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Exploring the relationship between urban morphology types and household-level flood vulnerability profiles in Ho Chi Minh city

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A R T I C L E I N F O

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A B S T R A C T

Flood vulnerability in rapidly urbanizing cities is not only a function of hazard exposure but is also produced through the social and spatial configurations of urban life. In Ho Chi Minh City, Vietnam, we examine how household-level vulnerability is shaped by the intersection of urban morphology and everyday socio-economic conditions. Drawing on 554 households in 2020 and 2023, we develop groups based on both indices and profiles of social vulnerability and flood exposure, using factor analysis of mixed data and hierarchical clustering. These are situated within two distinct morphological frameworks: Urban Structure Types and Local Climate Zones. Our analysis shows, first, that household groups are unevenly distributed across morphologies, reflecting underlying urban development stages or regional climate conditions. Second, vulnerability is not fixed but relative, shifting across space and time in relation to social differentiation and morphological context. Third, during the COVID-19 pandemic, many households reported greater resilience, linked to improved warning systems, reduced flood events, and enhanced collective organization. We argue that interpreting vulnerability through both morphology and social profiling illuminates the entanglement of urban form, inequality, and adaptation, offering new entry points for inclusive resilience planning in flood-prone megacities.

1. Introduction

Households both shape and are shaped by urban morphology through intertwined socioeconomic, political, and cultural processes operating across scales [1,2]. The interaction between households and urban morphology produces new vulnerabilities and, over time, magnifies existing ones [3]. The rapid expansion of Ho Chi Minh City, Vietnam, often into flood-prone areas, has sparked debate over

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how these spatial changes are affecting household-level flood vulnerability. In this context, flood vulnerability is shaped by increasing inequalities, limited governance, and inefficient adaptation measures [4,5]. While urban households often face greater exposure to flood risk than their rural counterparts, recent evidence suggests that this distinction does not translate into significant differences in reported vulnerability among flood-affected households [6]. In response to this ongoing debate, this study examines the intersection of household-level flood vulnerability and urban morphology. Here, we intend to facilitate a deeper understanding of the subjects and formulate effective responses in the transformation of Ho Chi Minh City, Vietnam.

Urban morphology, the study of city form, can be interpreted in multiple ways, based on the conceptual and methodological lens through which it is examined [7–11]. Past research has reflected the regional environmental, local climate, social, political, and economic impacts of urban morphology. For instance, spatial-analytical approaches interpret the interaction between city form and local climate [10,12–16], while process-typological urban morphology focuses on the city form shaped by city plans and proposals [17,18]. On the other hand, historical-geographical urban morphology traces the evolution of city form (or human settlement) patterns over time [19,20], while the configuration approaches understand, improve, and shape its future form [8]. The development of these urban morphologies has been facilitated by the contributions of urban designers, geographers, historians, and economists, as well as the advancements in big data and remote sensing techniques [11,16].

These urban morphologies provide a comprehensive context of flood vulnerability in risk-hazard and political-economic dimensions. For example, the Local Climate Zone (LCZ), based on the spatial-analytical approach, is influenced by broader climatic conditions, as reflected in physical surroundings, including built height, built density, ground space, the ratio of green cover, and distance to water bodies [21]. Here, the classification of the urban water or thermal environment has the potential to mitigate urban flood or urban heat island (UHI) effects, thereby demonstrating the regional environmental conditions and related cultural heritage [14,16]. Another example is the Urban Structure Type (UST) approach, which employs a process-typological framework to classify built forms according to attributes such as archetype and density. These classifications are further contextualized and validated in collaboration with local stakeholders, particularly urban development authorities [22,23]. Together, these approaches highlight how urban morphology intersects with issues of social equity, emergency service provision, and access to essential resources for vulnerable urban households [24,25].

While urban morphologies have been employed to elucidate flood vulnerability [4,24], complementary vulnerability indices and profiles have also been developed to access these dynamics across risk-hazard and political-economic dimensions [26]. Here, the risk–hazard dimension is treated as a primary domain of knowledge, serving as the basis for understanding and measuring vulnerability through index construction. The index offers insights into the magnitude, spatial distribution, and temporal evolution of (overlapping) risk hazards at all scales [26–28]. On the other hand, profiles attempt to identify vulnerable groups within the political-economic dimension. This attempt shifts from hazard exposure inequality to political entitlement inequality, further, the root cause of vulnerable groups [3,27,28]. These root causes underlie causal agents, thereby revealing the underlying social, political, and environmental processes that differentiate flood vulnerability and drive related groups [29–33]. Overall, indices and profiles are two sides of the same coin, with the former reflecting the absolute magnitudes of vulnerability, and the latter reflecting the relative similarity [26,34].

In response to the mounting demand for deeper insights into flood vulnerability and the identification of at-risk groups, indices and profiles have been developed and operationalized based on expert- or data-driven approaches [27,34–36]. These measures serve as indicators of broader social, political, and environmental processes, drawing on variables such as demographics, socioeconomic status, race, health, and individual attitudes derived from census data, international databases, or targeted surveys. In doing so, they often portray vulnerable groups as the old, poor, ethnic minorities, or those with health-impairments [3,6,37]. In this context, expert-driven approaches entail the selection and weighting of indicators by specialists or based on previous studies. However, the indicators that either exacerbate or mitigate flood vulnerability are frequently overlooked and remain rarely subject to critical examination.

Subsequently, data-driven methodologies leveraging statistical techniques can identify and integrate key indicators and multiple profiles within large and complex datasets. For instance, principal component analysis (PCA) is a data reduction technique that transforms a set of indicators into a single continuous number by reducing the number of components [38]. Another is hierarchical clustering, which captures multiple groups with similar vulnerability characteristics based on convergent and intersectional indicators. These data-driven measurements empower decision-makers to quantify vulnerability magnitude, identify or categorize vulnerability groups, and trace the driver indicators of them [35,36,39,40]. Consequently, data-driven approaches have the potential to diminish the role of human judgment and to facilitate the equitable categorization of vulnerable groups.

Furthermore, the urban morphology and flood vulnerability may also reflect shifting roles and responsibilities between central and local government divisions. It is acknowledged that the process of urban transition is protracted and gradual. Hence, external forces, such as the COVID-19 pandemic, may serve to accentuate the strengths and weaknesses of the prevailing system. This phenomenon is particularly evident in Vietnam, where the decentralization of government responsibilities has historically led to convoluted and fragmented approaches to disaster risk management and climate change responses [41]. The longitudinal patterns of household flood vulnerability during the COVID-19 pandemic may reflect this phenomenon. Hence, we propose integrating grounded empirical insights with advanced data techniques to examine this relationship during the COVID-19 pandemic in Ho Chi Minh City, Vietnam.

This study builds on an understanding of the relationship between household-level urban morphology and flood vulnerability. It emphasizes the need to measure the magnitude of vulnerability, identify vulnerable groups, and trace its underlying drivers. Indices and profiles have proven valuable tools in this regard, particularly when applied to urban morphologies. Hence, this study aims to examine how household-level flood vulnerability, as measured through both indices and profiles, intersects with urban morphologies, as measured by local climate zones and urban structure types, in Ho Chi Minh City, Vietnam. To this end, we first ask: which household groups are relatively vulnerable? We then examine how these vulnerabilities intersect with urban morphology, and finally, how they evolved during the pandemic.

2. Materials and methods

2.1. Study area

Ho Chi Minh City, located in the southeastern region of Vietnam, is a rapidly urbanizing coastal megacity undergoing profound socioeconomic transformation. The city spans from 106.20° to 107.0° E and 9.40°–11.20° N, with an estimated population of 8.9 million. The climatic conditions—90 % yearly average rainfall happens between May and November, the geographical location—45 % is located below 1 m above sea level, and 65 % below 2 m above sea level [42–44], and the human activities, about 65–85 % of slum areas are exposed to floods [5,45,46], make Ho Chi Minh City highly vulnerable to flooding [47–50].

