding confirms that rapid urban expansion causes the emergence of household vulnerability and flood exposure, especially considering that the dramatic urban expansion of the economic transformation is challenging in terms of sensitivity and capacity [45]. Furthermore, the similar share of inequality in certain sub-components, such as social network, suggests that vulnerability research may benefit from a political ecology or political economy model [46].

This study also contributes to climate adaptation and finance research based on the inequality and spatial analysis of household vulnerability and flood exposure indices (Fig. 5). Our results show that most sample households tend to adapt to flood events independently, such as upgrading the house floor (floor height (FH)), rather than relying on support from government or non-government organizations, such as receiving support such as money, housing, and food during or after flood events (relief and help (RH)). This finding indicates a gap in adaptation responses between households, municipalities, and the national government. The gap remains due to resources are not adequately augmented in line with clear roles and responsibilities [47–49], and are heavily dependent on the capacity and perspective of the sector involved [50,51]. Another gap is evident in climate finance, where the current law allows the local governments to design budget plans based on local needs, but the final approval ultimately rests with the National Assembly and the Ministry of Finance [52]. Meanwhile, the private sector is reluctant to invest in future climate adaptation because it does not always generate profits. Therefore, promoting coordination among sectors and hierarchical institutional structures (national, provincial, district, and ward) may enable effective future adaptation. In addition, it is critical to recognize that climate finance in Vietnam is not only for climate adaptation, but also for beneficial budgetary purposes, such as upgrading health care systems and water

