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Effective Adaptation Options to Alleviate Nuisance Flooding in Coastal Megacities—Learning From Ho Chi Minh City, Vietnam

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Key Points:

- The damage to residential buildings from pluvial nuisance flooding in Ho Chi Minh City is quantified based on an integrated risk assessment
- Expected Annual Damage and Annually Affected Households are combined into a new, people-centered indicator to evaluate adaptation options
- Private precaution and rainwater retention are two complementary, decentralized options to effectively support large-scale flood protection

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The economies and livelihoods of many coastal megacities are at serious risk from flooding, despite investments in flood defenses. For instance, in Ho Chi Minh City, the construction of a large-scale ring-dike has mitigated negative effects from storm surges, yet damage is still frequently caused by high-intensity rainfalls leading to nuisance flooding, which is responsible for the highest proportion of flood losses in the city today. Because sustainable flood risk management requires detailed spatial information, we analyze the local risk and its components based on a chain of novel models previously calibrated and validated for Ho Chi Minh City. Furthermore, we assess the effectiveness of two decentralized adaptation options, namely private precautionary measures and rainwater retention, for mitigating pluvial flooding. Our integrated risk assessment reveals that the approaches are complementary, which is a major advantage for their implementation. Implementation of both approaches has the potential to reduce the expected annual damage and the number of annually affected households by 16% and 56%, respectively. This is also reflected in a significant reduction of annual losses per household, which we propose as an additional, people-centered indicator of flood risk. Moreover, these measures are well-suited to strengthen citizen participation in risk reduction beyond top-down protection schemes. Complementing the ring-dike with decentralized adaptation options can therefore be seen as an effective and generic strategy to alleviate the impacts of nuisance flooding in coastal megacities, such as Ho Chi Minh City, and should be incentivized by decision-makers. Aside from hydrological and metocean site conditions, both the methodology and findings of this study are transferrable to any coastal megacity facing similar challenges.

Plain Language Summary

In many delta cities like Ho Chi Minh City in Vietnam, flooding continues to be a serious threat, despite investments in flood defenses. Even with a large-scale ring-dike in place, high-intensity rainfalls that lead to so-called nuisance flooding continue to cause considerable damage. To support effective risk management, we analyze flood risk and its components by combining various innovative models that were calibrated and validated for Ho Chi Minh City. Moreover, we assess two decentralized adaptation measures against flooding, namely private precautionary measures and rainwater retention. To evaluate the effectiveness of these adaptation options, we calculate the achievable reduction of annual flood losses and the number of affected households. We also calculate the annual loss per household as a new, more practical indicator of flood risk. Our analysis shows that the two assessed adaptation options are complementary and can significantly reduce flood impacts. By implementing these measures alongside the ring-dike, decision-makers can thus adopt an effective strategy to manage flood risk in Ho Chi Minh City and similar settings.

1. Introduction

Two major challenges converge in the risk of urban flooding, namely climate change and urbanization (Garschagen & Romero-Lankao, 2015). On the one hand, natural hazards from meteorological extremes are becoming more frequent in most regions of the world (IPCC, 2021). On the other hand, population growth, urban sprawl and densification are increasing the exposure to these hazards in many cities (IPCC, 2022). This is even more relevant since almost 900 Million people live in coastal cities and settlements within low elevation coastal zones subjected to rising sea levels (Haasnoot et al., 2021). The risk is particularly disproportionate in coastal cities with informal settlements that inherently exhibit higher vulnerability (Bangalore et al., 2019; Hallegatte et al., 2017; Roy et al., 2016). In the context of disaster risk reduction, it is important to understand that all three components—hazard, exposure and vulnerability—contribute to the local risk, but their share is highly site-specific (Garschagen et al., 2019; Winsemius et al., 2016). In order to plan suitable adaptation to urban flood risk, decision-makers can use this fact by addressing individual risk components (or their combinations) in due consideration of their local distributions. Where traditional large-scale protection schemes have already been implemented (top-down), risk reduction may specifically be complemented by locally led, that is, decentralized (bottom-up) adaptation which also enhances citizen participation in risk reduction (Westoby et al., 2021).

Assessments of flood risk and its individual components are typically performed using a combination of models, including hydrological and hydrodynamic models to assess hazards, combined with an exposure estimation approach and loss models (Moel et al., 2015). Flood hazard describes the probability and intensity of flood scenarios, which can be derived on the basis of measured time series, sometimes extended using stochastic weather generators (e.g., Falter et al., 2015; Nguyen et al., 2021). Discharges and hydrographs of a specific probability can also be derived from a hydrological simulation. Then, discharge is often transformed into inundation characteristics (e.g., water depths) using 1D/2D hydrodynamic simulations (Apel et al., 2016; Scussolini et al., 2017). To assess the exposure of built-up areas to flooding, land-use data sets (Scussolini et al., 2017) and more recently, OpenStreetMap (OSM, www.openstreetmap.org) and their derivative products have been used (Paprotny et al., 2020; Steinhausen et al., 2020). Flood hazards can be very local, for example, following the topography at a site. The use of low-resolution exposure, such as building stock and population models aggregated by district can thus skew the results of flood risk assessments (Smith et al., 2019). Therefore, it is crucial to obtain exposure at a high resolution, for example, a model describing structural values for each individual building.

To estimate flood damage and corresponding economic losses, several models of varying complexity have been developed and implemented—ranging from uni-variable depth-damage curves to multi-variable models (Gerl et al., 2016). Loss models use characteristics from the exposure data set to identify its physical vulnerabilities (Jaiswal et al., 2010). Multi-variable loss models with probabilistic predictions have the inherent capability to quantify uncertainty in the data and modeled processes and thus inform about the reliability of the model predictions (Rafiezadeh Shahi et al., 2023; Schoppa et al., 2020). To estimate the social impacts of flooding, in contrast, it is a common practice to estimate the number of affected people or households (e.g., Alfieri et al., 2017; Doocy et al., 2013; Neumann et al., 2015; Tellman et al., 2021).

The current scientific literature shows a lack of engagement with adaptation scenarios (i.e., representations and simulations of coherent assumptions on present and future adaptation options and pathways) and an evaluation of their effectiveness as well as feasibility and desirability (IPCC, 2022; van Maanen et al., 2023). Pivotal in the evaluation of adaptation strategies is their potential to reduce both economic losses and social impacts on the population, the latter ranging from mere disruptions of daily life to impairments of health. In Ho Chi Minh City (HCMC), Vietnam, the evaluation of flood adaptation options has been performed considering the expected annual damage in residential land-use for present and future (2050) climate scenarios (Couasnon et al., 2022; Scussolini et al., 2017). Even after the construction of large-scale flood protection (i.e., a ring-dike) in HCMC, high-probability rainfall events may lead to so-called nuisance flooding, that is "low levels of inundation that do not pose significant threats to public safety or cause major property damage, but can disrupt routine day-to-day activities, put added strain on infrastructure systems such as roadways and sewers, and cause minor property damage" (Moftakhari et al., 2018, p. 1). Such events have shown to be responsible for the highest share of long-term damage and losses (Scheiber, Hoballah Jalloul, et al., 2023). In addition to the ring-dike, decentralized measures such as rainwater retention were found to reduce both flood severity and the overall number of affected small and medium enterprises (Scheiber, David, et al., 2023). However, so far there is no quantification of the economic and social impacts of urban inundations, especially from rain-induced nuisance flooding in HCMC. Furthermore, no studies are known to investigate and deliberately compare the effectiveness of decentralized adaptation options on the whole.