Subsequently, since Đổi Mới, the city has experienced marked urbanization, modernization, and a shift from rural livelihoods to an urban economy [51]. In Ho Chi Minh City, urban development has progressed through distinct phases: a compact city core until the mid-1990s; suburban expansion into new urban districts during the 2000s; and more recently, decentralization and bypass leapfrog urbanization in peri-urban areas [52–56].

Furthermore, Ho Chi Minh City has further expanded into the neighboring provinces, Ba Ria - Vung Tau and Binh Duong, marks a historic phase of urban transformation. This growth has intensified contemporary challenges in urban planning and flood management by extending the city's geographical scope and generating new zones characterized by diverse urban morphologies. These newly integrated areas face heightened flood risks, owing to uneven infrastructure provision and inadequate flood control systems.

2.2. Household-level flood vulnerability

Household-level flood vulnerability has been measured using two household surveys and a conceptual framework and subsequently categorized into household groups (Fig. 1). First, we drew indicators from two comprehensive and multipurpose household surveys, which represented households' perceptions of their social and physical surroundings. The objective of these surveys was to collect information on the socioeconomic status, productive capacity, as well as household behavior, before and after flood events. Furthermore, they also gathered information on how households perceived the impact of the pandemic.

These household surveys were undertaken as part of the Vietnamese-German joint project Decisions for the Design of Adaptation Pathways and the Integrative Development, Evaluation, and Governance of Flood Risk Reduction Strategies in Changing Urban-Rural Systems [57]. Households were selected for interview if they had experienced flooding since 2010 and had incurred associated damages or losses. Paper-based questionnaires were administered face-to-face, in Vietnamese, to household heads. The initial survey was conducted in September–October 2020 with 1000 households, and a subsequent follow-up survey was conducted in July–August 2023 with 750 households.

In this study, indices and profiles were determined individually for the three research questions, based on the surveys of 560 households in both 2020 and 2023. These two household datasets were used for household groups categorized in the following paragraphs. Moreover, the two surveys of 560 households were merged into a single dataset for a consistent comparison during the

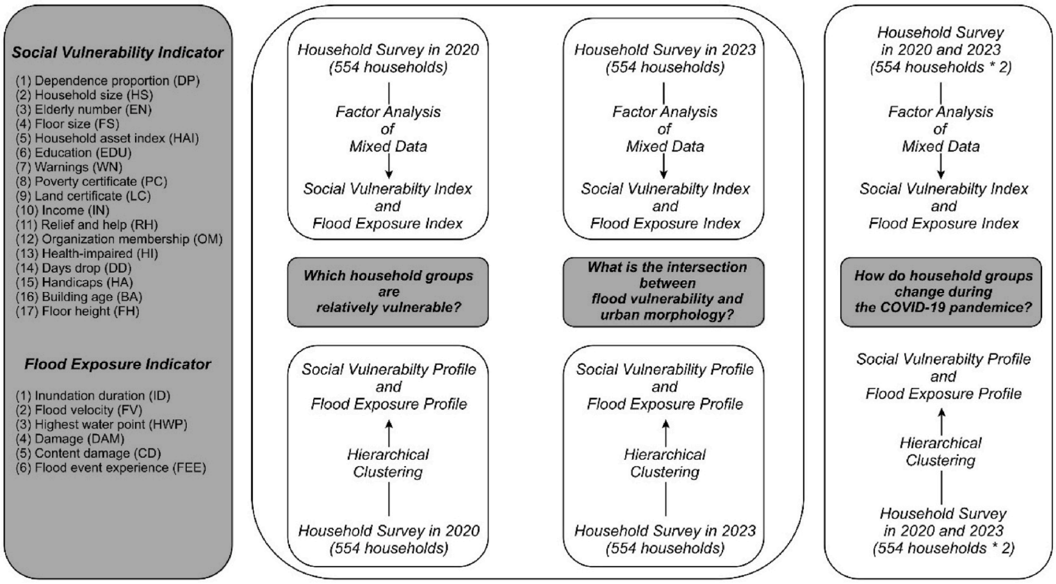

Fig. 1. Research questions and methods.

COVID-19 pandemic. In addition, we deleted six households that were located outside of Ho Chi Minh City. Hence, this study uses 554 response households (see Fig. 2).

Second, the conceptual framework of household-level flood vulnerability is defined by social vulnerability and flood exposure in order to distinguish social and climate impacts [6]. Social vulnerability refers to the households' social information, such as socio-economic status, knowledge and capacity, and livelihood strategies. Flood exposure, on the other hand, refers to the household flood experience, such as the flood inundation duration, flood velocity, and past flood events. Moreover, the previous study used Pearson correlation to examine the correlation among indicators and presented an insignificant correlation [6]. This lack of significant correlations underscores the multidimensional nature of household-level flood vulnerability identified both in that study and in the present one.

In addition, as we are using the urban structure types and local climate zones (see section 2.3) for household-level built structures and materials, the indicator 'house quality index' — which serves to evaluate the quality of the built structures and materials — overlaps. Therefore, we excluded the house quality index, and ultimately, we have seventeen social vulnerability and six flood exposure indicators (see Appendix A for the list of considered indicators).

Finally, based on the framework of household-level flood vulnerability, and drawing indicators from household surveys, we categorized household groups based on their index levels and profile under- or over-representative indicators. To refresh your memory, the index reflects the absolute magnitude of flood vulnerability, and the profiles reflect its relative similarity.

In this context, the social vulnerability index, as well as the flood exposure index, were generated based on factor analysis of mixed data (FAMD). FAMD is a type of component analysis that reduces the number of dimensions needed to explain a significant amount of the variance. The model is capable of handling both continuous and categorical indicators. This approach allows the transformation of the most correlated indicators into separate dimensions, which are subsequently aggregated to yield a numerical value [58]. In this study, the FAMD function of the FactoMineR package in R was employed to aggregate the indices, and ultimately, each household has a continuous value for its social vulnerability and flood exposure.

Subsequently, four levels of social vulnerability index, as well as flood exposure index, were categorized based on the quartile distribution, to further understand the magnitude and develop household groups. The indices were divided into the following 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).

The social vulnerability profile, as well as the flood exposure profile, were derived based on Gower distance and hierarchical clustering. The indicators were first merged in a bottom-up manner based on Gower distance, and then hierarchical clustering based on Ward D linkage. The Gower distance is used to measure the similarity of indicators, and the Ward D to measure the cluster linkage. Subsequently, the hierarchical clustering merging process employs a linkage criterion to divide each cluster. The five linkage