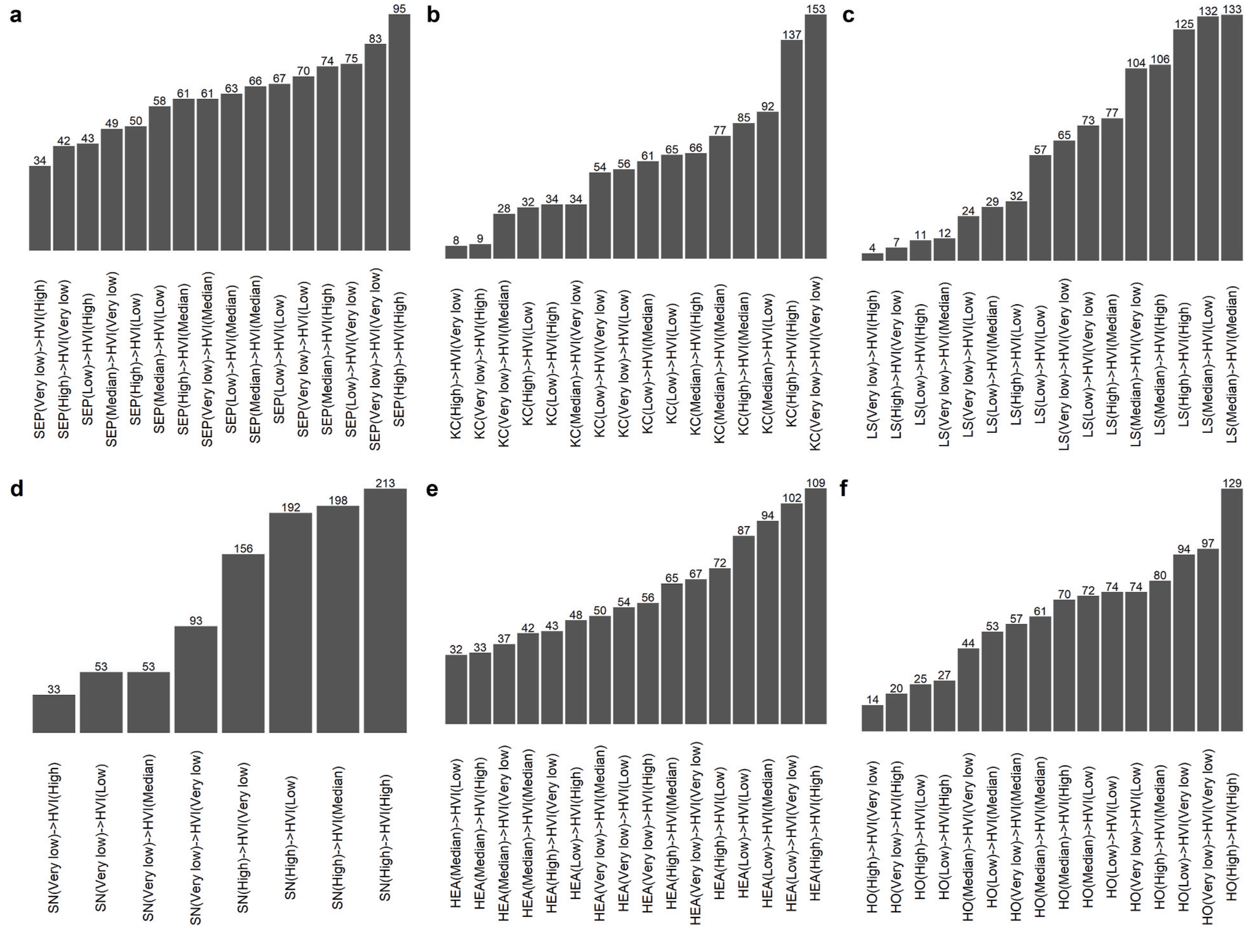

Fig. 8. The quartile combination of a) *socio-economic profile (SEP)*, b) *knowledge and capacity (KC)*, c) *livelihood strategies (LS)*, d) *social network (SN)*, e) *health (HEA)*, f) *housing (HO),* and household vulnerability index (HVI), respectively.

infrastructure [53].

This study recognizes limitations in terms of spatial and temporal scale. First, the lack of multi-scale vulnerability assessment can lead to statistically significant uncertainty due to the variance of the global population and the sample population. For example, our sample households have a higher dependence proportion, larger household size, and household asset ownership, while having a smaller average floor size (14.29 m^2) than the national average (23.2 m^2) [54]. This shows obstacles from absolute vulnerability to relative vulnerability assessment depending on the size of the global population to the sample population [9]. Second, there is a need for vulnerability assessments that account for temporal changes, as the vulnerability can evolve due to both climate change and societal developments [55]. In addition, there is a need for comprehensive data sets that cover a longer period with sufficient temporal resolution to assess the temporal evolution and dependencies of vulnerability.

5. Conclusion

This article advocates for addressing vulnerability and flood experiences to advance household-level climate adaptation efforts in a targeted approach. The results show that flood is not a causal problem to vulnerability, indicating some degree of pre-existing adaptation problems in households, such as social network - households often adapt independently rather than through institutional support. Additionally, disparities in specific sub-components of vulnerability suggest a dilemma between prioritizing economic development or climate adaptation. These inequalities point to underlying issues in both social development and climate adaptation efforts. Furthermore, vulnerability and flood risk tend to be more pronounced in urban areas in the flood-prone areas of Ho Chi Minh City.

The study identifies four key points for further research on vulnerability: there is a demand for studies that compare the expert-driven and data-driven assessments to validate vulnerability models; there is a demand for multi-scale vulnerability assessments to help national governments as well as local households to understand vulnerable groups and develop specific adaptation strategies; there is a demand for focusing on different vulnerability characteristics to reveal the vulnerability typologies; there is a demand for consider additional stress factors, such as specific buildings and forms, which impact vulnerability. Future studies could also enhance understanding by assessing vulnerability trends and comparing household-level vulnerability across diverse urban environments.

CRediT authorship contribution statement

Jiachang Tu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Andrea Reimuth:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Nivedita Sairam:** Writing – review & editing. **Heidi Kreibich:** Writing – review & editing. **Antje Katzschner:** Writing – review & editing. **Nigel K. Downes:** Writing – review & editing. **Matthias Garschagen:** Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Code availability

The code used for analysis can be provided upon request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Appendix A
Steps of household vulnerability index and flood exposure index.

Question from survey	Data type	Indicator	Step 1: Value	Step 2: Indicator Value	Step 3: Sub-component Value
How many people are living in your household (SEPA)? How many are 0–14 years old (SEPB)? Out of these, how many age 65 years or older (SEPC)?	Continuous	Dependence proportion (DP)	$DP = \frac{SEPB + SEPC}{SEPA}$		$SEP = \frac{DP + HS_n + EN_n + FS_n + HAI}{5}$
How many people are living in your household (SEPA)?	Discrete	Household size (HS)	$HS = SEPA$	$HS_n = \frac{HS_{act} - HS_{min}}{HS_{max} - HS_{min}}$	
Out of these, how many age 65 years or older (SEPC)?	Discrete	Elderly number (EN)	$EN = SEPC$	$EN_n = \frac{EN_{act} - EN_{min}}{EN_{max} - EN_{min}}$	
How many people are living in your household (SEPA)? What is the floor size of the house in m^2 (SEPD)?	Continuous	Floor size (FS)	$FS = -\frac{SEPD}{SEPA}$	$FS_n = \frac{FS_{act} - FS_{min}}{FS_{max} - FS_{min}}$	
Which and how many of the following things does your household have? (a) Basic household assets (BA): landline telephone, ventilator (sealed, stand-alone), bicycle.	Continuous	Household asset index (HAI)	Step 1 $BA_n = \frac{BA_{act} - BA_{min}}{BA_{max} - BA_{min}}$ $AA_n = \frac{AA_{act} - AA_{min}}{AA_{max} - AA_{min}}$		