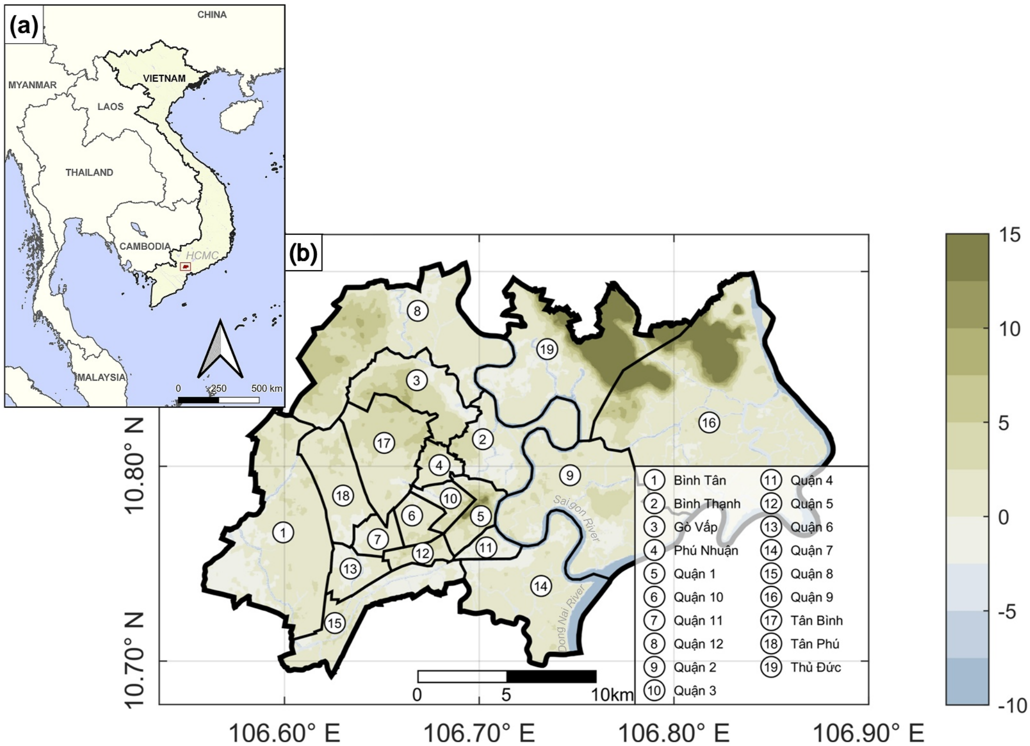

Figure 1. STUDY AREA. (a) Location of Ho Chi Minh City (HCMC) in the South of Vietnam. The Dong Nai River connects the HCMC metropolitan area with the coast. (b) The tributary Saigon River crosses the urban districts from north to south, dividing the city into 16 western and 3 eastern districts, which were consolidated in the sub-city Thu Duc in 2021. The underlying color map represents the surface elevation of HCMC in meters above sea level (mASL).

In this study, we bring together advances in probabilistic loss modeling along with a validated flood hazard model and object-level exposure data sets to evaluate the effectiveness of decentralized adaptation measures. In particular, we aim to answer the following research questions.

1. How are flood risk and its three components—hazard, exposure and vulnerability—distributed across HCMC?
2. What is the effectiveness of decentralized adaptation options, such as private precautionary measures and rainwater retention, in reducing flood risk?
3. How can flood risk indicators—here, the estimated annual damage to residential buildings, the number of annually affected households and the expected annual loss per household—influence decision-making in adaptation planning?

The description of the study site is provided in Section 2. The data requirements and methods of the integrated flood risk assessment are explained in the following Section 3. Subsequently, findings on the spatial distribution of flood risk and its components as well as possible reductions due to decentralized adaptation options are presented in Section 4, which also offers a discussion of inherent limitations and future research objectives. Conclusions with regard to political and scientific implications are presented in the final Section 5.

2. Study Site

A prime example of the complex interplay of physical and socio-economic drivers of flood risk in coastal cities is HCMC in Southern Vietnam (Hallegatte et al., 2013; Hanson et al., 2011). Located at the northern fringe of the Mekong delta and about 50 km from the coastline, HCMC is one of the most important economic hubs in Southeast Asia and home to some 9 Million people (Vietnam Census, 2019). The city is regularly facing floods that are driven by extreme water levels of the adjacent Dong Nai and Saigon estuaries (cf. Figure 1). Except for a small area in the north of Thu Duc, HCMC can be defined as a low-elevation coastal zone with a land surface elevation of less than 10 m above mean sea level. The urban areas of HCMC are first of all affected by storm surges which are becoming more frequent with absolute sea level rise (Downes & Storch, 2014; Tran Ngoc