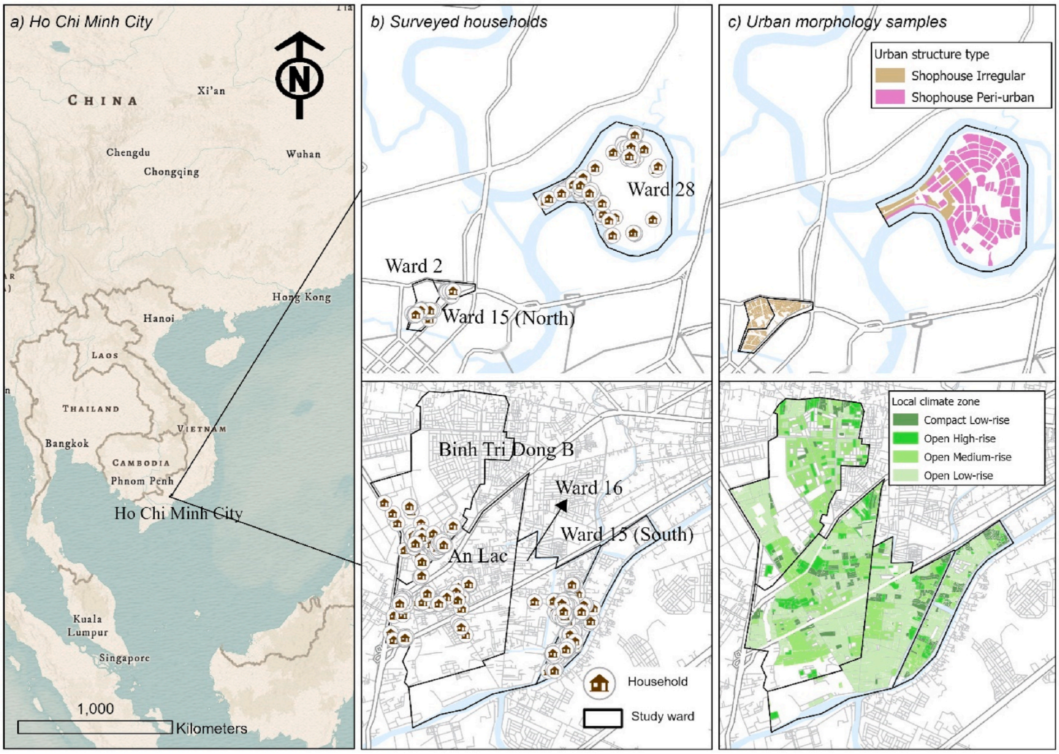

Fig. 2. Ho Chi Minh City, surveyed households, and their corresponding urban structure type and local climate zone (Background from Esri).

criteria—average, complete, single, Ward D, and Ward D2 [59]—were tested to cluster the sample households, and Ward D was determined to be the most significant [60]. The daisy function and hclust function of the Cluster package in R were employed to derive the profiles. Households were categorized into four profiles based on the social vulnerability profile, as well as flood exposure, along with their corresponding under- or over-representative indicators.

2.3. Urban morphology types

This study examines the intersection of household groups and their corresponding urban morphologies in 2020 and 2023 (Fig. 1), using the same time windows. In this context, we employ two urban morphologies, urban structure types for 2020, and local climate zones for 2023, which correspond to household groups of flood vulnerability in the respective year.

The urban structure types in Ho Chi Minh City were developed by Downes and colleagues and validated by the local planning stakeholders [22,23]. The framework distinguishes 80 urban structure types based on local building archetypes, such as height,

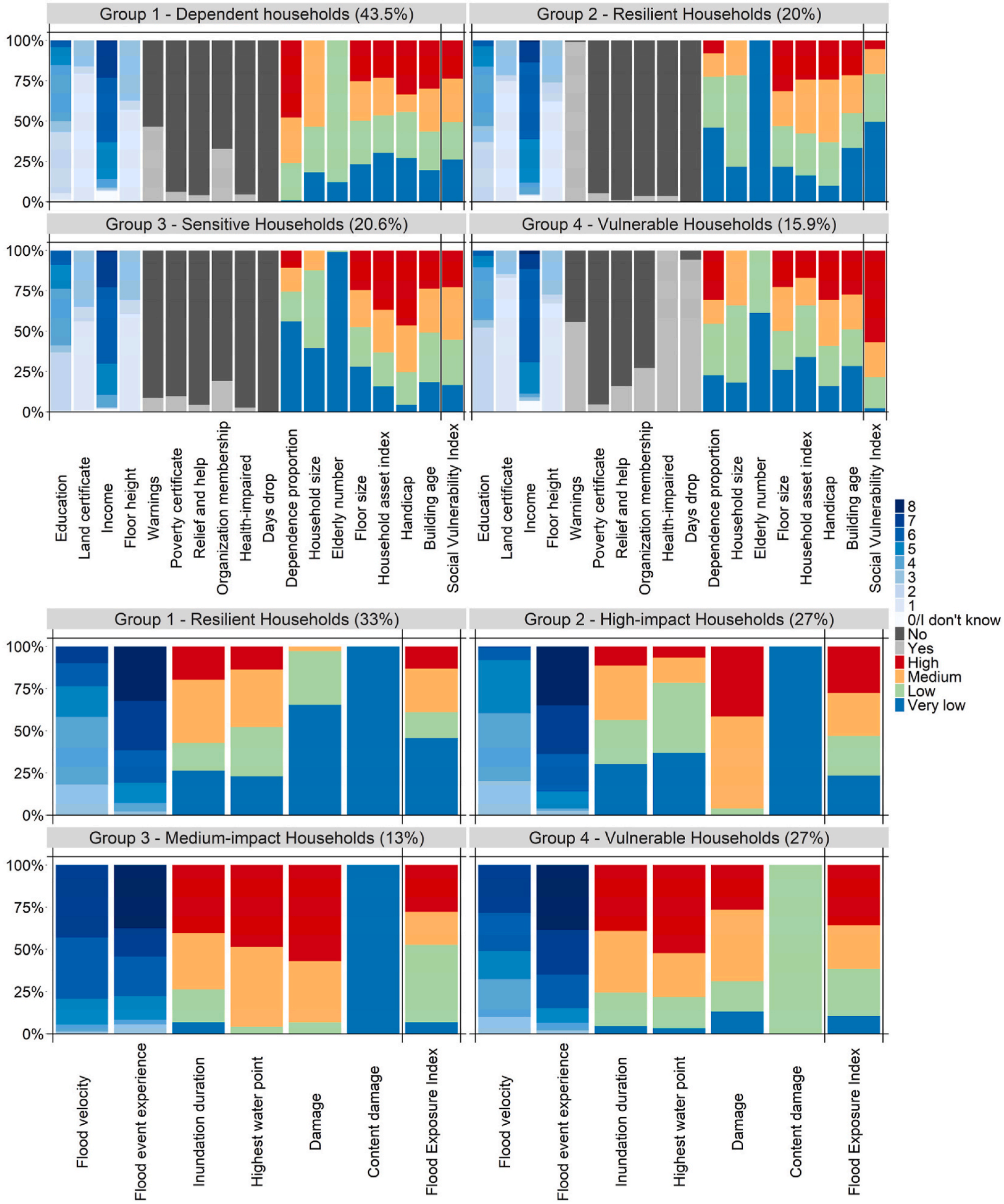

Fig. 3. Household groups of social vulnerability (top) and flood exposure (bottom) in 2020.

materials, and spatial arrangement—mapped onto official land-use geometries. The approach integrates architectural traditions and planning frameworks, making it legible across disciplinary domains. Its design captures fine-grained variation at the scale of individual structures while still being scalable to city- and region-wide analyses. This combination of methodological rigor, institutional validation, and cross-disciplinary accessibility positions the urban structure types as a distinctive tool for examining the intersection of urban morphology and flood vulnerability.

Shophouses represent the dominant building typology in Ho Chi Minh City and remain one of its most iconic architectural forms [61–63]. To integrate biophysical and socio-economic characteristics, the urban structure types framework differentiates shophouses into sub-categories. 'Shophouses irregular' denotes heterogeneous mixes of detached, semi-detached, and terraced archetypes, arranged without a regular layout and interspersed with narrow, organic alleyways. In contrast, 'shophouses peri-urban' describe clusters of rudimentary, temporary, low-rise terrace shophouses, often accompanied by a notable presence of peri-urban green space [22,23,64].

The local climate zones for Ho Chi Minh City were developed by Braun and his colleagues and classified by the Random Forest [21].