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Appendix A (*continued*)

Question from survey	Data type	Indicator	Step 1: Value	Step 2: Indicator Value	Step 3: Sub-component Value
(b) Advanced household assets (AA): television, mobile phone, refrigerator, oven (gas, electricity), motorbike (>1 year), and other. (c) Assets indicating raised standard of living (RL): computer (desktop, laptop), cable/wireless internet, air condition, washing machine, and motorbike new (in one year). (d) Luxury assets (LA): car, van, and truck.			$RL_n = \frac{RL_{act} - RL_{min}}{RL_{max} - RL_{min}}$ $LA_n = \frac{LA_{act} - LA_{min}}{LA_{max} - LA_{min}}$ Step 2 $HAI = BA_n \times \frac{1}{10} + AA_n \times \frac{2}{10} + RL_n \times \frac{3}{10} + LA_n \times \frac{4}{10}$		
Which is the highest educational attainment in your household (KCA)?		Nominal	Education (EDU)	$EDU = KCA$	$EDU_n = \frac{EDU_{act} - EDU_{min}}{EDU_{max} - EDU_{min}}$
$KC = \frac{EDU_n + WN_n}{2}$	Type of warning (KCB).	Discrete	Warning (WN)	$WN = -KCB$	$WN_n = \frac{WN_{act} - WN_{min}}{WN_{max} - WN_{min}}$
Does your household have a poverty certificate (LSA)?	Ordinal	Poverty certificate (PC)	$PC = LSA$	$PC_n = \frac{PC_{act} - PC_{min}}{PC_{max} - PC_{min}}$	$LS = \frac{PC_n + LC_n + IN_n}{3}$
Do you have a formal land use certificate for your house (red and pink book) (LSB)?	Ordinal	Land certificate (LC)	$LC = LSB$	$LC_n = \frac{LC_{act} - LC_{min}}{LC_{max} - LC_{min}}$	
How high is the available income per month (million VND) (LSC)?	Nominal	Income (IN)	IN = LSC	$IN_n = \frac{IN_{act} - IN_{min}}{IN_{max} - IN_{min}}$	
What kind of relief did you receive in the flood emergency (SNB)?	Nominal	Relief and help (RH)	$RH = SNB$	$RH_n = \frac{RH_{act} - RH_{min}}{RH_{max} - RH_{min}}$	$SN = \frac{RH_n + OM_n}{2}$
Are household members part of the People's committee (SNC)? Are household members part of organizations (SND)?	Discrete	Organization membership (OM)	$OM = SNC + SND$	$OM_n = \frac{OM_{act} - OM_{min}}{OM_{max} - OM_{min}}$	
How many people are living in your household (SEPA)? Did any household members suffer injuries, sickness, or diseases related to those events (HEAA)?	Continuous	Health-impaired (HI)	$HI = \frac{HEAA}{SEPA}$		$HEA = \frac{HI + DD_n + HA_n}{3}$
How many days of drop out from work or study (specific in days) (HEAB)?	Discrete	Days drop (DD)	$DD = HEAB$	$DD_n = \frac{DD_{act} - DD_{min}}{DD_{max} - DD_{min}}$	
How many people are living in your household (SEPA)? Do your household members have health conditions (HEAC)?	Continuous	Handicaps (HA)	$HA = \frac{HEAC}{SEPA}$	$HA_n = \frac{HA_{act} - HA_{min}}{HA_{max} - HA_{min}}$	
When was the house constructed (HOA)?	Continuous	Building age (BA)	$BA = -2020 - HOA$	$BA_n = \frac{BA_{act} - BA_{min}}{BA_{max} - BA_{min}}$	$HO = \frac{BA_n + FH_n + HQI}{3}$
House ground floor comparing with surrounding land: same level to street, lower level to steer, and higher level to street (HOB).	Nominal	Floor height (FH)	$FH = HOB$	$FH_n = \frac{FH_{act} - FH_{min}}{FH_{max} - FH_{min}}$	
Material type of the house. Foundation (MFO): (grave/sand (MFOA); stilt (wood) (MFOB); stilt (cement) (MFOC); brick/cement (MFOD); stone/cement (MFOE); metal stilt/pole (MFOF)). Floor (MF): grave/sand (MFA); wood plank (MFB); cement (MFC); ceramic tiles (MFD)). Wall (MW): bricks (MWA); cement (MWB); wood plank (MWC); tin or metal (MWD)). Roof (MR): terracotta/clay tiles (MRA); corrugated metal (MRB); shingle (metal) (MRC)). Doors/windows (MDW): only opening (MDWA); only grid (MDWB)).	Continuous	House quality index (HQI)	Step 1 $\mathrm{MFO} = \mathrm{MFOA} \times \frac{6}{21} + \mathrm{MFOB} \times \frac{5}{21} + \mathrm{MFOC} \times \frac{4}{21} + \mathrm{MFOD} \times \frac{3}{21} + \mathrm{MFOE} \times \frac{2}{21} + \mathrm{MFOF} \times \frac{1}{21}$ $\mathrm{MF} = \mathrm{MFA} \times \frac{5}{15} + \mathrm{MFB} \times \frac{4}{15} + \mathrm{MFC} \times \frac{3}{15} + \mathrm{MFD} \times \frac{2}{15} + \mathrm{MFD} \times \frac{1}{15}$ $\mathrm{MW} = \mathrm{MWA} \times \frac{4}{10} + \mathrm{MWB} \times \frac{3}{10} + \mathrm{MWC} \times \frac{2}{10} + \mathrm{MWD} \times \frac{1}{10}$ $\mathrm{MR} = \mathrm{MRA} \times \frac{3}{6} + \mathrm{MRB} \times \frac{2}{6} + \mathrm{MRC} \times \frac{1}{6}$		