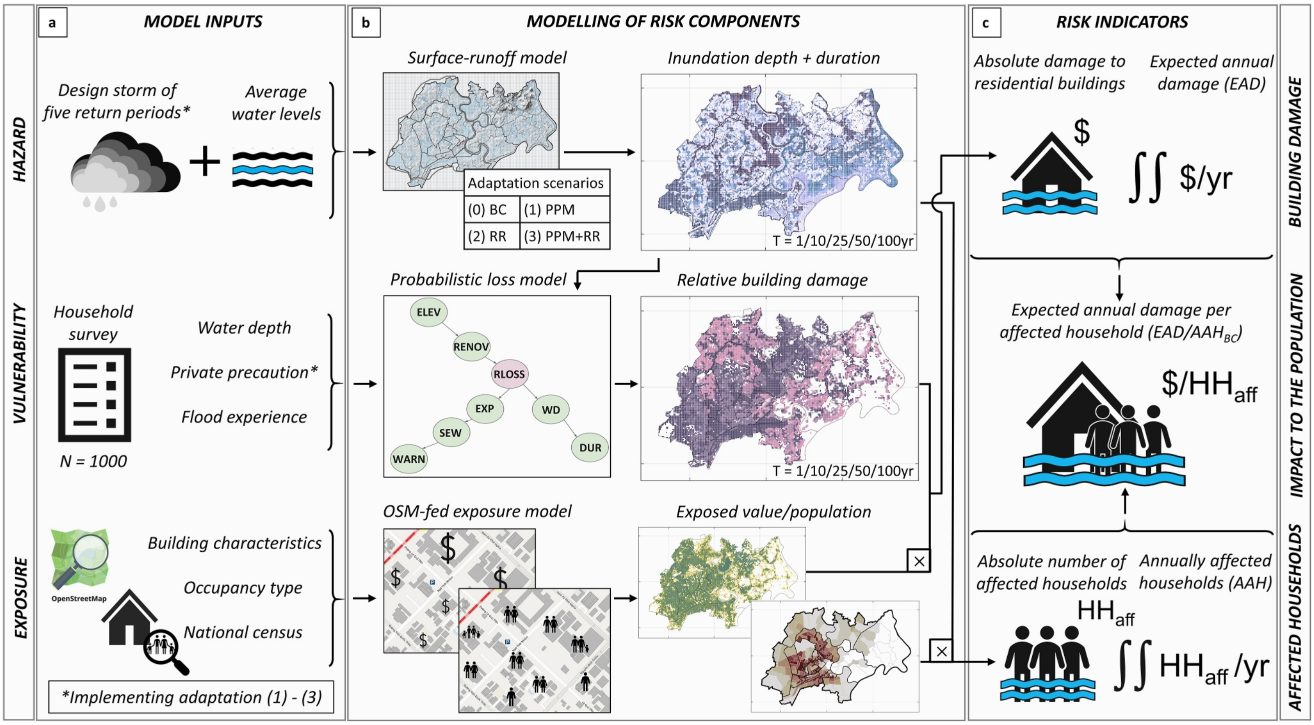

Figure 2. WORK FLOW. The integrated risk assessment distinguishes between three components of flood risk: hazard, vulnerability and exposure. Based on multiple model inputs (a), each risk component is analyzed in an individual modeling approach (b). The effectiveness of two adaptation options is evaluated based on the potential reduction of three risk indicators (c).

et al., 2016). Unsustainable groundwater withdrawals and soil compaction, however, have caused considerable subsidence across HCMC and thus relative sea level rise as well (Duffy et al., 2020; Minh et al., 2015; van Leeuwen et al., 2016). What is more, an ever-increasing percentage of paved surfaces has led to a significant increase in surface runoff regularly causing backwater effects in the outdated drainage system (Downes & Storch, 2014; Eckert, 2023; Nguyen et al., 2019; Tran Ngoc et al., 2016). Especially, the flood-prone areas along the Saigon River are subjected to rapid urban sprawl, in the context of which the most vulnerable parts of the population are exposed to the highest risk (Cao et al., 2021; Lasage et al., 2014; Storch & Downes, 2011).

Barely any pluvial flood event in HCMC jeopardizes the lives of its citizens today, but public life is regularly affected by inundations in the order of 10–50 cm (Duy et al., 2018). Even though the term is often referring to inundation depths in the range of 3–10 cm (Moftakhari et al., 2018), this situation can be described as nuisance flooding given how regularly it occurs and how accustomed residents have become to disruptions of their day-to-day life, literally "living with floods" (cf. UNESCO-IFI, 2007). After the construction of large-scale protection against extreme storm surges and in view of the aspired modernization and development of the city, nuisance flooding is the next cause of flood-related risk concerning the population and political elite. Ongoing trends will only exacerbate such problems for the local communities in the future, requiring well-informed and sustainable adaptation planning (Cao et al., 2021; Vachaud et al., 2019).

3. Materials and Methods

3.1. Components of Flood Risk

Covering about two thirds of all urban structures, residential buildings are the most common building type in the metropolitan area and their total value accounts for the largest part of building values (GEM, 2018). Consequently, the integrated risk assessment in this study focuses on the quantitative estimation of monetary losses to residential buildings as well as the number of affected private households. Our analysis distinguishes between three components of flood risk: hazard, vulnerability and exposure (see Figure 2). Based on multiple input variables (Figure 2a), all risk components are analyzed in an individual modeling approach (Figure 2b).

Specifically, these are a schematic surface-runoff model to estimate inundation depths, durations and the number of flood-prone households, a machine learning-based approach to estimate the relative damage to residential buildings as well as a workflow to quantify average building values from open-access data. The modeling outputs are used to compare two adaptation options (PPM: private precautionary measures; RR: rainwater retention) as well as their combination (PPM + RR). The effectiveness of these options is evaluated based on the potential reduction of three risk indicators (Figure 2c), that is, the absolute damage to residential buildings, the absolute number of affected households as well as the damage per household for which the two previous values are divided. This workflow is summarized in Figure 2 and the individual components are described below.

Flood Hazard is characterized by maximum inundation depths and durations during five rain events with different return periods (i.e., 1, 10, 25, 50, 100 years) and under present climatic conditions. These spatial characteristics were generated by a two-dimensional surface runoff model, which was implemented in HEC-RAS (Hydrologic Engineering Center River Analysis System). This hydro-numerical setup was previously calibrated and validated against locally reported inundation hotspots (Scheiber, Hoballah Jalloul, et al., 2023). The model was used to simulate a set of rain-induced flood events assuming different adaptation scenarios. More specifically, the volume of a 3-hr design storm was adjusted regarding its return period and combined with average tidal water levels and mean river discharge as hydrological boundary conditions. It should be noted that this setup was primarily designed for a conceptual comparison between the effectiveness of different adaptation options, but does not allow for an unconfined hindcasting of past inundation events, since any effect of the local drainage system was neglected as is common practice in conceptual flood adaptation modeling (e.g., Scussolini et al., 2017).

Flood Vulnerability is represented by a flood loss model. In order to assess the relative damage to individual residential buildings (in %), the Bayesian Network-based Flood Loss Estimation Model (BN-FLEMO$_\Delta$) (Rafiezadeh Shahi et al., 2023) is applied. This multivariable model was trained and validated using a comprehensive household survey (N = 1,000). The survey targeted flood-affected households from diverse socioeconomic backgrounds in four different urban districts of HCMC and included questions on flood experience, early warning protocols and private precautions over the last 10 years (Vishwanath Harish et al., 2023). BN-FLEMO$_\Delta$ returns probabilistic damage/loss estimates, wherein it allows decision-makers to quantify not only building losses but also model uncertainties (Rafiezadeh Shahi et al., 2023).

Economic **Exposure** of private households was considered in terms of the (constant) reconstruction cost per residential building. The HCMC data set was created for the purpose of this study using OSM buildings with attributes extracted on 1 July 2023. Reconstruction costs were deduced based on a comparison of the OSM buildings' attributes with the building assets of the Global Exposure Model, which defines an average structural cost for each building type (Yepes-Estrada et al., 2023). In areas where OSM was identified to be incomplete in terms of the building data, the number of buildings was estimated using the Global Human Settlement Layer (European Commission, 2022) and structural costs were added as average from the Global Exposure Model (GEM, 2018). The population density was derived from demographic data, that is, population and household densities per ward obtained in the context of the recent Vietnam Census (2019).