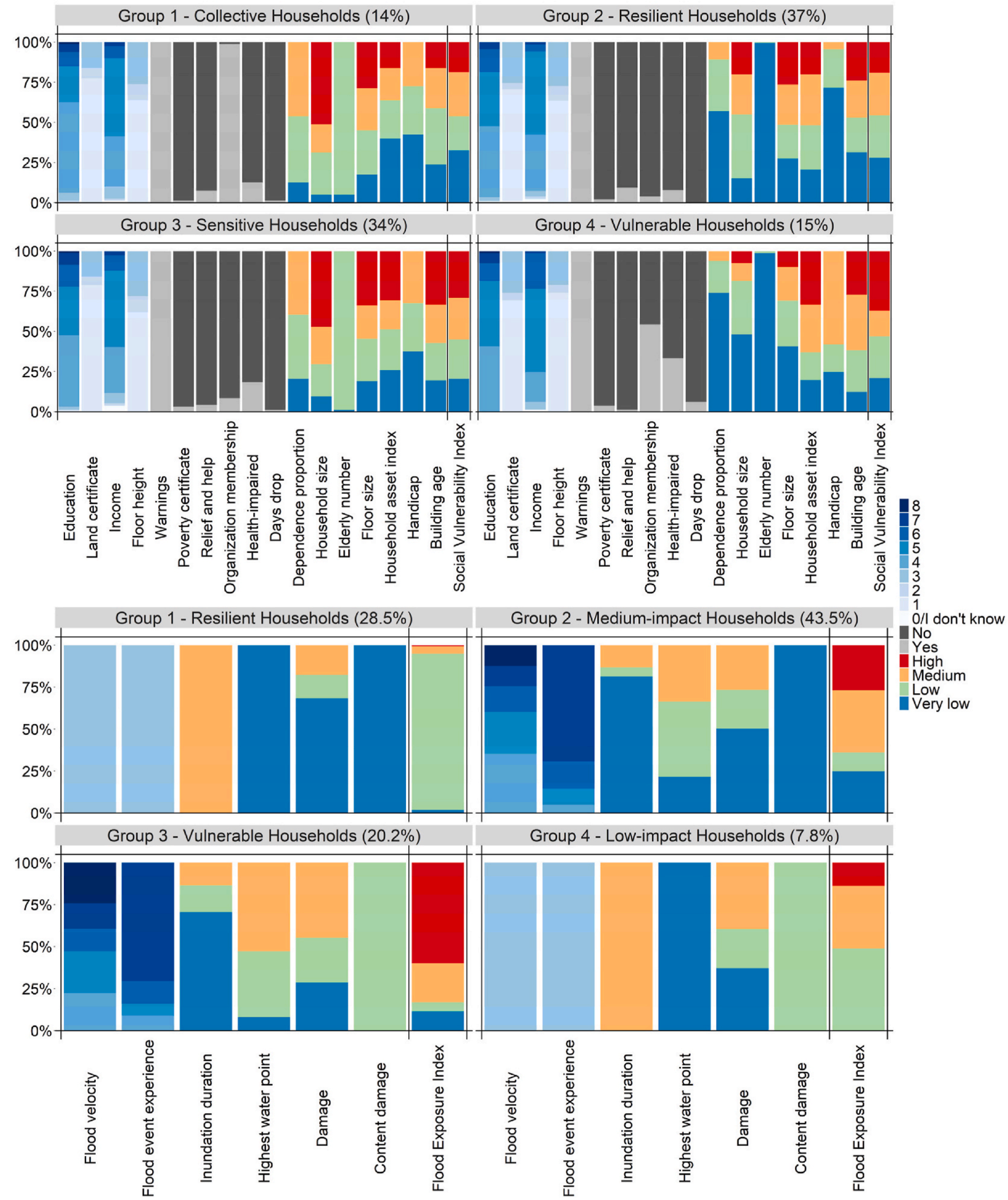

Fig. 4. Household groups of social vulnerability (top) and flood exposure (bottom) in 2023.

This classification was originally developed to assess how different urban structures influence the urban microclimate. It includes nine categories based on physical building characteristics (e.g., building density, building size, their proximity to rivers, average building height, nearest neighbour index, ground space index, green cover ratio, and accessibility).

An *open high-rise*, for instance, is an open arrangement of high-rise buildings with tens of stories made of construction materials such as concrete, steel, stone, and glass. These buildings have an abundance of previous land cover, such as low plants and scattered trees [14]. *Open medium-rise*, and *open low-rise* refer to open arrangements of mid-rise (three to nine stories), and low-rise (one to three stories) buildings with similar construction materials and previous land cover as open high-rise buildings. A *compact low-rise* is a dense mix of low-rise buildings, where vegetation is limited and the land cover consists mostly of pavement [14].

3. Results

3.1. Which household groups are relatively vulnerable?

Four household groups have been generated based on the 2020 and 2023 household datasets, respectively. These groups were created along with the social vulnerability index and social vulnerability profile, as well as for flood exposure. Compared to 2020, household groups have a significant improvement in terms of receiving flood warning information and participating in the organization. This has led to fewer missed work and school days, as well as smaller populations affected by health impairments due to flood events. Furthermore, the household groups showed a decrease in flood exposure experience, resulting in less housing damage and furniture damage (Appendix A).

Subsequently, we determined the household groups and selected 'vulnerable households' based on the index levels and profile under- or over-represented indicators for the social vulnerability and flood exposure, respectively. For instance, in terms of 2020, 'vulnerable households' is defined as Group 4 for social vulnerability and flood exposure, respectively (Fig. 3).

Regarding social vulnerability, Group 1 is *dependent households* (43.5 %). It is characterized by equally distributed social vulnerability index households. Meanwhile, it is represented with a large dependent (i.e., dependence population), elderly (i.e., elderly number) population, and large family numbers (i.e., household size). Group 2 (20 %) are *resilient households*, which are characterized by low social vulnerability index households. Those households have a less dependent and younger population, while most of them receive flood warning information (i.e., warnings). Group 3 (20.6 %) is *sensitive households*, represented by low to medium social vulnerability index households, as well as not receiving flood warning information, and a large physically disabled (i.e., handicap) population. Group 4 (15.9 %) are *vulnerable households*, which are represented by high social vulnerability index households. Those households are mostly having health issues (i.e., health-impaired) and drop out of work or school (i.e., days drop) due to flood events, although to some extent, households have participated in an organization (i.e., organization membership), received warning information in advance, and support (i.e., relief and help) afterwards.

At the same time, regarding flood exposure, Group 1 is *resilient households* (33 %), characterized by low flood exposure index households, as well as households that experienced calm flood velocity, short inundation duration, less built physical damage (i.e., damage), and housing furniture damage (i.e., content damage). Group 2 is *high-impact households* (27 %). It is characterized by medium flood exposure index households, as well as high built physical damage. Group 3 is *medium-impact households* (13 %). It is represented by low to medium flood exposure index households. However, it is presented with long inundation duration, high water point, and physical damage to the built. Group 4 is *vulnerable households* (27 %). It is represented by high flood exposure index households, as well as torrential flood velocity, long inundation, high water point, and, eventually, caused high housing physical and furniture damage.

In 2023, 'vulnerable households' is defined by Group 4 for social vulnerability and Group 3 for flood exposure (Fig. 4). In terms of social vulnerability, all household groups have received flood warning information. To be more specific, Group 1 is *collective households* (14 %). This group is characterized by equally distributed social vulnerability index households. It is characterized by household participation in organizations (i.e., organization membership). Meanwhile, it has large household numbers and smaller spaces (i.e., floor size) for each person in the housing. Group 2 (37 %) is *resilient households*, characterized by equally distributed social vulnerability indices. These households have low organization participation, with a less dependent and elderly population, as well as a less physically disabled population. Group 3 (34 %) are *sensitive households*, characterized by medium to high social vulnerability index households. These households are characterized by more dependence and elderly populations, who have smaller household sizes with larger spaces for each person in the housing. Group 4 (15 %) are *vulnerable households*, characteristic by high social vulnerability index households. It is characterized by fewer assets (i.e., household asset index) and aging housing (i.e., building age), as well as health impairment, and school or work days dropped out due to flood events.