(*continued on next page*)

Appendix A (*continued*)

Question from survey	Data type	Indicator	Step 1: Value	Step 2: Indicator Value	Step 3: Sub-component Value
			$MDW = MDWA \times \frac{3}{4} + MDWB \times \frac{1}{4}$ Step 2 $MD_n = \frac{MD_{act} - MD_{min}}{MD_{max} - MD_{min}}$ $MF_n = \frac{MF_{act} - MF_{min}}{MF_{max} - MF_{min}}$ $MW_n = \frac{MW_{act} - MW_{min}}{MW_{max} - MW_{min}}$ $MR_n = \frac{MR_{act} - MR_{min}}{MR_{max} - MR_{min}}$ $MDW_n = \frac{MDW_{act} - MDW_{min}}{MDW_{max} - MDW_{min}}$ Step 3 $HQI = \frac{MD_n + MF_n + MW_n + MR_n + MDW_n}{5}$		
		$HVI = \frac{SEP + KC + LS + SN + HEA + HO}{6}$			
Duration of inundation at the house (hours, minutes) (FEIA).	Continuous	Inundation duration (ID)	ID = FEIA	$ID_n = \frac{ID_{act} - ID_{min}}{ID_{max} - ID_{min}}$	
Flow velocity on the street (scale 1 to 5) (FEIB).	Nominal	Flood velocity (FV)	FV = FEIB	$FV_n = \frac{FV_{act} - FV_{min}}{FV_{max} - FV_{min}}$	
Highest water point from your ground floor (cm) (FEIC).	Continuous	High water point (HWP)	HWP = FEIC	$HWP_n = \frac{HWP_{act} - HWP_{min}}{HWP_{max} - HWP_{min}}$	
If you would have repaired your house/ business building completely, what would this cost in VND (million) (FEID)? To estimate the actual cost of damage including the damages that they did not repair.	Continuous	Damage (DAM)	DAM = FEID	$DAM_n = \frac{DAM_{act} - DAM_{min}}{DAM_{max} - DAM_{min}}$	
How much did you need for repairing/ replacing all the damage contents together (VND) (FEIE)?	Continuous	Content damage (CD)	CD = FEIE	$CD_n = \frac{CD_{act} - CD_{min}}{CD_{max} - CD_{min}}$	
How many times have you been flooded since 2010 (i.e., flood water entering your house) (FFEF)?	Discrete	Household experience flooded since 2010 (FEE)	FEE = FFEF	$FEE_n = \frac{FEE_{act} - FEE_{min}}{FEE_{max} - FEE_{min}}$	
		$FEI = \frac{ID_n + FV_n + HWP_n + DAM_n + CD_n + FEE_n}{6}$			

Appendix B

Descriptive statistics of indicator value.