Absolute flood losses are the product of building reconstruction values (in $) obtained from the exposure data set and relative building damage (in %) as a function of local water depth and other influencing factors estimated by BN-FLEMO$_\Delta$. Assuming social impacts wherever streets and adjacent ground floors are considerably inundated, the number of affected households is quantified by multiplying the absolute number of households per ward (irrespective of their number of floors) with the proportion of inundated cells. Both damage to residential buildings and the number of affected private households are computed for flood events with different return periods and then integrated over time yielding average annual estimates. As a synthesis of these two risk indicators, flood impacts on the population are finally expressed as expected annual damage per affected household.

3.2. Adaptation Scenarios

To reduce flood-related losses, the HCMC administration decided on a large-scale flood protection project in 2008, including a ring-dike around all urban districts west of the Saigon River as well as six sluice gates and pumping stations at the outlets of the largest inner-city canals ("Decision No. 1547/QĐ-TTg," p. 2008). Given that the corresponding construction works are almost finished at this point in time, this setting was taken as the base case (0). The main purpose of this project is to protect the central urban districts of HCMC from extreme tidal water levels and storm surges. But, since regular nuisance flooding is caused by surface runoff from precipitation, sustainable flood risk management needs additional and decentralized adaptation strategies. One way of complementing the large-scale ring-dike project are (1) private precautionary measures (PPM), which are typically realized in the form of elevated building entrances or stop logs but also by raising valuables to higher floors (wet-proofing). Given that this prime example of decentralized adaptation aims to reduce the relative damage to individual buildings, it is considered as an offset in the probabilistic loss model, that is, the first 30 cm of water depth do not lead to any damage to buildings or inhabitants as observed for PPM-applying households during the household survey described by Vishwanath Harish et al. (2023) and reported by previous studies (e.g., Scussolini et al., 2017). In this numerical representation, PPM does not allow for any volumetric changes in the surrounding area. Potential negative effects caused by the surplus of water (blocked from protected houses) are thus not covered in the model, which makes it more comparable to pure wet-proofing. In our study case, it was assumed that every other household across the city implements this measure in addition to any existing adaptation in the base case. A second decentralized adaptation option is (2) rainwater retention (RR). The way these buffer volumes reduce the local hazard is modeled in terms of an attenuated hyetograph, that is, rainfall is not directly converted into surface runoff, but initially reduced in depth (by an absolute offset, i.e. the maximum retention capacity) and then emitted over a prolonged time span (cf. Scheiber, Hoballah Jalloul, et al., 2023). In this way, it mimics the working principle of throttled discharge from many decentralized basins or green roofs, assuming again that an additional +50% of all households possess or utilize such elements. Besides their comparably decentralized character, these two adaptation options were selected because of their very different concepts and inherent working principles, that is mitigating losses from runoff versus mitigating runoff itself, and their potential to stimulate citizen participation. Finally, both options were simulated in (3) a combined adaptation scenario (PPM + RR).

3.3. Evaluation of Adaptation Scenarios

The expected damage to (residential) buildings critically depends on rain intensity or, in the present case, the probability or return period of the 3-hr design storm. A well-established means to estimate monetary losses from events across a range of return periods is the Expected Annual Damage (EAD). The EAD is the sum of all damage values (d) caused by a rain event (N) multiplied by its respective probability of occurrence per year ($1/T$), which can be expressed as follows:

$$EAD = \int \left(d(N_{D,T}) \cdot \frac{1}{T} \right) dT$$

where the hyetograph of each rain event N follows the 3-hr duration (D) design storm, while its volume is determined by a selection of return periods (T). With this study focusing on the impacts of nuisance flooding rather than extreme events, floods corresponding to return periods of 1, 10, 25, 50 and 100 years were selected to compute EADs. This range was considered a representative spread of return periods, acknowledging that the upper end ($T_R = 100$ years) is a common threshold separating regular from extreme events (Merz et al., 2021) yet high-probability events affect risk curves much more substantially than those of low probability (cf. Ward et al., 2011). The resulting EADs were later aggregated on ward, district and municipality levels. Moreover, inundation maps from the hydro-numerical model were used to determine the average number of households considerably affected by flooding. This was done by multiplying the number of households per ward (HH_{tot}) by the proportion of areas (p_{aff}) that experience considerable flood water levels (h). In this connection, nuisance flooding was considered to start at inundation depths above the (arbitrary) threshold of 10 cm. By analogy to the EAD, event-specific impacts on people can be integrated to estimate the number of annually affected households (AAH):

$$AAH = \int \left(HH_{\text{tot}} \cdot p_{\text{aff}} \, (h(N_{D,T}) > 10\ cm) \cdot \frac{1}{T} \right) dT$$

In the present study, both EAD and AAH are designed as indicators to identify risk hotspots for prioritization of in-depth analyses and subsequent investments. Moreover, these metrics allow for a quantitative comparison of adaptation options based on their potential to reduce specific flood impacts locally. In order to illustrate the potential of decentralized adaptation beyond city-wide damage summation, we develop a combination of both

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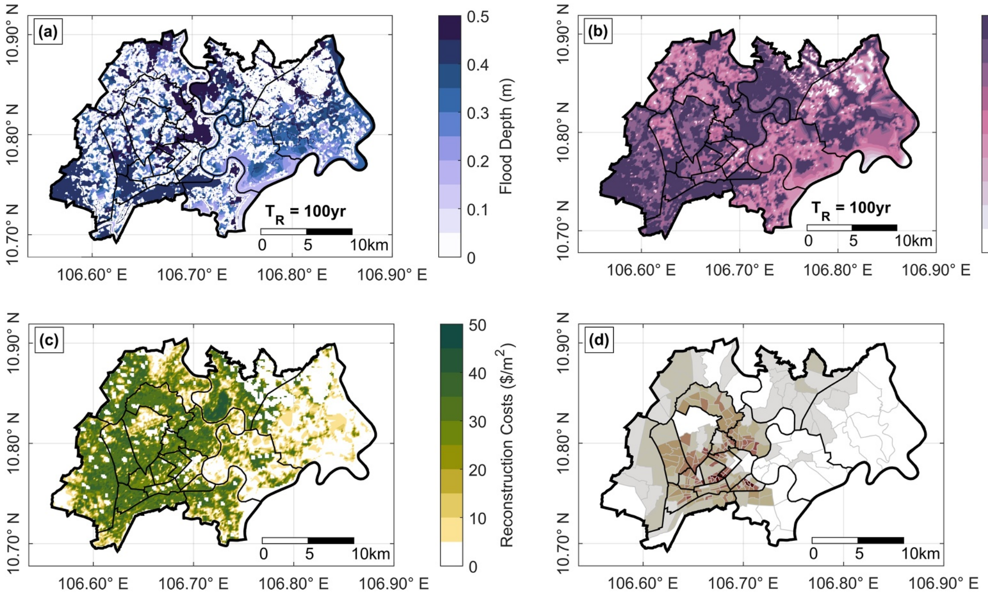