In terms of flood exposure, Group 1 is *resilient households* (28.5 %), characterized by low flood exposure index households. Although they have medium inundation duration, the built physical and housing furniture damage is relatively very low. Group 2 is *medium-impact households* (43.5 %). It is characterized by medium flood exposure index households. With low to medium water points, households have low to medium built physical and very low furniture damage. Group 3 is *vulnerable households* (20.2 %). It is characterized by high flood exposure index households. Meanwhile, it is represented by relatively frequent flood events, medium water points, and built physical damage, and a degree of housing furniture damage. Group 4 is *low-impact households* (7.8 %). It is represented by low flood exposure index households. Meanwhile, this group has calm flood velocity, few flood events, but medium inundation duration, which caused a small proportion of built physical and housing furniture damage.

3.2. What is the intersection between flood vulnerability and urban morphology?

When intersected with measures of flood vulnerability, the urban structure types households (2020) exhibited more significant overlaps of social vulnerability and flood exposure. While the local climate zones of households present more significant vertical social vulnerability or horizontal flood exposure (2023). This is reflected in both index levels and profile indicators, ultimately resulting in different household groupings.

A total of 323 households were classified by urban structure types for 2020, while 324 households were classified by local climate zones for 2023 (Fig. 5). Among urban structure types, the most pronounced household group is 'dependent households–resilient households' in terms of social vulnerability and flood exposure in 'shophouse irregular', while 'dependent households–vulnerable households' in 'shophouse peri-urban'.

Meanwhile, local climate zones show more pronounced 'sensitive households' in terms of social vulnerability, while 'medium-impact households' for flood exposure. This has been shown in all sample climate zones except for 'open medium-rise' households, which are 'resilient households' as the most pronounced. In other words, household groups are mostly pronounced as vertical social vulnerability or horizontal flood exposure in local climate zones.

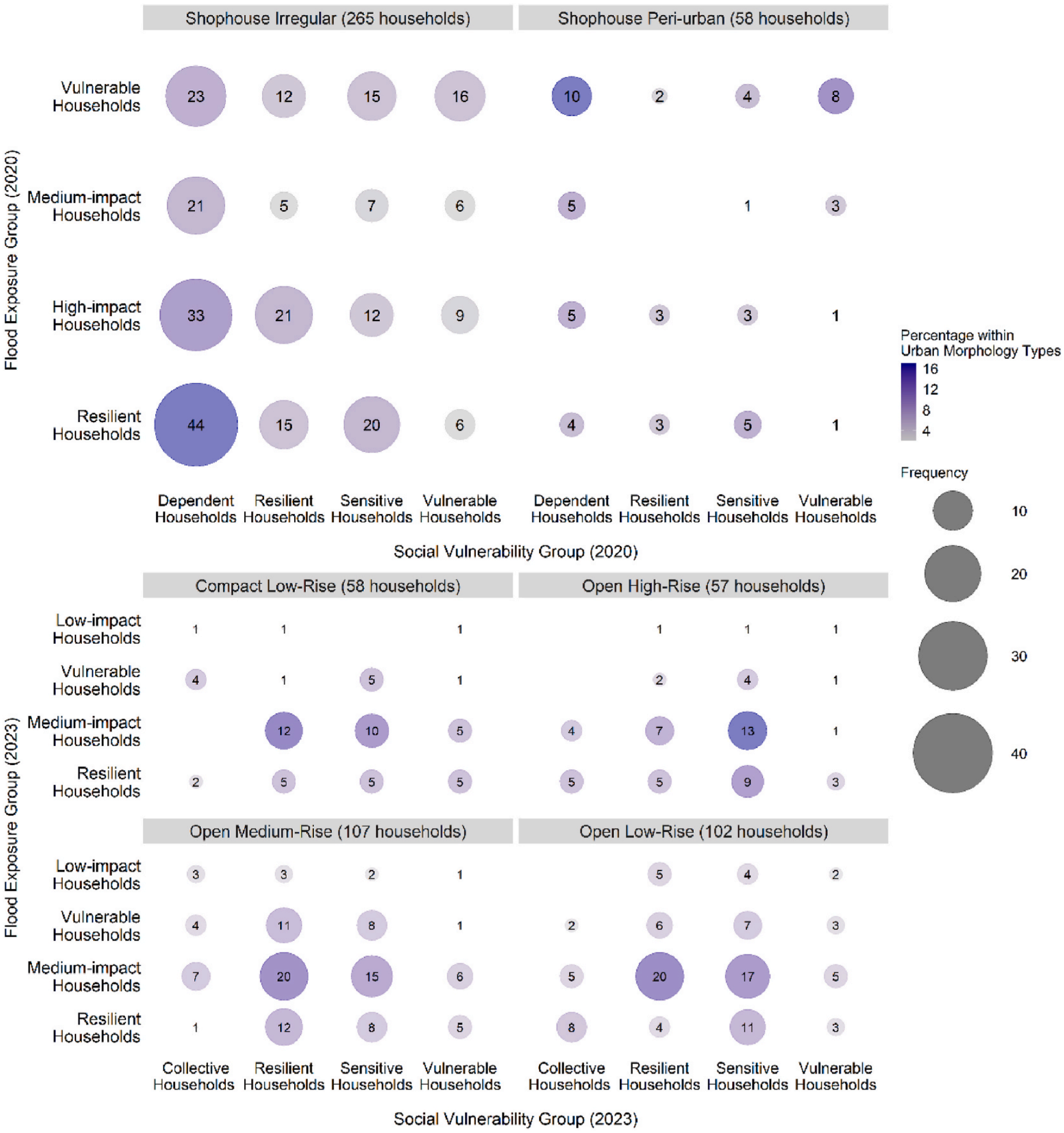

Fig. 5. Flood vulnerability groups in the corresponding urban structure types (top) and local climate zones (bottom).

3.3. How do household groups change during the COVID-19 pandemic?

Household groups demonstrate that households improved their flood resilience during the COVID-19 pandemic. The *index levels* show that most households experienced a reduction in social vulnerability and flood exposure (Fig. 6a and b), and some even