	Minimum	Q1	Median	Mean	Q3	Maximum	SD	95%CI
Dependence Proportion	0.00	0.13	0.33	0.31	0.50	1.00	0.24	0.01
Household Size	1.00	4.00	4.00	4.97	6.00	20.00	2.44	0.08
Elderly Number	0.00	0.00	0.00	0.53	1.00	4.00	0.72	0.02
Floor Size	1.67	8.75	14.29	19.05	22.50	300.00	19.90	0.63
Household Asset Index	0.42	0.87	0.90	0.88	0.92	0.98	0.05	0.00
Education	0.00	3.00	5.00	4.38	5.00	8.00	1.31	0.04
Warning	0.00	0.00	2.00	1.21	2.00	5.00	1.11	0.04
Poverty Certificate	1.00	1.00	1.00	1.07	1.00	2.00	0.26	0.01
Land Certificate	0.00	1.00	1.00	1.46	2.00	3.00	0.82	0.03
Income	0.00	6.00	7.00	6.44	7.00	9.00	1.78	0.06
Relief and Help	0.00	0.00	0.00	0.10	0.00	5.00	0.48	0.02
Organization Membership	0.00	0.00	0.00	0.24	0.00	3.00	0.54	0.02
Health-impaired	0.00	0.00	0.00	0.06	0.00	1.00	0.17	0.01
Day Drop	0.00	0.00	0.00	1.45	0.00	90.00	5.66	0.18
Handicap	0.00	0.17	0.25	0.31	0.33	2.00	0.24	0.01
Building Age	0.00	10.00	19.00	19.76	25.00	100.00	14.29	0.45
Floor Height	1.00	1.00	1.00	1.70	3.00	3.00	0.91	0.03
House Quality Index	0.09	0.36	0.43	0.42	0.48	0.69	0.09	0.00
Inundation Duration	0.00	2.00	3.00	7.64	4.00	600.00	28.78	0.91
Flood Velocity	1.00	2.00	3.00	2.81	4.00	5.00	1.29	0.04
High Water Point	1.00	10.00	20.00	26.62	40.00	220.00	23.32	0.74
Damage	0.00	10.00	100.00	253	300.00	5000.00	459.82	14.61
Content Damage	0.00	0.00	0.00	3831988	2000000	200000000	12126676	385217
Flood Event Experience	1.00	4.00	5.00	4.71	6.00	6.00	1.24	0.04

Appendix C
The Gini coefficient of the indicator, sub-component, and index.

	Dependence Proportion	Household size	Elderly number	Floor size	Household asset index	Socio-economic Profile	Education	Warning
Gini Coefficient	0.41	0.41	0.66	0.01	0.03	0.11	0.17	0.12
	Knowledge and capacity	Poverty Certificate	Land certificate	Income	**Livelihood strategies**	Relief and help	Organization membership	**Social network**
Gini Coefficient	0.12	0.90	0.26	0.08	0.20	0.00	0.03	0.03
	Health-impaired	Day drop	Handicap	**Health**	Building age	Floor height	House quality index	**Housing**
Gini Coefficient	0.86	0.89	0.46	0.61	0.44	0.60	0.13	0.29
	Household vulnerability index	Inundation duration	Flood velocity	High water point	Damage	Content damage	Flood event experience	***Flood exposure index***
Gini Coefficient	0.08	0.87	0.35	0.58	0.79	0.88	0.14	0.26

Appendix D
Descript statistics of the indicator, sub-component, and index value.

	Very Low	Low		Median		High		
	Minimum	Q1	Median	Mean	Q3	Maximum	SD	95%CI
Socio-economic Profile	0.31	0.44	0.50	0.50	0.56	0.77	0.08	0.003
Knowledge and Capacity	0.19	0.55	0.68	0.65	0.75	1.00	0.14	0.004
Livelihood Strategies	0.00	0.33	0.37	0.43	0.52	1.00	0.16	0.005
Social Network	0.27	1.00	1.00	0.95	1.00	1.00	0.11	0.003
Health	0.00	0.03	0.04	0.08	0.08	0.78	0.09	0.003
Housing	0.08	0.19	0.25	0.32	0.50	0.77	0.16	0.005
Household Vulnerability Index	0.32	0.45	0.49	0.49	0.52	0.71	0.05	0.002
Flood Exposure Index	0.01	0.17	0.23	0.23	0.29	0.68	0.09	0.003

Data availability

Data will be made available on request.

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