Figure 3. RISK COMPONENTS. (a) Flood hazard in terms of inundation extents and maximum water depths due to a rain event with a 100-year return period ($T_R = 100$ years). (b) Relative damage to residential buildings due to the same inundation scenario. (c) Economic value of residential buildings in terms of total reconstruction costs and (d) exposure of people in terms of the ward-aggregated household density. Please see Figure 1 for an overview of district names and locations in HCMC. The depicted data sets can be retrieved from Zenodo (Scheiber, 2024b).

metrics, in terms of their ratio EAD/AAH. This combined indicator is people-centered and hence can be of practical use in making socially equitable decisions.

4. Results and Discussion

4.1. Spatial Distribution of Flood Risk Components

Figure 3 illustrates the spatial distribution of risk components in HCMC considering a 100-year rain event without further adaptation. In particular, inundation hotspots are located in direct proximity to the largest receiving canals as well as some untrained parts of the Saigon River (see Figure 3a). In these areas, extreme precipitation volumes can overload the local drainage system and cause adverse backwater effects. For the exemplarily depicted $T_R = 100$ years scenario, which is the highest return period considered, this leads to (maximum) inundation depths with a median of 0.33 m and an interquartile range (IQR) of 0.22–0.44 m (excluding areas without flooding). However, other than these values might suggest, the statistical distribution of inundation depths is not normally distributed but skewed toward smaller inundation depths (moment coefficient of skewness after Pearson: $\gamma_1 = +3.4$). The pattern of relative building damage depicted in Figure 3b has a strong resemblance with water depths in Figure 3a. This does not come as a surprise, given that traditional loss models use water depth-damage relationships to predict flood losses (Gerl et al., 2016). Since flood experience was empirically associated with raised levels of awareness and preparedness in HCMC (Vishwanath Harish et al., 2023), flood losses from the multi-variable loss model BN-FLEMO$_\Delta$ are also negatively influenced by past flood experience and private precaution, characterized by the elevation of each building (cf. Figure 2; Rafiezadeh Shahi et al. (2023)). Based on this approach, the lowest relative damage occurs in District 2, east of the Saigon River (see Figure 3b). The highest relative damage values are observed in Thu Duc, Binh Thanh and Binh Tan (in descending order). For the depicted 100-year event, the average damage to residential buildings amounts to 20.7% of the total reconstruction costs.

Exposed to the adverse effects of flooding are, on the one hand, residential buildings whose value can be quantified in terms of total reconstruction costs ($/m^2) (see Figure 3c) and, on the other hand, households which are here expressed through household density (10³ HH/km^2) (see Figure 3d). The sub-city Thu Duc east of the Saigon River shows the least exposure in terms of residential building values and household density. The median absolute value of residential buildings in HCMC is 29 $/m^2 and the IQR is between 12 and 34 $/m^2, whereas the median household density is 7,300 HH/km^2 with an IQR between 3,900 and 10,000 HH/km^2.

4.2. Effectiveness of Flood Risk Adaptation Scenarios

The integrated risk analysis covers flood scenarios from a range of return periods and compares the risk indicators EAD and AAH under different adaptation scenarios. Both indicators highlight flooding hotspots across the study area and illustrate the potential reduction of flood risk due to the implementation of three different adaptation options. Figure 4 juxtaposes the EAD map of the base case scenario (0) and the differences of the EADs under the three adaptation scenarios (1)–(3) in relation to this base case (also see Figures 3c and 3d for a comparison with reconstruction costs and household densities). The choropleth map in Figure 4a shows a mainly homogeneous distribution of EADs to residential buildings (aggregated on ward level). 85% of the wards are characterized by EADs below 10 Million $, while only three of all 259 wards have values higher than 30 Million $. Two of these wards are located in Binh Tan and one in Thu Duc, which also lead the EAD ranking (see Figure 4a, bottom) followed by District 12. For the base case, the total Expected Annual Damage (EAD_{tot}) for HCMC amounts to 1,418.1 Million $. Owing to the probabilistic nature of the applied loss model, the uncertainty of this estimate can be quantified with an IQR of 756.7–2078.4 Million $. In general, all wards experience negative EAD changes, that is, a reduction in EAD, irrespective of whether private precautionary measures (PPM) (see Figure 4b) or rainwater retaining (RR) solutions (see Figure 4c) were implemented. Even though this could be expected from sustainable adaptation planning, it is an essential finding that none of the two options causes a deterioration of the flooding situation in any ward. In fact, the total ΔEADs for PPM (1) and RR (2) are of the same order of magnitude with prevented EADs of 114.4 Million $ and 120.9 Million $, respectively. It is worth noting that (1) PPM shows its highest reduction potential for the three most flood-prone districts, while (2) RR is most effective in districts with moderate EADs. Given that the spatial pattern for (3) PPM + RR resembles the pattern for (1), it can be inferred that private precaution (in its considered form) is better suited to tackle flood risk at its origin, that is at the level of affected households (see Figure 4d). Still, the total ΔEAD of 227.2 Million $ for the combined approach is very close to the summation of the individual EAD reductions, highlighting that decentralized RRs are a valuable and effective option to complement PPM.

In comparison with the spatial distribution of absolute EADs, the choropleth map of AAHs in Figure 5a paints a similar, yet less homogeneous, picture. The most impacted districts with regard to the number of affected households are Binh Tan, Thu Duc and District 12 (in descending order). In the case of Binh Tan, an absolute number of 117,000 households corresponds with just about 50% of the local population. The least impacted district, in turn, is District 1 with only 13,000 (33.6%) households affected. Overall, the analysis suggests that on average 842,000 households in HCMC are annually affected by inundations of more than 10 cm, which amounts to 41.5% of the population. As Figure 5b suggests, the number of affected households could be reduced by 403,000, if PPM were implemented to the outlined extent, whereas RR reduces this number by only 111,000 (see Figure 5c). In other words, PPM reduces the number of affected households three to four times as effectively as RR. Although both adaptation strategies are most effective in Binh Tan, nominal improvements regarding the number of affected households in Thu Duc, the second-most flood-prone district, are limited. The sum of the two individual AAH reductions for adaptation options (1) and (2) is more than 10% higher than in the simulated combined case (3), implying that the suggested complementarity is less clear-cut than compared to building losses (i.e., EADs).