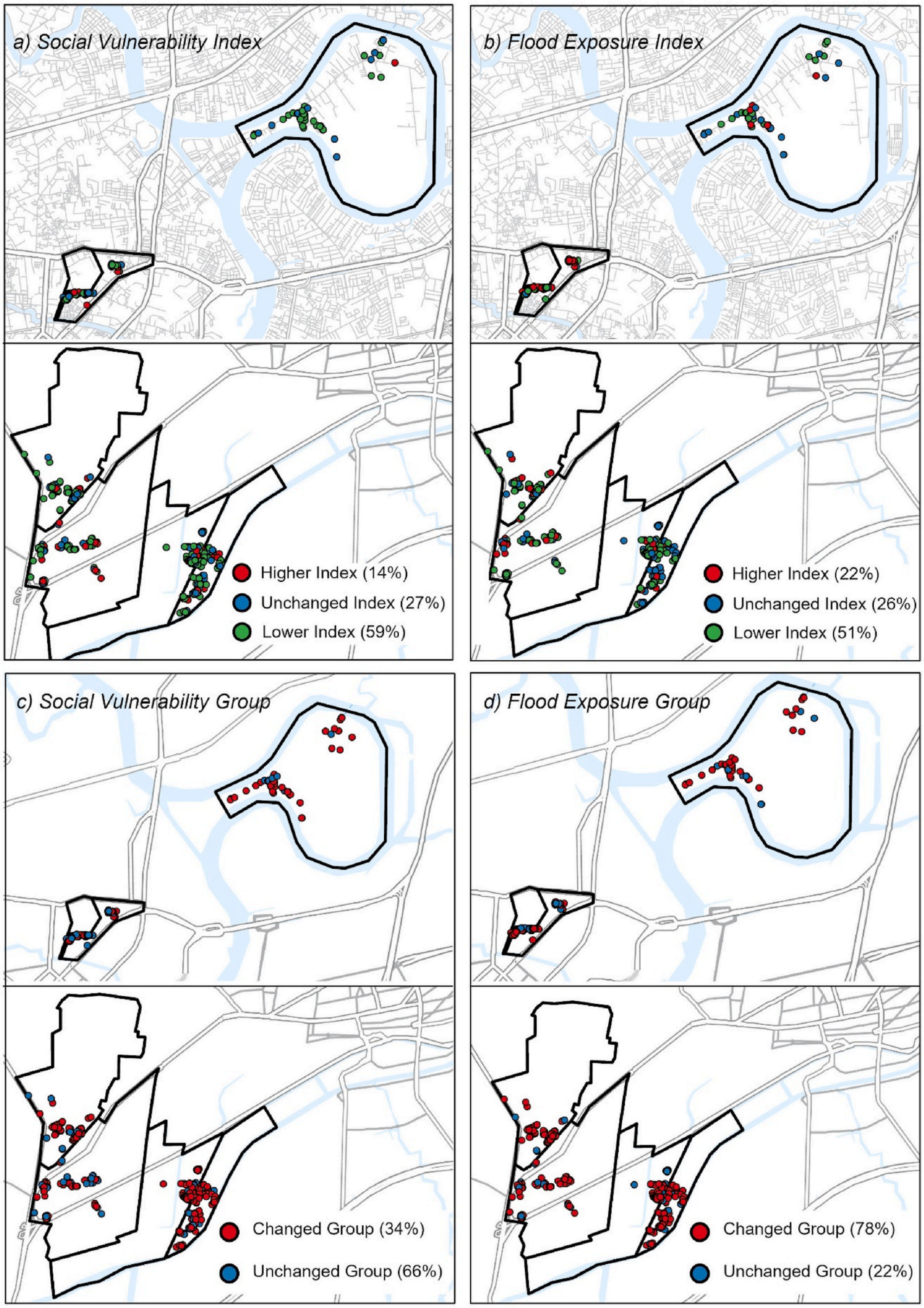

Fig. 6. Changes of the index levels (top) and household groups (bottom) during the COVID-19 pandemic.

experienced a significant reduction in social vulnerability. Moreover, *household groups* show that 'vulnerable households' in terms of social vulnerability have declined from 90 households to 11, while in terms of flood exposure, they have declined from 210 to 76. This transition occurs due to receiving more flood information and experiencing fewer flood events (Fig. 6c and d, and Appendix B).

The changes in household groups are shown in Appendix B. In terms of social vulnerability, Group 1 is *sensitive households* (36.2 %). This group is represented by equally distributed social vulnerability index households. Although households are receiving flood warning information and participating in organization activities. However, they are also characterized by dependent and elderly populations, with large households with a smaller share of space in housing. Group 2 is *resilient households* (34.6 %), which are represented by very low to low social vulnerability index households. Most of these households received flood warning information, while having fewer dependents and elderly populations. Group 3 is *dependent households* (20.2 %), represented by high social vulnerability index households. Most households do not receive flood warning information. Meanwhile, it is characterized by dependence proportion and the physically disabled population. Group 4 is *vulnerable households* (9 %), which are characterized by high social vulnerability index households. This group is represented by a large health-impaired population who miss school or work after the flood event.

In terms of flood exposure, Group 1, *resilient households* (18.1 %), are characterized by very low flood exposure index households. Although they experience long inundation durations, floods are generally of calm velocity and low frequency, resulting in minimal water levels and limited damage to housing and furniture. Group 2, *low-impact households* (29.6 %), exhibit medium exposure index values, typically facing low to moderate water levels and correspondingly minor housing and furniture damage. Group 3, *medium-impact households* (26.8 %), display medium-to-high exposure index values, with moderate housing damage and low furniture damage. Group 4, *vulnerable households* (25.5 %), has the highest exposure index values, frequently experiencing prolonged inundation, higher water levels, and recurrent flood events, leading to more severe damage to both housing and furniture.

4. Discussion

Household-level flood vulnerability is closely linked to urban morphology types and has shifted during the COVID-19 pandemic, as reflected in index levels and profile indicators across household groups. First, our results show that 'dependent households-resilient households' are dominant in terms of social vulnerability and flood exposure among urban structure types. While 'resilient households' and 'sensitive households' are dominant in terms of social vulnerability, 'medium-impact households' are dominant in terms of flood exposure, among local climate zones. Second, household groups, such as 'vulnerable households', are relative and change spatially and temporally among sample households. The results also show that households became more flood-resilient during the COVID-19 pandemic. Growing attention is being paid to the role of urban morphology and its interaction with vulnerable groups in shaping pathways for inclusive urban transformation [32,65–67]. This highlights the fundamental role played by the political ecology and economy of cities in shaping their ability—how and what actors are learning from this interaction, and acting upon it [68]? This connects with the urban transformation from a modernization and development perspectives, and with vulnerable groups from multi-level and multi-loop social learning [65,69]. The following section will open up the urban transformation, vulnerable groups, and multi-level and multi-loop social learning in relation to our findings, existing literature, and potential uncertainties.

4.1. *Urban transformation for modernization and development*

When it comes to the urban transformation in Ho Chi Minh City, the term refers to the urban modernization and development since the beginning of Đổi Mới [70,71]. It draws from mainstream literature and informed assumptions on urban transformation, while urban modernization refers to the political and cultural experience of contemporary behavior, and urban development refers to the ambition to improve socioeconomic life, especially for vulnerable groups [67,69,72]. This urban transformation has been shaped by different forces of actors, including real estate market globalization, the interplay of formal and informal institutions, the interactions between state and non-state actors, and a governance mode of control and permissiveness [65,67,73].

This urban transformation indicates a shift in urban planning from both authoritarianism and laissez-faire to the regular implementation of governance control [73]. It has been shown from the aftermath of past urban development in terms of urban morphology types. A history of lax regulatory enforcement has contributed to the proliferation of unplanned housing. Within our flood-impact sample, households located in 'shophouse irregular' and 'shophouse peri-urban' urban structure types fall into this category. While such unplanned housing is often associated with increased vulnerability, it has paradoxically supported urban transformation by expanding the housing stock accessible to low-income and migrant households [23,73]. While most of our sample households own the land on which their unplanned housing is built, land ownership (i.e., land certificate) is not a driver of flood vulnerability. Moreover, the legacy of post-colonial urbanization in Ho Chi Minh City has produced densely packed housing along the river and canal banks. Our sample households are located in local climate zones and are mostly close to the river. These are potentially grouped into 'sensitive households' in terms of social vulnerability, and 'medium-impact households' in terms of flood exposure.

Furthermore, the urban transformation witnessed the interplay over who has the right to design and brand the new model for the city, and who can and/or will harness political gains from it [71,74]. The urban morphologies depend on material effectiveness, such as housing materials and the construction process, as well as equitable urban design, such as affordability and feasibility [75,76]. These factors reflect the household socioeconomic status of households and their capacity for housing-related flood adaptation. Our 2020 household survey shows that the sample households have a lower floor size than the national average [6]. Our results also show that housing damage (i.e., damage) is an over-represented indicator of 'vulnerable households' in terms of flood exposure. It is indicated that the housing material is a driver of flood vulnerability. In addition, the urban transformation is driven by well-connected elites and rampant real estate speculation [77], which has led to disputes over the distribution of economic gains among the displaced [78]. This has caused dispossession, displacement, and precarization, producing vulnerable households [79]. Hence, there is a demand for social learning from the individual to the nation in the long term.