4.3. Relevance of Flood Risk Indicators

A quantitative summary of the key results is given in Table 1 including total EADs, AAHs and their corresponding reduction rates. Most essentially, adaptation option (3) the combined approach has the potential to reduce the expected annual damage and the number of annually affected households by 16% and 56%, respectively. An additional indicator of flood risk is the EAD per affected household (EAD/AAH_{BC} in $), where AAH_{BC} refers to the number of households affected in the base case, in order to ensure comparability across the adaptation scenarios. While the total EADs suggest comparable effectiveness of adaptation scenarios (1) PPM and (2) RR, the corresponding total AAH reduction rates diverge. Taking the base case as a reference, the EAD/AAH_{BC} suggests an average annual flood loss of 1,559 $ per affected household with a local maximum of 2647 $ in Thu Duc (cf. Supplemental Material, Figures S3 and S4 in Supporting Information S1). Our simulations suggest that average losses per household could be reduced by 131 $ if PPM were implemented and by 151 $ in the case of RR.

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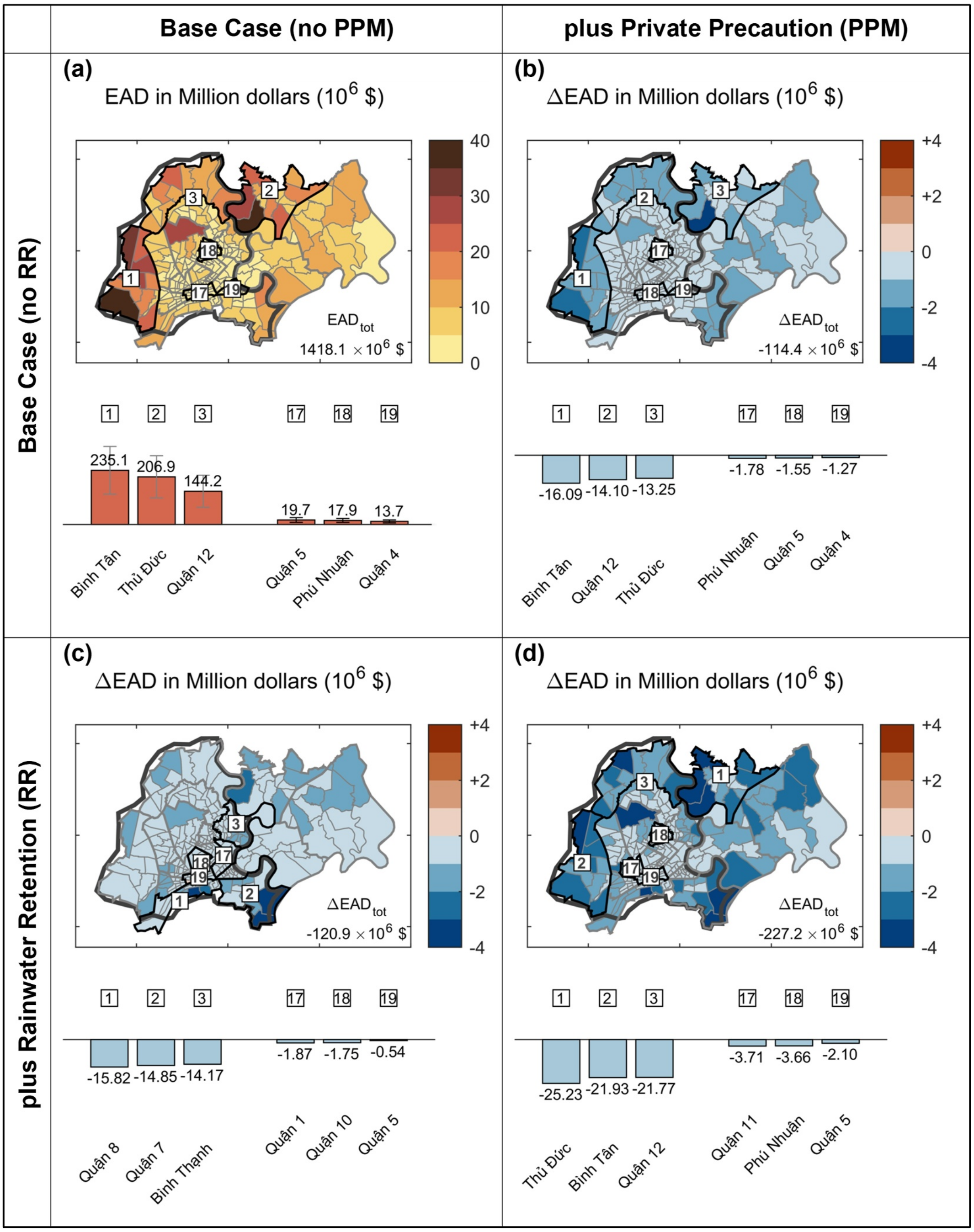

Figure 4. BUILDING DAMAGE. Ward-aggregated choropleth maps of (a) the Expected Annual Damage (EAD) to residential buildings including its uncertainty bounds for the base case (0) as well as (b)–(d) its potential changes (ΔEAD) in adaptation scenarios (1)–(3). All panels are complemented by a district-aggregated ranking at the bottom to highlight the three regions with the highest and lowest flood impacts, respectively. EADs are generally aggregated on the level of wards, which are depicted as light gray lines. However, the ranking below focuses on urban districts, which are highlighted by bold black lines, if contained in the ranking. Both EAD and ΔEAD are expressed in Million dollars (10^6 $). The depicted data sets can be retrieved from Zenodo (Scheiber, 2024b).

This translates into an effective reduction of flood impacts by 8.4% (PPM) and 9.6% (RR), respectively, supporting the idea that both strategies are similarly effective. A reduction rate of 17.5% for scenario (3) finally corroborates the high complementarity of the two adaptation options in reducing the impacts of nuisance flooding. A map of the spatial distribution of EAD/AAH_{BC} values and their possible reduction can be found in the

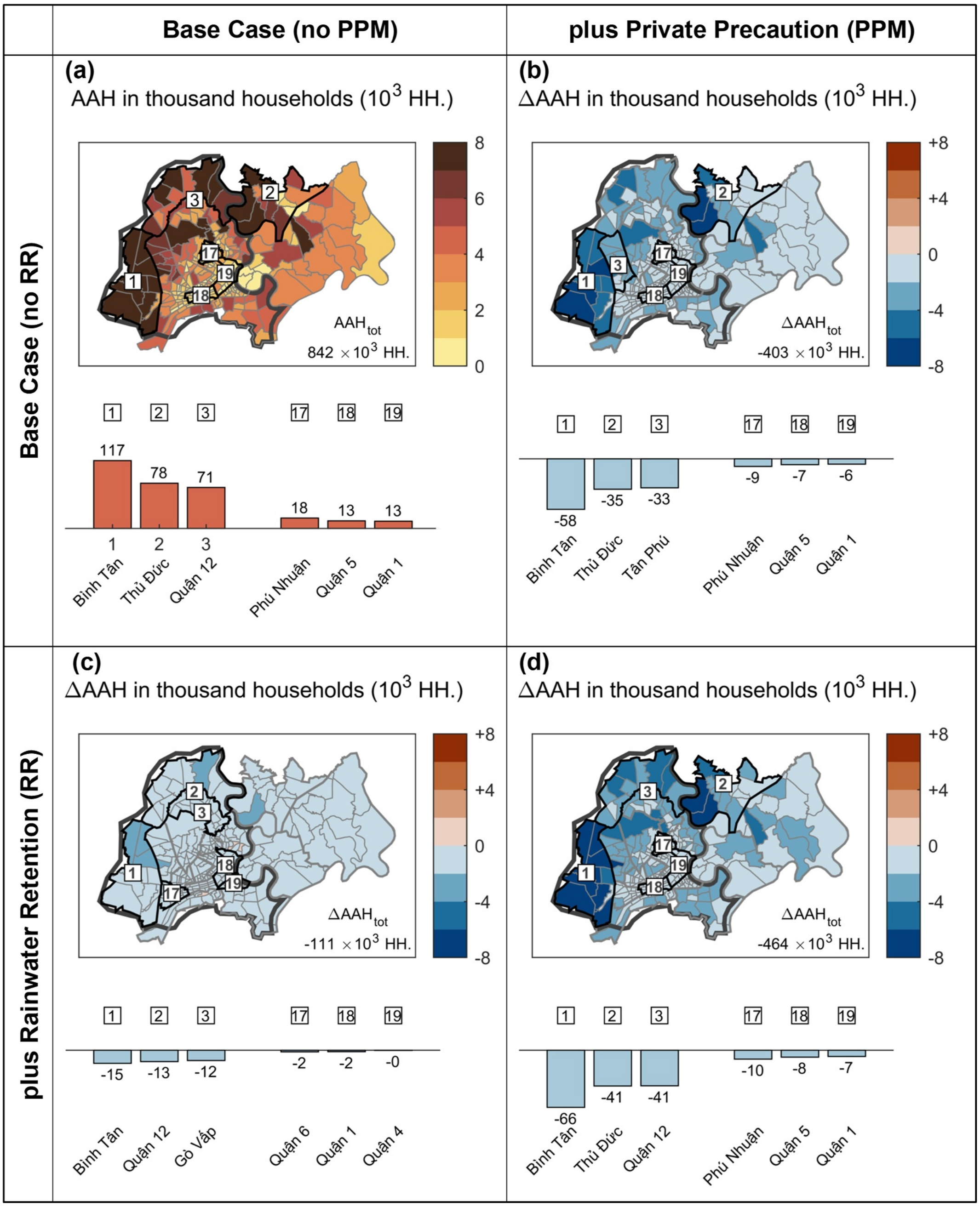

Figure 5. AFFECTED HOUSEHOLDS. Ward-aggregated choropleth maps of (a) the Annually Affected Households (AAH) for the base case (0) as well as (b)–(d) its potential changes (ΔAAH) in adaptation scenarios (1)–(3). All panels are complemented by a district-aggregated ranking at the bottom to highlight the three regions with the highest and lowest flood impacts, respectively. AAHs are generally aggregated on the level of wards, which are depicted as light gray lines. However, the ranking below focuses on urban districts, which are highlighted by bolder black lines, if contained in the ranking. Both AAH and ΔAAH are expressed in thousands of households (10^3 HH). The depicted data sets can be retrieved from Zenodo (Scheiber, 2024b).

Supplemental Material (cf. Figures S3 and S4 in Supporting Information S1). All output data are furthermore available at Zenodo (Scheiber, 2024b).

In previous studies on HCMC, the most common indicator to evaluate flood adaptation was the EAD and its respective reductions (e.g., Couasnon et al., 2022; Scussolini et al., 2017). This means following a narrow,

Table 1
Summary of Flood Impacts in Terms of Expected Annual Damage to Residential Buildings (EAD), Annually Affected Households (AAH) and the EAD per (Initially) Affected Household (EAD/AAH$_{BC}$) As Well As the Potential Reduction of These Three Indicators of Flood Risk in the Assessed Adaptation Scenarios (1)–(3)

	(0) Base case	(1) Private precaution	(2) Rainwater retention	(3) Combination
EAD (Million $)	1,418.1	1,303.7	1,297.1	1,189.9
Reduction rate		−7.55%	−8.04%	−15.62%
AAH (Million HH_{aff})	0.842	0.436	0.732	0.374
Reduction rate		−48.22%	−13.06%	−55.58%
EAD/AAH$_{BC}$ ($/$HH_{aff}$)	1,559	1,428	1,409	1,287
Reduction rate		−8.4%	−9.62%	−17.45%

exclusively economic perspective, which was shown to disadvantage the poorer parts of the population (Kind et al., 2020). In contrast, the here presented assessment is much more comprehensive as it integrates various indicators of risk that represent both an economic view on (monetary) building losses and a social view on affected population and households. In this regard, the additional consideration of the expected annual loss per affected household is a more practical and people-centered way of describing flood impacts. This risk indicator allows for a much-needed and socially more sensitive description of the benefits to be gained by adaptation (Hino & Nance, 2021). Especially in the context of decentralized adaptation, this can support decision-makers on all scales to balance priorities based on the aforementioned perspectives. Nevertheless, other perspectives on adaptation effectiveness, such as the rather intangible benefits of public participation, unhindered traffic or ecosystem services are still not represented and may be part of future research.

4.4. Plausibility of Results and Limitations

A comparison with previous research on annual flood losses in HCMC shows that the presented EAD estimates are generally plausible. For instance, Hallegatte et al. (2013) calculated flood losses in major coastal cities and quantified the EAD (then called average annual loss) in HCMC to be 104 Million $ in 2005, but this value was predicted to increase to 1,743–1,953 Million $ until the year 2050. Scussolini et al. (2017) estimated the EAD from storm surges (in all three economic sectors) to be 1,140 Million $. The corresponding EAD changes achievable through various adaptation options ranged from +21% to −86%. A follow-up study by Couasnon et al. (2022) corrected the initial EAD estimate to be 1,020 Million $ after conducting a statistical analysis on the co-occurrence of coastal and riverine extremes. Even though a direct comparison with these earlier studies is complicated—if not questionable—considering the different model schemes and research scopes, it can be summarized that the computed EAD of 1,418 Million $ ranges in the same order of magnitude, notwithstanding exchange losses and a focus on residential buildings. It is noteworthy, though, that the reductions from adaptation are significantly smaller here (cf. Figures S3 and S4 in Supporting Information S1). Loss estimations are generally associated with high uncertainty, which is due to the large local heterogeneity and the prevailing stochasticity of the damage processes, as is often neglected in risk assessments. The probabilistic loss model utilized in this study is able to quantify the uncertainty range of EAD estimates (756.7 Million $ < IQR < 2078.4 Million $). Also, the surface runoff model is constrained by the limited availability of information on the boundary conditions (e.g., topographic, bathymetric, hydrological data) and existing technical facilities (e.g., drainage system, private flood protection, etc.). What is more, exposure values were estimated based on a global framework leaving limited room for case-specific particularities. Even though the presented results should not be mistaken with a case-specific hindcast (or ex-ante prediction) of absolute water levels and local building losses, the presented multi-perspective analysis provides highly relevant information on the spatial patterns of flood risk for private households including the identification of hotspots as well as on the mitigation potential of different adaptation strategies.