4.2. Social learning for vulnerable households

As the urban transformation in Ho Chi Minh City demonstrates entanglement [72], it demands a multi-level and multi-loop social learning process for all actors from individual to nation [65,80,81]. The multi-level and multi-loop social learning process refers to complex iterative collective learning and corresponding changes in the roles of different actor groups [82,83]. This social learning process can be enormously meaningful for vulnerable groups as they face not only changing urban morphology and climate but also deal with the dire consequences of crises such as COVID-19.

Vulnerable groups can be understood either as those subjected to systemic inequalities, viewed through a political–economic lens, or as those exposed to environmental hazards, framed within a risk–hazard perspective [26]. It has to open up the political-economic structures and understand risk-hazard surroundings, and the focus on these groups highlights the social roots and resources inequality [84–86]. These affect the elderly, children, those with health impairments, and the poor, in both static policy analysis and dynamic political practice [32,87]. It emphasizes what, who, and why vulnerable groups are produced, but lacks follow-up political instrumental actions [32,83]. Hence, multi-level social learning ability at national, city, and individual levels to improve household food resilience, especially of vulnerable groups, is an essential requirement for urban transformation in Ho Chi Minh City.

Vulnerable groups in this study are defined as vulnerable households, by the index levels and the profile indicators, based on factor analysis of mixed data and hierarchy clustering, following a household-level flood vulnerability framework [6]. The changes to household groups during the COVID-19 pandemic reveal a certain degree of social learning at the national and individual levels. For example, at the national level, although there was no significant change in flood disaster risk support, such as relief and help, the number of 'resilient households' increased due to improvements in the flood warning system and large-scale grey infrastructure, such as ring dikes [43,88]. Moreover, green infrastructure, such as Metro Line one, could improve connectivity for different household groups and efficiency for urban morphology towards a polycentric spatial model [89,90]. At the individual level, increasing organization membership improved the collective actions in terms of flood resilience among the sample households (Fig. 4). In this case, the national level considers the grey-green engineer to be the outcome of the learning process, while the individual level considers collective organizations to be more important.

While this study evidences the social learning process of households and the nation in terms of flood adaptation, what actions can be taken further? A multi-loop social learning process should be applied to all actors in relation to urban morphology and flood vulnerability. The multi-loop social learning process refers to a feedback loop embedded in a specific societal and environmental governance structural context, and that leads to specific outcomes [65,91]. For instance, the COVID-19 pandemic provides an opportunity to understand different household groups, and to identify which actors can contribute to improving urban resilience. Urban stakeholders thus require urban transformative capacity to perform radical change within and across the multiple political-ecological and socio-technical systems embedded in cities [68]. The multi-level and multi-loop social learning for socio-technical systems, in the context of grey-green infrastructure, requires pre-planning tools. Tools, such as the index, the profile, and perhaps the future scenarios, under particular social vulnerability or flood exposure narrative, along with the corresponding data and approaches, are necessary for Ho Chi Minh City, Vietnam [92,93].

For many developing countries, cities, and their populations, building liberal resilience is part of the multi-level and multi-loop social learning [81]. It underscores the need to engage with vulnerability not as a static condition but as a relational outcome shaped by urban form, governance, and inequality. Our results suggest that systemic shocks such as COVID-19 can catalyze more profound resilience gains than the slow-onset experience of nuisance flooding, underscoring the importance of embedding resilience into broader crisis governance rather than relying solely on technical flood control. Planning agencies should integrate fine-grained urban morphology classifications into flood risk assessments to better capture household-level differentiation. These insights must be coupled with investments in the social infrastructure that proved effective during the pandemic, warning systems, collective organization, and targeted household support. More broadly, our findings contribute to debates on resilience in global megacities, where rapid urbanization, inequality, and exposure to compound risks converge. They demonstrate that resilience building must simultaneously address the chronic stresses of everyday flooding and harness the adaptive capacities revealed during systemic shocks, an approach with direct relevance for other coastal megacities facing similar trajectories of risk.

5. Conclusion

This study offers empirical evidence of the intersection between flood vulnerability and urban morphology at the household level in Ho Chi Minh City. First, the study recognizes that distinct patterns of flood vulnerability exist among household groups and their corresponding urban morphologies. Second, household groups are dynamic and depend on spatial and temporal factors, especially for identifying or categorizing 'vulnerable households,' which requires approaches grounded in a conceptual framework and research methodologies. Third, households improved their overall flood resilience with national and individual learning improvements. Moreover, with stronger political structures and improved collaboration, households may benefit from the long-term urban transition, not only from urban planning but also from climate adaptation.

This study provides a foundational step toward linking flood vulnerability with urban morphology. This is especially relevant for advancing the social learning process of what to act upon in the future, but also for flood risk models and urban simulation tools.

Building on the temporal and spatial patterns observed here, future work should integrate longitudinal household socio-economic and risk-hazard information, detailed urban morphology mapping, and causal inference methods to more accurately identify the underlying drivers of vulnerability and their root cause. In addition, there is a need to assess how well urban morphology types can capture shifts or reflect transitions in vulnerability driven by densification, informal expansion, or state-led redevelopment. These efforts should be complemented by deeper political-economic analyses to understand the structural inequalities facing urban transformation and vulnerable groups.

Ultimately, urban modernization and development partners, such as institutions and community-based organizations, are well placed to foster everyday resilience, especially for vulnerable groups, through information sharing and stronger household–municipality–national linkages. Across all actors, attention must be paid to preventing climate adaptation from reproducing dispossession or climate gentrification. Furthermore, inclusive investments in grey–green infrastructure, affordable housing retrofits, and socially attuned disaster governance can ensure that resilience building both reduces the chronic stress of recurrent nuisance flooding and leverages the adaptive capacities revealed during systemic shocks.

CRediT authorship contribution statement

Jiachang Tu: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Nigel K. Downes:** Writing – review & editing, Validation, Software, Methodology, Data curation. **Gebhard Warth:** Writing – review & editing, Validation, Software, Methodology, Data curation. **Olabisi Sakirat Obaitor:** Writing – review & editing, Methodology. **Andrea Reimuth:** Writing – review & editing. **Nivedita Sairam:** Writing – review & editing. **Do Ly Hoai Tan:** Data curation. **Hong Quan Nguyen:** Data curation. **Heidi Kreibich:** Writing – review & editing. **Matthias Garschagen:** Writing – review & editing, 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 A. Description of indicators

Indicator	Explanation	2020 (554 households)	2023 (554 households)
Education	The highest education level among the household members	−0: 3 (I don't know) −1: 11 (PhD or higher) −2: 219 (Master) −3: 36 (University bachelor) −4: 194 (Vocational training) −5: 64 (High school) −6: 26 (Secondary school) −7: 1 (Primary school) −8: 0 (No member never went to school)	−1: 4 (PhD or higher) −2: 1 (Master) −3: 13 (University bachelor) −4: 252 (Vocational training) −5: 177 (High school) −6: 71 (Secondary school) −7: 32 (Primary school) −8: 4 (No member never went to school)

(continued on next page)

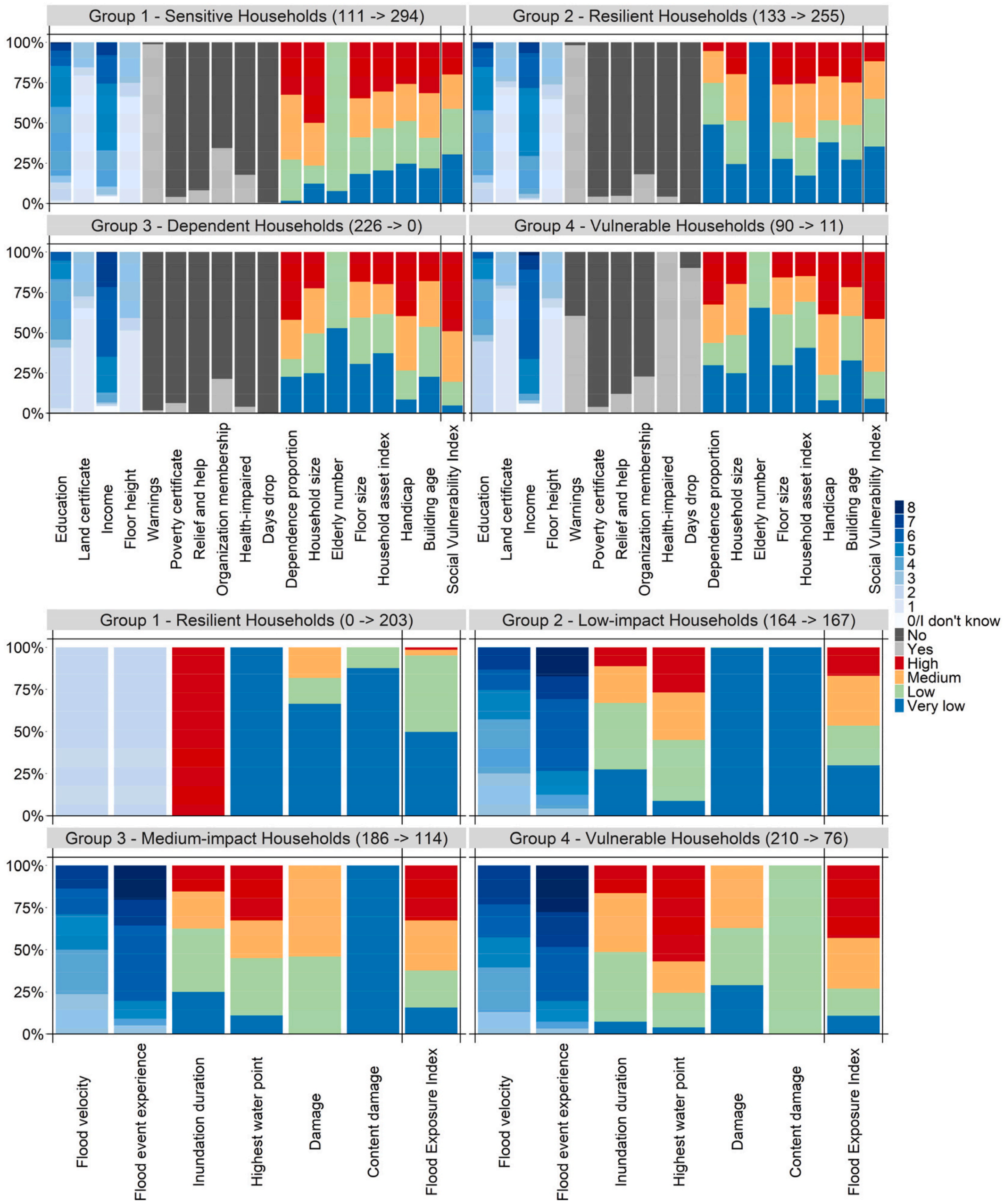
(*continued*)

Indicator	Explanation	2020 (554 households)	2023 (554 households)
Land Certificate	The ownership of land	−0: 2 (I don't know) −1: 409 (Yes) −2: 27 (Partly) −3: 116 (No)	−0: 2 (I don't know) −1: 409 (Yes) −2: 27 (Partly) −3: 116 (No)
Income	Monthly available income (million VND)	−0: 28 (I don't know) −1: 1 (>100 million VND) −2: 3 (80–100 million VND) −3: 5 (50–80 million VND) −4: 32 (30–50 million VND) −5: 124 (20–30 million VND) −6: 254 (10–20 million VND) −7: 102 (5–10 million VND) −8: 5 (1–5 million VND) −9: 0 (less than 1 million VND)	−0: 13 (I don't know) −1: 1 (>100 million VND) −2: 7 (80–100 million VND) −3: 29 (50–80 million VND) −4: 165 (30–50 million VND) −5: 277 (20–30 million VND) −6: 51 (10–20 million VND) −7: 11 (5–10 million VND) −8: 0 (1–5 million VND) −9: 0 (less than 1 million VND)
Floor Height	The relative height of the built floor	−1: 334 (House floor is higher) −2: 42 (Same level) −3: 178 (House floor is lower)	−1: 357 (House floor is higher) −2: 50 (Same level) −3: 147 (House floor is lower)
Warning	Flood warning information	-Yes: 281 -No: 273	-Yes: 554
Poverty Certificate	Below the poverty line or not	-Yes: 36 -No: 518	-Yes: 14 -No: 540
Relief and Help	Amount of support and help received after the floods	-Yes: 30 -No: 524	-Yes: 34 -No: 520
Organization Membership	Number of joint governmental and non-governmental organizations	-Yes: 129 -No: 425	-Yes: 147 -No: 407
Health-impaired	Ratio of household members injured, sick after floods	-Yes: 106 -No: 448	-Yes: 88 -No: 466
Days Drop	Number of days household members lost work or school days	-Yes:84 -No:470	-Yes:8 -No:546
Dependence Proportion	Ratio of household members under the age of 15 and over the age of 64	-High:163 -Medium:114 -Low:140 -Very low:137	-Medium:139 -Low:190 -Very low:225
Household Size	Number of household members	-Medium:197 -Low:228 -Very low:129	-High:177 -Medium:118 -Low:167 -Very low:92
Elderly Number	Number of household members over the age of 64	-Low:247 -Very low:307	-Low:265 -Very low:289
Floor Size	Floor area of the occupation per household member	-High:144 -Medium:133 -Low:142 -Very low:135	-High:149 -Medium:128 -Low:138 -Very low:139
Household Asset Index	Assets for household day-to-day life	-High:140 -Medium:138 -Low:137 -Very low:139	-High:139 -Medium:139 -Low:137 -Very low:139
Handicap	Ratio of household members who have disabilities	-High:188 -Medium:127 -Low:144 -Very low:95	-Medium:139 -Low:144 -Very low:271
Building Age	The number of years after built construction	-High:147 -Medium:140 -Low:137 -Very low:130	-High:147 -Medium:140 -Low:137 -Very low:130
Flood Velocity	Flood speed	−1: 79 −2: 170 −3: 116 −4: 96 −5: 93	−0: 201 −1: 110 −2: 88 −3: 52 −4: 46 −5: 57
Flood Event Experience	The average number of flood events per year	−1: 15 −2: 20 −3: 60 −4: 115 −5: 148 −6: 196	−0: 201 −1: 22 −2: 31 −3: 54 −4: 246 −5: 0
Inundation Duration	Minutes or hours that floodwater remains in the house	-High:141 -Medium:195	-Medium:248 -Low:31 -Very low:275

(*continued on next page*)

(*continued*)

Indicator	Explanation	2020 (554 households)	2023 (554 households)
		-Low:113 -Very low:105	
Highest Water Point	Highest water level from the built floor	-High:149 -Medium:157 -Low:146 -Very low:102	-Medium:140 -Low:152 -Very low:262
Damage	Repair cost of physical damage	-High:143 -Medium:176 -Low:96 -Very low:139	-Medium:159 -Low:118 -Very low:277
Content Damage	Repair or replace the damaged content	-Low:151 -Very low:403	-Low:155 -Very low:399



Appendix B. Household groups and changes in social vulnerability (top) and flood exposure (bottom) during the COVID-19 pandemic

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Data availability

The authors do not have permission to share data.

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