4.5. Transferability and Future Research

In their "Report on Impacts, Adaptation and Vulnerability", the IPCC emphasizes the need to develop robust and comparable metrics for reporting damages and losses from climate change impacts, highlighting the necessity for better quantification of the effectiveness of adaptation options and how to prioritize them at national and regional levels (IPCC, 2022). Against this background, the case of rain-induced nuisance flooding in HCMC is an informative example of the changing adaptation requirements arising from local governance, urbanization and climate change, and of the need to combine measures of large-scale centralized adaptation (like the ring dike protecting the center of HCMC) with small-scale decentralized approaches (like private precautionary measures or rainwater retention). Urbanization trends (i.e., concentration of exposed values and vulnerable population groups) and resulting challenges for flood adaptation (e.g., governance in informal settlements, uncontrolled land subsidence etc.) are very similar across many coastal megacities, particularly in the global south (Barragán & Andrés, 2015; Magnan et al., 2023; Wannewitz et al., 2024). Moreover, HCMC's location in the low-elevation coastal zone between the Mekong delta and the Dong Nai and Saigon estuaries make the physical setting comparable to many other coastal cities, particularly in Southeast Asia, for example, Jakarta or Bangkok (Kulp & Strauss, 2019). Adaptation planning can make use of this similarity by applying and customizing the generic adaptation pathways available for the most common coastal archetypes (Haasnoot et al., 2019). Considering, additionally, that most of the utilized data stem from open-access sources, the methodology, results metrics and findings of this study are readily transferable to a great range of other coastal megacities particularly in developing countries and emerging economies.

Future risk assessments would benefit from additional and more accurate input information, particularly in relation to the social vulnerability and adaptive capacity of local residents but also other stakeholders, for example, from the public sector (cf. Nguyen et al., 2019). For example, flood impacts on physical health, mental health or income loss were not considered in this study but will be analyzed in upcoming publications. In addition, the scenario analysis will need to be expanded in order to substantiate recommendations for adaptation planning. Most importantly, HCMC will, like many other cities, undergo major changes in its morphology (notably sprawl and further densification) as well as its demographic and economic profile in the next years and decades, whilst climate change adaptation will need to unfold. Hence, loss models need to be linked to urban growth and change modeling in close collaboration with local stakeholders to assess the future urban development pathways possible under different assumptions on socio-economic development (Reimuth et al., 2023; Zwirglmaier et al., 2024). Such scenario assessment will allow for an evaluation of integrated adaptation pathways over time, in which large-scale infrastructure will need to be combined with different levels of small-scale adaptation as scrutinized here. While the current study assumes the same intensity of small-scale measures throughout the city, the actual implementation of such measures will most likely be different under different socio-economic pathways (comparing e.g. high poverty reduction with only modest poverty reduction) and in different parts of the city (e.g., its emerging middle-income neighborhoods vs. its low-income quarters). Scenario work is underway to capture these heterogeneities in space and time in order to allow for more realistic simulations and a future-proofing of adaptation policies under consideration. In that sense, the current study presents an important step within a larger endeavor to improve risk and adaptation assessments for HCMC and other delta cities facing similar challenges.

5. Conclusions

This study goes beyond previous investigations of risk as it is based on a chain of novel models that were calibrated and validated for the case study region using local inundation reports for hazard mapping and object-specific data with respect to exposure and probabilistic loss models. We assess two decentralized adaptation options and their combination to complement the large-scale ring-dike to address rain-induced nuisance flooding, which was previously neglected yet has become the next priority of risk reduction efforts in HCMC. However, measuring the effectiveness of adaptation options solely using the EAD results in a purely economic perspective that demonstrably penalizes the poorer parts of the population (Kind et al., 2020). In order to overcome this limitation, our assessment integrates two indicators of flood risk (EAD and AAH) that represent both an economic view on (monetary) building losses and a social view on the affected population and households. The EAD/AAH risk indicator allows for a much-needed socially sensitive description of the benefits of adaptation, enabling actors on all scales to make well-informed and balanced decisions. Regarding the adaptation options considered in this study, PPM excels in reducing the number of affected households, whereas RR reduces absolute damage and damage per household more effectively. The complementary nature of these decentralized adaptation options is an advantage with respect to their implementation. Moreover, both measures are apt for enhancing citizen participation in bottom-up risk reduction efforts beyond the existing top-down protection scheme but could be incentivized by the local government. To mitigate the effects of nuisance flooding in HCMC, decision-makers should hence rely on a multi-faceted adaptation portfolio including decentralized measures as shown in this study. Yet future research will have to investigate how different socio-economic pathways may alter flood risk in HCMC with regard to its individual components as well as the implementation of adaptation.

Data Availability Statement

The risk assessment that we present in this study integrates results from various independent models. In particular, we utilized flood hazard maps stemming from an inundation model that is exclusively based on freely available data provided in Scheiber, Hoballah Jalloul, et al. (2023). To estimate exposure, we determined the reconstruction costs of residential buildings based on free data sources as well, specifically OpenStreetMap (OSM, www.openstreetmap.org) retrieved on 1 July 2023, the Global Human Settlement Layer (European Commission, 2022) and the Global Exposure Model (GEM, 2018). The population data used to determine human exposure, in turn, was published in connection with the Vietnam Census (2019). The probabilistic loss model explained in Rafiezadeh Shahi et al. (2023) is provided as lookup table at Rafiezadeh Shahi (2023). These data sets were post-processed, integrated and visualized utilizing custom Matlab and R codes provided on GitHub (www.github.com/LeonSchei/HCMC-RiskAssessment2024; Scheiber, 2024a). Finally, all model outputs are available via Zenodo (www.zenodo.org/records/13912900; Scheiber, 2024b) and were also published as a decision support tool in the context of the research project DECIDER (www.decider-project.org and www.plan-risk-consult.de/decider).

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